EXTERNAL VERSION – PLEASE SEE DISCLAIMER BELOW

PHILADELPHIA WATER DEPARTMENT

Climate-Resilient Planning and Design Guidance

Building Our Future Today

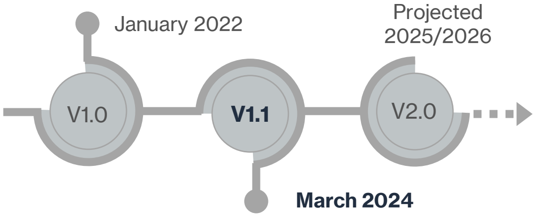
Version 1.1
March 2024

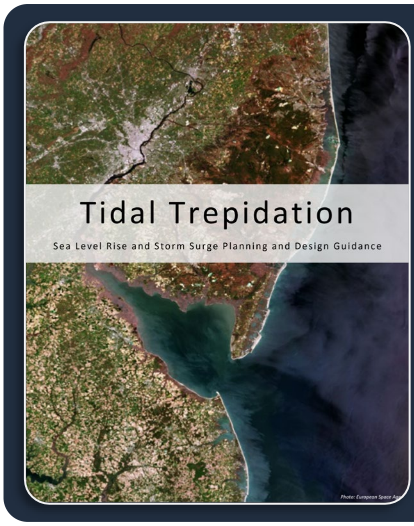
The information, tools and data being shared in this Guidance document were created solely for Philadelphia Water Department (PWD) infrastructure planning and design applications. PWD reserves the right to utilize or refrain from utilizing this Guidance at any given time without notice. Those choosing to use this Guidance or other PWD Climate Change Adaptation Program (CCAP) products for external (i.e. non-PWD) purposes should understand the methodologies utilized, including assumptions and known uncertainties and errors therein. This Guidance document should not be distributed without permission from PWD, and PWD does not assume any risk or liability with its use.

PWD Climate-Resilient Planning and Design Guidance V1.1

Summary of Key Updates, March 2024

Version 1.1 of the Guidance includes updated climate science, guidance and tools for each major climate impact, outlined below. As with V1.0, the precipitation and air temperature projections in V1.1 are based on Global Climate Model (GCM) output from Coupled Model Intercomparison Project Phase 5 (CMIP5). Outputs from a new suite of GCMs (CMIP6), which were released with the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, are currently being analyzed by the PWD Climate Change Adaptation Program (CCAP) and will be included in V2.0.



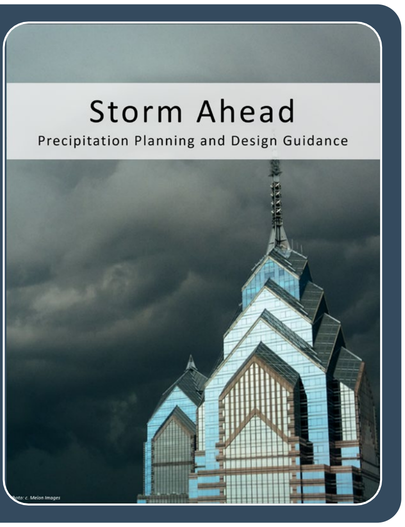

Tidal Trepidation
Sea Level Rise and Storm Surge Planning and Design Guidance

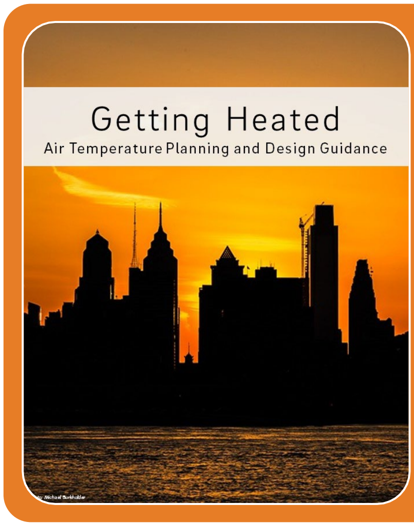
Key updates include new sea level rise (SLR) and storm surge estimates from the *2022 Sea Level Rise Technical Report*, revision of tools to align with the new projections, and adjustments to the Coastal Design Flood Elevation (DFE).

- V1.1 uses SLR projections from NASA's *Interagency Sea Level Rise Scenario Tool* at the Philadelphia tide gauge (Pier 9N).
- The Inundation Mapping Tool, Changing Flood Frequency Tool, and Interceptor Sewer and Regulator Dam Analysis Tool were updated to align with the new projections.
- Updates to the Coastal DFE requirement based on the new projections include:
    - For critical assets, the mid-century and end-of-century DFE increased to 14 ft. NAVD88.
    - New option for a lower DFE with an approved justification and Adaptive Management Plan (AMP) based on asset/system criticality and useful life.

Key updates include new extreme precipitation projections and updated intensity-duration-frequency (IDF) curves.

- To address GCM limitations in simulating extreme events, PWD developed new methods to project a range (low, medium, high) of extreme rainfall increases.
- IDF and depth-duration-frequency (DDF) curves updated with new precipitation projections:
    - Decadal IDF and DDF results generated for 2020-2090.
    - Results from the 'high' method are included in V1.1; use of medium and low results are application-dependent and available upon request.
- A new tool was created to evaluate changes to event return intervals (results available upon request).
- A new method was developed to generate future riverine streamflows and flood elevations, which is being used to establish riverine design flood elevations (DFEs) at PWD facilities.


Storm Ahead
Precipitation Planning and Design Guidance


Getting Heated
Air Temperature Planning and Design Guidance

Key updates include guidance on maintaining safe working conditions for employees who spend time working outdoors. Higher temperatures or longer, more frequent periods of heat may result in greater occupational heat stress, potentially leading to increased occurrence of heat-related fatigue and illnesses. V1.1 provides:

- Information on the current status of proposed regulatory standards for the protection of workers from extreme heat.
- Published guidance on recommended safety precautions to take while working in hot environments.
- Results from two CCAP analyses performed to estimate the increase in risks to outdoor workers by mid- and end-of-century based on (1) heat index – associated risk levels published by the U.S. Occupational Safety and Health Administration (OSHA), and (2) the City of Philadelphia's definition for Code Red Events.

A Message from the Philadelphia Water Department Commissioner

Climate change is here, and the impacts Philadelphia is already facing will only continue to grow over this century. Our city will experience more rain, extreme storms, higher air temperatures, rising sea levels and possibly increased drought. As with other water utilities across the country and the world, climate impacts pose significant challenges to maintaining our core services – providing clean, safe, reliable drinking water and effective, environmentally progressive wastewater and stormwaterservices.

PWD has been committed to providing high-quality services and protecting our region's water resources throughout our nearly 200-year history, and we will continue to fulfill these commitments in the future. To this end, it is our obligation to prepare for climate change by considering climate impacts and adaptation strategies in our planning, design, operations, and management decisions. Our Climate Change Adaptation Program (CCAP) continues to track the latest climate change science and transform that science into actionable products and tools. This Guidance document is a compilation of much of their work and represents an integral component of PWD's climate adaptation approach: mainstreaming the use of climate information in all that we do.

Per official PWD policy adopted in January 2022, it is required that this Guidance be used in the planning, design and construction of all PWD projects to the extent feasible, including the renewal and replacement of existing assets and the constructionof new assets. To the extent relevant, the Guidance must also be applied to the operation and maintenance of PWD infrastructure systems and facilities, including our drinking water treatmentplants and water pollution control plants. We must incorporate and communicate this information in our work to ensure our long-lived investments remain operationally and economically viable, despite the impacts of climate change.

Thank you for being part of the important effort to strengthen the resilience of our utility. By planningfor climate change, we are upholding our commitment to our customers and helping to ensure that our precious resources and critical services are available for generations to come.

Randy E. Hayman, Esq.
Water Commissioner

Preface

This guidance document is intended to provide actionable climate change information that can be directly applied to PWD planning and design processes. In addition to providing guidance and information in memos, reports and this document, the CCAP team is available to help apply climate change information to specific projects and planning efforts. The CCAP team can also provide information to help PWD staff better understand the uncertainty inherent in climate projections, provide strategies to effectively communicate and apply this information and assist with technical assessments to understand risks.

The CCAP SharePoint site has numerous internally available documents that provide detailed information on research areas and technical assessments: *[LINK REMOVED – for internal PWD access only].*

Due to the evolving nature of climate change science, research and modeling efforts at both the international (e.g. Intergovernmental Panel on Climate Change (IPCC)) and national (e.g. National Climate Assessment) levels, this Guidance is a living document that will be updated at a frequency of once every few years. Updates will always be communicated to all relevant PWD staff. Version 1.1 represents an interim update that contains the latest localized sea level rise and storm surge projections from NASA and NOAA, as well as new CCAP extreme precipitation projections and information regarding location-based riverine design flood elevations (DFEs). Additional flexibility has also been added to the most prescriptive requirement in the Guidance, the coastal design flood elevation (DFE), through the use of adaptive management planning. **Any newly initiated planning or design project, from this point forward, should use the information contained in V1.1.**

As with V1.0 (released January 2022), V1.1 still relies on Global Climate Model (GCM) projections from Coupled Model Intercomparison Project Phase 5 (CMIP5). CCAP is carrying out preliminary analyses using statistically downscaled GCM projections from the more recent CMIP6, but downscaled output for the full suite of CMIP6 models is not yet available. Once all downscaled CMIP6 projections are available, CCAP will release a Guidance V2.0 based on the updated projections and emissions scenarios.

Should you have questions regarding this Guidance document, please contact PWD CCAP at: pwd.ccap@phila.gov.

Table of Contents

List of Figures

List of Tables

1 Introduction

The Philadelphia Water Department (PWD) provides essential services to its customers and owns thousands of assets, many of which are critical and costly to design, construct, install and maintain. PWD invests significant capital dollars on improvements, asset replacement and new projects each year. Many of these assets are or will become vulnerable to climate change impacts, making it essential for PWD to ensure that climate risk information is included in the planning, design, operations, and maintenance of infrastructure investments.

In a changing climate, weather patterns shift and can become more extreme. Philadelphia is expected to see increasing temperatures, more precipitation, higher sea levels and more frequent and/or extreme weather events like heat waves – regardless of what future emissions scenario is realized (ICF, 2014). PWD formed the Climate Change Adaptation Program (CCAP) in 2014 to study and address PWD's vulnerabilities and risks to these climate change impacts. To initiate development of the CCAP, a vulnerability survey was carried out with two main objectives: 1) to seek input from staff on perceived vulnerabilities to PWD from climate change impacts; and 2) to evaluate staff input to determine the most immediate, or primary, planning needs for climate change adaptation at PWD. To address these primary planning needs, carry out critical risk assessments and develop effective adaptation strategies, CCAP needed to first develop actionable climate change science and information. The projections, recommendations, and requirements in this guidance document, which will be periodically updated as the climate change science evolves, are a culmination of that effort. In order to ensure the long-term climate resilience of PWD infrastructure systems to sea level rise, increasing precipitation and higher air temperatures, it will be critical to embed this actionable climate change information within all levels of planning, design and operations.

1.1 Purpose and Context

Traditional engineering practice relies on observed data to develop probability-based tools, like design storms and intensity-duration frequency curves, to characterize the level of service a project will provide. Using observed data to characterize risks and associated levels of service assumes that conditions in the past will be the same as conditions in the future – in other words, the climate will remain stationary. With climate change already being observed in our region and around the world, the assumption of stationarity is no longer accurate. Despite this, planners and engineers are still tasked with designing and implementing projects that will be resilient and able to maintain a desired level of service throughout an asset's useful life.

This guidance document was developed to support and supplement planning and design processes at PWD. It is intended to provide staff across the Department with the information and tools necessary to make decisions in the face of uncertainty and include forward-looking climate risk information in all planning and design efforts, including those related to structural *and* non-structural systems. For example, information in this document can be used to inform PWD long-term infrastructure plans, watershed-scale planning initiatives, water quality assessments, standard renew and replace projects, and projects captured by the capital planning process that require an Alternatives Identification Memo (AIM) and Alternatives Evaluation and Recommended Outcome (AERO) report. It should be noted that certain prescriptive requirements, like the coastal design flood elevation (DFE), are relevant to specific applications only (in the case of the coastal DFE, above-ground physical assets in the coastal floodplain).

This guidance was developed based on the best available science and engineering guidance from the international and U.S. climate science community, the academic community, (e.g. Columbia University), foundations (e.g. the Water Research Foundation), peer cities (e.g. New York City), professional societies (e.g. ASCE) and peer utilities (e.g. Water Utility Climate Alliance).

Please note, the information found in this document does not negate the Department's obligation to plan, design and construct projects in accordance with federal, state and local regulations and building codes. The guidance presented here complements, and in most cases enhances, the level of protection achieved through current regulations and requirements.

1.2 Guiding Principles

a. Engineering Standards and Professional Judgement

Engineers are obligated by the American Society of Civil Engineers (ASCE) Code of Ethics to "first and foremost, protect the health, society, and welfare of the public" and to "adhere to the principles of sustainable development" (ASCE, 2020). To specifically address climate change and its implications for the engineering profession, ASCE adopted Policy Statement 360 – Impact of Climate Change (ASCE, 2021). This statement acknowledges that engineering practice in a changing climate requires development of a new paradigm that is guided by updated policies, standards, codes, and regulations.

> ***ASCE supports:*** *'…anticipation of and preparation for impacts of climate change on the built environment and revisions to engineering and design standards, codes, regulations and associated laws that strengthen the sustainability and resiliency of infrastructure at high risk of being affected by climate change.' – Policy Statement 360*

Engineering judgement, in combination with planning expertise, will be fundamental to developing plans and designs that will be robust to future environmental conditions over the service life of an infrastructure system or asset. Climate change requires the expertise of both engineers and planners due to the nature of the dilemma: consequences from climate change, some of which are uncertain, will occur over the long-term, resulting in significant and far-reaching impacts (APA, 2021). The American Planning Association (APA) acknowledges the importance of long-range thinking by stating that professional planners, in striving to comply with their obligation to the public, should "…have special concern for the long-range consequences of past and present actions" (AICP, 2021). This guidance document provides the necessary information for PWD to proactively address climate change in the planning and design of infrastructure by supplementing historic climate data with localized climate change projections.

b. Planning Frameworks for a Non-Stationary Climate

Fundamental to effective climate change adaptation is an understanding of future risk. Risk is defined as the potential for consequences where something of value is at stake and where the outcome is uncertain. Risk is often considered a function of the likelihood or probability of occurrence of a hazardous event and the impact or consequence that results if the event occurs. Risk results from the interaction of vulnerability, exposure, and hazard (IPCC, 2018). When using a risk-based approach, there are several factors that planners and engineers must consider when applying climate projections to a project or plan, specifically:

- the anticipated useful service life of the project;
- the exposure to specific climate change impact(s) (sea level rise, increasing precipitation, higher air temperatures, etc.) that will affect the ability of the project to meet its objectives;
- the vulnerability of the project to climate change impact(s), considering both adaptive capacity[1] and sensitivity[2] to plausible climate change scenarios;
- the criticality of the project to PWD's core services and overall mission and objectives; and,
- the general view that PWD, in relying on critical infrastructure to provide core services, has a low risk tolerance[3] when it comes to climate risks.

Section 3 of this guidance document provides information on risk-based and adaptive management planning approaches that address some of the complexities in working with climate change projections. Adaptive management planning is an effective way to deal with the uncertainty of future climate change and help ensure that sound investment decisions are made. CCAP staff are familiar with adaptive management planning approaches and are available to consult with PWD staff who are hoping to use this planning method.

---

[1] ***Adaptive capacity*** *is defined as the ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences (IPCC, 2018). An asset or system with a high adaptive capacity will be able to practically adapt over time and maintain current functions and/or levels of service as the climate changes.*

[2] ***Sensitivity*** *(sometimes called elasticity) is the degree to which an asset or system is affected by or responds to a climate impact/hazard (i.e., it is a way of characterizing how tolerant to or susceptible to harm the asset or system is to climate change).*

[3] ***Risk tolerance****, in the context of this guidance document, refers to the level of risk the Department is willing to accept when considering climate change impacts. For an asset or infrastructure system risk tolerance may be related to understanding how level of service goals may be impacted.*

c. Fulfilling PWD's Mission through Integrated and Equitable Water Resources Management

A central goal of all utilities is to maintain high levels of service that are driven by factors including regulatory requirements and customer or stakeholder needs and demands (EPA, 2016). In broad terms, the PWD mission is analogous with the utility's level of service goals – to provide a continuous supply of clean, safe and reliable drinking water and effective, environmentally progressive wastewater and stormwater management services. The equitable provision of these services is a critical component of PWD's mission, as indicated below.

> ***PWD Mission:*** *The primary mission of the Philadelphia Water Department is to plan for, operate, and maintain both the infrastructure and the organization necessary to purvey high quality drinking water, to provide an adequate and reliable water supply for all household, commercial, and community needs, and to sustain and enhance the region's watersheds and quality of life by managing wastewater and stormwater effectively.* ***In fulfilling its mission, the utility seeks to be customer-focused, delivering services in a fair, equitable, and cost-effective manner, with a commitment to public involvement.***

Level of service goals, however they are defined, can become challenging to achieve as forces both within and outside a utility's ability to manage occur, including: changing regulatory requirements, changing risk tolerance levels (i.e. acceptable business risk), aging infrastructure, loss of pervious land cover through urbanization and development, population shifts, economic factors and changing climatic conditions (U.S. EPA, 2016). The guidance in this document specifically addresses one of those challenges--it will help ensure that PWD can maintain today's level of service during future climate conditions.

This guidance document presents climate projections, tools and risk management approaches that, if incorporated into a project or plan, will help ensure its long-term resilience. However, this document does not speak to the specific projects or strategies that are needed for PWD to adapt (i.e. this is not a climate adaptation plan). There will always be more than one pathway, or solution, to achieve a desired level of service and meet regulatory requirements, but not all pathways will be as resilient, robust, affordable, adaptable and equitable as others. What is becoming fundamentally clear based on the experiences of other cities and utilities planning for climate change is that new approaches and solutions are needed to maintain levels of service and address the challenges we face today and those we will face in the future. Resilient investments will be adaptive in nature and ideally developed through an integrated water resources management framework[4] that maximizes synergies and produces efficient solutions to meet stormwater, wastewater and drinking water goals.

The importance of integrated water resource planning, specifically, has already been recognized by regulatory agencies. In 2012, the EPA introduced an integrated planning framework for utilities to

---

[4] *For more information on integrated planning frameworks, please see:* https://www.epa.gov/npdes/integrated-planning-municipal-stormwater-and-wastewater.

consider in meeting Clean Water Act (CWA) requirements. Through the Water Infrastructure and Improvement Act (WIIA) of 2019, the CWA was amended to include this integrated planning framework as a voluntary path for utilities to pursue. While integrated water resources management is still in a nascent phase at many utilities, PWD's Green City, Clean Waters (GCCW) program is a notable example of including one aspect of the EPA's definition of an integrated approach: i.e., meeting combined sewer overflow (CSO) regulations by emphasizing the use of green infrastructure. Other aspects of integration stressed by the EPA include NPDES requirements for separate sanitary sewer systems, combined sewer systems, MS4 systems, and wastewater treatment plants. CCAP believes that by addressing climate resilience and prioritizing adaptive, equitable and economically feasible strategies in all the Department's planning processes, additional opportunities for integrated water resources management will arise.

d. Supporting Citywide Resilience

This guidance document currently pertains to PWD infrastructure only, but the Department acknowledges that effective resilience to climate change requires significant coordination and collaboration with other local and regional entities. CCAP is engaged in regional and citywide efforts including the Flood Risk Management Task Force (FRMTF), resilience planning through the Office of Sustainability (OOS), Philadelphia City Planning Commission (PCPC) and the Delaware Valley Regional Planning Commission (DVRPC), and Hazard Mitigation Planning through the Philadelphia Office of Emergency Management (OEM). This document may serve as a reference for City partners also seeking to incorporate climate change projections into their plans and projects.

1.3 A Note on Uncertainty

Climate change adaptation work relies on projections from Global Climate Models (GCMs), which are currently the most credible source available for providing information about the response of global climate systems to increasing greenhouse gas (GHG) concentrations (Hailegeorgis & Burn, 2009*)*. These models are simplified representations of the complex physical processes occurring on earth and the GHG emissions scenarios used to drive GCMs are based on uncertain future socio-economic conditions. Confidence in climate models comes from the fact that they are based on physical principles and can reproduce many aspects of the current climate, including observed trends that are driven by human-induced changes, or anthropogenic forcing *(*Barnett et al., 2005; Hayhoe et al., 2017; Knutti, 2008*)*.

However, climate change impact assessments which use GCM output to inform planning and decision-making processes are subject to uncertainties which originate from multiple sources, including:

- level of future GHG emissions (i.e. emissions scenario);
- the Earth system response to temperature increases; and,
- complex natural and physical processes that are difficult to model or not yet fully understood.

Despite these uncertainties, it is imperative to consider climate change in water resource planning and management. The topic of uncertainty in climate change adaptation—and how to plan and make decisions despite considerable, or deep, uncertainty—is broad and complex. The CCAP explores this topic and attempts to characterize uncertainty in local climate change projections in the memo titled *Characterizing and Addressing Uncertainty in Climate Change Adaptation Planning at the Philadelphia Water Department.*

1.4 Evolving Science and Document Updates

Climate adaptation work is inherently iterative as climate change science and modeling rapidly improve and new information is uncovered about the earth's response to a warming atmosphere. The needs and priorities of the Department also evolve over time, informing what is contained in this Guidance document. Periodic updates, at an estimated frequency of once every few years, will be made with new climate science and potentially more detailed information on risk-based planning methodologies. Updates to this document will generally follow major climate science report updates at the international level (i.e. the Intergovernmental Panel on Climate Change (IPCC) reports) and the national level (i.e. National Climate Assessments).

Throughout this guidance document, links to existing CCAP memos and documents provide more detail on certain research areas and technical analyses. Projections used in earlier memos and reports may not be the most up to date given the rapidly evolving field of climate science. The primary purpose of referencing earlier memos is to provide information on CCAP methods and assumptions. For the most recent projections, this guidance document (and subsequent updates) should be referenced. If specific, up-to-date information and projections pertaining to earlier memos and reports is being sought, please contact CCAP.

1.5 In Summary

Despite uncertainties regarding the magnitude and pace of climate change, there is enough information that is certain to warrant the use of climate change projections in PWD planning and design processes.

What is certain regarding climate change in Philadelphia?

- ➢ *For our region, there is very high confidence in the direction of change for multiple climate impacts.*
  - Temperatures will continue to increase. Even if global greenhouse gas emissions are stopped today, the world is locked into a certain amount of warming.
  - Precipitation volumes and intensities will increase as the climate warms.
  - Sea levels will continue to rise and the rate of rise will continue increasing.

What is less certain?

- ➢ *There is lower confidence in the specific rate and magnitude of climate change impacts over the coming century. Many of these uncertainties, including those listed below, hinge on the future emissions scenario that occurs.*
  - The future rate and magnitude of temperature rise
  - The effect of climate change on the natural variability of precipitation
  - The percent change and variation in increasing precipitation for different event sizes
  - The future frequency and intensity of extreme events like hurricanes
  - The rate and magnitude of sea level rise
  - The changing frequency and/or severity of droughts

How is PWD's Climate Change Adaptation Program (CCAP) dealing with these uncertainties and helping the Department become climate-resilient?

- *CCAP carries out the following as part of its mission to ensure PWD's long-term resilience to climate change:*
    - **Utilize the best available science to inform decision-making.** This guidance document provides current estimates of climate change based on today's best available science.
    - **Adopt new science consistent with recommendations from leading scientific organizations.** CCAP will continue to track how climate science evolves and will provide periodic updates to this guidance as new projections are officially recognized by leading organizations like the National Oceanic and Atmospheric Administration (NOAA) and the Intergovernmental Panel on Climate Change (IPCC).
    - **Provide support on ways in which to plan, design and implement changes despite uncertainty.** Planning approaches that address decision-making under deep uncertainty are available and considered an important aspect of effective adaptation. CCAP can provide resources and support efforts to incorporate best practice planning approaches at PWD.

CCAP can provide the information and tools necessary to help PWD adapt to climate change, but effective adaptation is only possible with the input and applied expertise of staff across this organization. Together, PWD employees can help ensure the utility's long-term resilience in the face of climate change.

1.6 References

American Institute of Certified Planners (AICP). (2021, November). *AICP Code of Ethics and Professional Conduct.* American Planning Association. https://www.planning.org/ethics/ethicscode/

American Planning Association (APA). (2021, January 1). *Climate Change Policy Guide.* Climate Change Policy Guide (planning-org-uploaded-media.s3.amazonaws.com)

American Society of Civil Engineers (ASCE). (2020). *Code of Ethics*. https://www.asce.org/-/media/asce-images-and-files/career-and-growth/ethics/documents/asce-code-ethics.pdf

American Society of Civil Engineers (ASCE). (2021). *Policy Statement 360 – Climate change.* https://www.asce.org/advocacy/policy-statements/ps360---climate-change

Barnett, T. P., Adam, J. C., & Lettenmaier, D. P. (2005, November 17). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, *438*, 303-309. doi:10.1038/nature04141

Hailegeorgis, T. T. & Burn, D. H. (2009). Uncertainty Assessment of the Impacts of Climate Change on Extreme Precipitation Events. *Report to the Canadian Foundation for Climate and Atmospheric Sciences.* University of Waterloo. [PDF] Uncertainty Assessment of the Impacts of Climate Change on Extreme Precipitation Events | Semantic Scholar

Hayhoe, K., Edmonds, J., Kopp, R. E., LeGrande, A. N., Sanderson, B. M., Wehner, M. F., & Wuebbles, D. J. (2017). Climate models, scenarios, and projections. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. U.S. Global Change Research Program, Washington, DC, USA, pp. 133-160. doi:10.7930/J0WH2N54

ICF International. (2014, August). *Useful Climate Information for Philadelphia: Past and Future.* City of Philadelphia, Mayor's Office of Sustainability. https://www.phila.gov/media/20160505145605/Useful-Climate-Science-for-Philadelphia.pdf

Intergovernmental Panel on Climate Change (IPCC). (2018). Glossary. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 541-562. doi:10.1017/9781009157940.008

Knutti, R. (2008, September 25). Should we believe model predictions of future climate change? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 366*(1885), 4647-64. https://doi.org/10.1098/rsta.2008.0169.

Rockwell, Julia. (2015). *Climate Change Adaptation Program: Vulnerability Survey.* Philadelphia Water Department.

United States Environmental Protection Agency (U.S. EPA). (2016). *Fundamentals of Asset Management: Step 5. Set Target Level of Service: A Hands-On Approach.* https://www.epa.gov/sites/production/files/2016-01/documents/set-target-level-of-service.pdf

2 User Guide

2.1 Document Purpose

This guidance document was developed to support and supplement planning and design processes at PWD. While the primary end users of this information will be planners and design engineers, this document is intended to provide staff across the Department, as well as their consultants, with the information and tools necessary to make decisions in the face of climate-related uncertainty and include forward-looking climate risk information in all project plans and designs. CCAP will continue to track the latest climate science, research and modeling efforts and incorporate any critical updates into future versions of this guidance.

Please note, the information found in this document does not negate the Department's obligation to plan, design and construct projects in accordance with federal, state and local regulations and building codes. The guidance presented here complements, and in most cases enhances, the level of protection achieved through current regulations and requirements.

2.2 The Contents of this Document

The guidance in this document is presented in sections that are organized by climate change impact. The approach taken to develop planning and design guidance for each climate impact depends on several factors, most notably the risk the impact poses to PWD, the current approach(es) for using climate data in PWD planning and design processes and the consideration of level of service goals. Although the content and approach differ by climate impact, the ultimate goal of each section in this document is the same: provide actionable climate information that can be used to ensure the long-term resilience of PWD infrastructure.

For each climate impact currently under consideration by CCAP, the following guidance is presented in this document:

- **Sea level rise and extreme storms (4-1 through 4-40)**
    - This section presents information and tools developed by CCAP to apply sea level rise projections in planning and design at PWD. It also establishes a required design flood elevation (DFE), or design standard, for PWD assets that are vulnerable to current and/or future surface flooding along the tidal Delaware River.
- **Precipitation (5-1 through 5-25)**
    - This section presents a series of products developed by CCAP that allow for precipitation projections to be directly applied to PWD planning and design efforts, including future intensity-duration-frequency (IDF) curves and riverine design flood elevations (DFEs) that reflect future precipitation increases.
- **Air temperature (6-1 through 6-27)**
    - The focus of this section is to characterize local air temperature projections. Guidance is provided on maintaining safe working conditions for employees with work assignments outside of the office, as higher temperatures or longer, more frequent periods of heat may result in greater occupational heat-related hazards.

Adaptation at water utilities is an iterative process that relies on technical assessments to fully understand and characterize risks. For each climate impact that is included in this guidance document, future areas of consideration will be summarized. While this document represents a culmination of several technical analyses and assessments, there are additional areas for CCAP to consider moving forward. For example, it will be necessary to evaluate the combined, or compound, flooding impacts of sea level rise and precipitation-induced flooding. Guidance on considering compound flooding events may be provided in future iterations of this document.

Additional resources for topics that are relevant but outside the scope of this current document can be found in the supplemental 'Additional Resources and Information' (AIR) sheets in Appendix A-1.

2.3 Relevance of Guidance Projections, Tools and Prescriptive Requirements

The matrix on the next page provides an inventory of the projections, tools and prescriptive requirements that can be found in this guidance document (**Figure 2-1**). The main sections in this document are organized by climate impact: sea level rise, precipitation and air temperature. For each of the major PWD programmatic and project-based planning and design groups, the likely relevance of the information in this guidance document is categorized as follows: *definitely relevant, potentially relevant* or *not relevant.* This matrix is meant to serve as a quick reference guide and is not necessarily inclusive of all PWD planning/design efforts or potential applications of the information in this document.

2.4 What is Recommended vs. What is Required?

It is required that climate change projections be considered in the planning and design of all PWD projects. However, for the majority of the information in this guidance document, there is no prescriptive requirement as to which specific climate change projections or future scenarios must be applied. The only exceptions to this are two new prescriptive planning and design requirements related to sea level rise: PWD's coastal design flood elevation (DFE) and the associated adaptive management plan requirement. ***Please note that it is the responsibility of PWD project manangers to ensure that contractors competing for a project/scope of work through the Request for Proposal (RFP) process are fully aware of PWD's climate resiliency planning and design requirements.*** See the RFP AIR sheet for more information *[LINK REMOVED – for internal PWD access only]*.

2.5 CCAP Support

CCAP staff is available to help apply the projections, information and tools described in this guidance document. They can provide input at the project-level to help identify climate change impacts and risks, alternatives and adaptive management strategies. The CCAP can also provide information to help users better understand the uncertainty inherent in climate and SLR projections, provide strategies to help communicate this information and assist with technical tasks, assessments and decision-making. For additional reference, a full list of CCAP documents, resources and tools can be found in Appendix A-1.

Please contact one of the following CCAP team members for support: Julia Rockwell, Manager, CCAP (julia.rockwell@phila.gov); Tsega Anbessie, Environmental Engineer, CCAP (tsega.anbessie@phila.gov);

Allison Lau, Civil Engineer, CCAP (allison.lau@phila.gov); or Ashley Ebrahimi, Civil Engineer, CCAP (ashley.ebrahimi@phila.gov).

🟦 Definitely relevant · 🟧 Potentially relevant · ╱ Not relevant

	Guidance Section, page #	Capital projects*	Water Master Planning	WW Master Planning	CSO Planning/LTCPU	MS4 Planning	Water Supply Planning	Flood Risk Management	Risk Assessments or Sensitivity Analyses**
Sea Level Rise									
Projections (NASA 2022)	4-13	🟧	🟦	🟦	🟦	🟦	🟦	🟦	🟧
Future tidal datums	4-17	🟧	🟦	🟦	🟦	🟦	🟧	🟦	🟧
Storm Surge and Future Storm Tide Elevations	4-19	🟧	🟦	🟦	🟦	🟦	🟧	🟦	🟧
Forward-Looking Inundation Mapping	4-19	🟧	🟦	🟦	🟦	🟦	🟧	🟦	🟧
Changing Flood Frequency Tool	4-22	🟧	🟦	🟦	🟦	🟦	🟧	🟦	🟧
Interceptor Sewer and Regulator Dam Analysis Tool	4-24	🟧	╱	🟦	🟦	🟦	╱	🟦	🟧
Design flood elevation (prescriptive req.)	4-26	🟧	🟦	🟦	🟧	🟧	╱	🟦	🟧
Adaptive management plan (prescriptive req.)	4-30	🟧	🟦	🟦	🟧	🟧	╱	🟦	🟧
Precipitation									
Average Precipitation Increases Based on Future Time Series	5-9	🟧	🟧	🟦	🟦	🟦	🟧	🟦	🟧
Event-Based Extreme Precipitation Increases	5-11	🟧	🟧	🟦	🟦	🟦	🟧	🟦	🟧
Projections for High Resolution Future Time Series	5-13	🟧	🟧	🟧	🟧	🟧	🟧	🟦	🟧
Projections for Future Design Storms and IDF/DDF Curves	5-13	🟧	╱	🟧	🟦	🟦	╱	🟦	🟧
Future Changes to Storm Return Intervals	5-15	🟧	🟧	🟧	🟦	🟦	🟧	🟦	🟧
Stochastic rainfall generator tool	5-16	🟧	╱	🟧	🟧	🟧	╱	🟦	🟧
Future Changes to Streamflow and Riverine Flood Return Intervals	5-16	🟧	🟧	🟧	🟧	🟧	╱	🟦	🟧
Air Temperature									
Drinking Water Impacts	6-5	🟧	🟦	╱	╱	╱	🟦	╱	🟧
Source Water and Regulatory Compliance Planning	6-7	🟧	🟧	🟧	🟧	🟧	🟦	╱	🟧
Wastewater Treatment	6-7	🟧	╱	🟦	╱	╱	╱	╱	🟧
Maintaining Safe Working Conditions	6-8	╱	╱	╱	╱	╱	╱	╱	🟧
Projections of Annual Average and Monthly Average Temperatures (RCPs 4.5 and 8.5)	6-17	🟧	🟧	🟧	🟧	🟧	🟦	╱	🟧
Projections of Extreme Summer Temperatures (RCPs 4.5 and 8.5)	6-21	🟧	🟧	🟧	🟧	🟧	🟦	╱	🟧

Figure 2-1. Matrix inventory of the projections, tools, and prescriptive requirements.

Includes new assets and renewal/replacement of existing assets; includes capital projects above **AND below $2M threshold.*

***Various assessments apply. If dealing with climate-related risks, will likely be led by CCAP.*

Uncertain Futures

Planning Under Deep Uncertainty

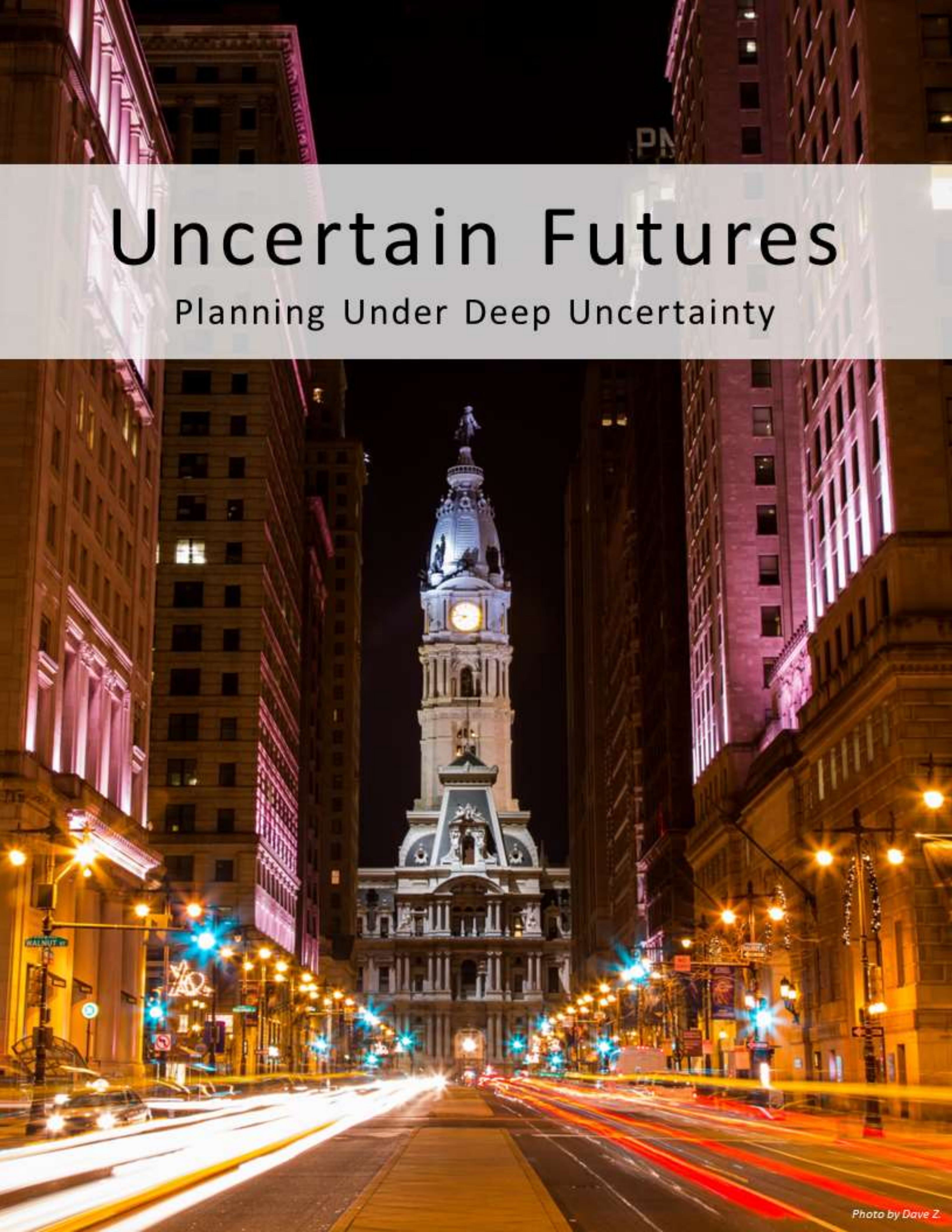


Photo by Dave Z.

3.1 Planning at PWD

Although there is consensus that increasing temperatures and precipitation as well as sea level rise will continue to occur, there is great uncertainty as to the magnitude and timing of these projections. For this reason, planning and design guidance must include recommendations for dealing with this uncertainty. This section is structured to provide information and tools that work within the existing PWD planning programs, rather than resulting in a separate climate adaptation plan. There are a number of planning efforts where climate change impacts must be considered, including during phases of plan development, updates and implementation. Including climate change projections in PWD planning efforts will ensure long-term resilience of infrastructure investments and the ability to meet regulations and compliance targets in the future. Relevant PWD planning efforts are listed below along with some of the primary climate change related impacts to be considered in each plan or planning process.

- **Wastewater Master Plan**: Assets related to the wastewater treatment plants must consider potential flooding issues related to both sea level rise and storm surges, as well as increased flows due to increases in precipitation. Part of the planning effort must include risk assessments for each critical asset.
- **Drinking Water Revitalization Plan**: Assets related to the water treatment plants must consider both potential flooding issues related to sea level rise, storm surges and riverine flooding, as well as the impacts of increasing temperature on source water quality and treatment processes. Part of the planning effort must include risk assessments for each critical asset.
- **Capital Planning Process**: The capital planning process includes alternatives identification and evaluation for each identified project need. This process must incorporate potential impacts of climate change in the alternative evaluation criteria, and considerations for responding to climate change impacts must be included within the basis for design.
- **CSO Long Term Control Plan Update (Green City, Clean Waters):** This plan is in response to the combined sewer overflow Consent Order and Agreement (COA) with PADEP. The plan includes both collection system storage and transmission improvements, wastewater treatment plant expansion, as well as green stormwater infrastructure implementation. Designs should consider the likelihood of increasing precipitation due to climate change and sea level rise.
- **Stormwater Planning (MS4):** The separate stormwater collection system is required to reduce pollutant loads to receiving waters. Plans and designs should consider the likelihood of increasing precipitation and sea level rise due to climate change.
- **Emergency Response Planning:** The Office of Emergency Management works to ensure the City of Philadelphia is ready for any kind of emergency, including those caused by natural hazards. The City's Hazard Mitigation Plan is a comprehensive assessment of natural and anthropogenic hazards that is updated regularly. In Philadelphia, flooding is a key element in emergency planning and response and should consider increased storm intensity and extreme rainfall due to climate change, as well as storm surge/sea level rise flooding risks.
- **Linear Asset Planning**: PWD plans and implements the renewal and replacement of stormwater and wastewater collection systems. Part of the program is to assess impacts of increasing precipitation intensity on level of service and selected design storms.

- **Water Resource and Source Water Protection Planning:** PWD uses a multi-barrier approach that includes emergency preparedness systems, computer modeling systems, regional and national partnerships, and the development and implementation of formal plans to protect PWD source waters and guide infrastructure investments. Climate change information should inform these initiatives as they relate to the long-term protection and reliability of Philadelphia's water resources.

3.2 Sources of Uncertainty

As mentioned in the Introduction to this document, GCMs are the most credible source available for providing information about the response of global climate systems to increasing greenhouse gas (GHG) concentrations. These models are simplified representations of the complex physical processes occurring on earth and the GHG emissions scenarios used to drive GCMs are based on uncertain future socioeconomic conditions. Confidence in climate models comes from the fact that they are based on physical principles and can reproduce many aspects of the historic and current climate, including observed trends that are driven by human-induced changes. However, climate change impact assessments which use GCM output to inform planning and decision-making processes are subject to uncertainties which originate from multiple sources. Some of the major uncertainties in projecting climate change impacts include:

- the likelihood of emission scenarios coming to fruition and all the factors that influence them including anthropogenic emissions, land use change, population growth, etc.;
- the Earth system response to temperature increases;
- models may not accurately represent the way the climate will change under emissions scenarios;
- complex natural and physical processes that are difficult to model or not yet fully understood; and,
- uncertainty related to downscaling approaches that transform the resolution of raw GCM output into finer spatial and temporal scales.

In addition to uncertainties related to GCMs that provide temperature and precipitation projections, sea level rise estimates, which rely on models and processes external to the GCMs, also must consider uncertainty related to many factors including: the dynamics of thermal expansion of the oceans, ocean circulation changes, vertical movement of the land surface, marine ice sheet dynamics and plausible estimates of ice sheet flow through outlet glaciers.

3.3 Dealing with Uncertainty

Planning and designing for an uncertain future are not new to PWD and the engineering practice; however, planners and designers at PWD must seek to deal with a new level of uncertainty when applying climate change projections, particularly those related to sea level rise and precipitation intensity for larger storms. CCAP is responsible for ongoing assessments of uncertainty in climate change impacts, in applying methods to reduce uncertainty where feasible, and to communicate uncertainty to the users of the climate change guidance. Traditional risk assessments have been the primary approach planners and engineers take to manage uncertainties in the future (American Society of Civil Engineers (ASCE), 2015; Ayyub, 2014). Risk is measured as the probability of the occurrence of an event and the outcomes or consequences (i.e., social, environmental, health consequences) associated with the occurrence of the event. Risk management uses information from the risk assessment to make informed decisions, either to accept the risk or reduce it.

In planning for uncertainty, there are a few key concepts that must be considered when deciding on the degree of acceptable risk for a given asset. These include:

- **Anticipated useful life.** A capital project should ideally be designed to withstand climate conditions projected all the way through the end of its anticipated useful life (the estimated number of years an asset will be in use before needing reinvestment to continue performing its normal function).
- **Criticality**. Climate design adjustments should consider and be tailored to the criticality of a project, with more critical projects or project components designed to higher protection standards.
- **Risk tolerance**. Climate design adjustments should be selected based on risk tolerance levels – and the corresponding climate projections – for relevant climate hazards. Familiar examples of risk tolerance levels are the 5-, 10-, 25-, or 100-year precipitation design storms used to design stormwater assets.

Over the last decade climate change adaptation research has focused on developing and adopting planning and decision-making methods to help develop robust adaptation strategies that help users deal with uncertainty (Döll & Romero-Lankao, 2016; Stratus Consulting & Denver Water, 2015). Adaptive management approaches (sometimes called ‘bottom-up’ approaches) are now being brought forward as most appropriate for addressing the deep uncertainty associated with climate change adaptation. The idea is to identify climate change related impacts during the planning and design phases of a project and pair them with measures that could be implemented as needed throughout the life of the infrastructure to address these impacts. **Section 4** of this document provides more information on this planning approach in the context of the Design Flood Elevation (DFE) and Adaptive Management Plan (AMP) requirement aimed at reducing the long-term risks of sea level rise and storm surge to PWD infrastructure.

More information on climate uncertainty can be found in the 2018 CCAP memo *Characterizing and Addressing Uncertainty in Climate Change Adaptation Planning at PWD*. Additionally, a brief literature review comparing traditional, risk-based planning approaches with a variety of uncertainty focused approaches, including adaptive management planning, can be found in the Additional Information and Resources (AIR) sheet titled *Adaptive Management Planning*. CCAP staff are ready to help in any planning effort seeking to incorporate uncertainty into the planning process.

3.4 Scale and System-Wide Considerations

When using the information provided in this guidance —and with all adaptation work in general—issues related to scale and scope arise. For example, if applying the PWD design flood elevation (DFE) detailed in Section 4 to one asset or one part of a system that is vulnerable to coastal flooding, there is a risk of creating “islands of resiliency” within an otherwise vulnerable facility. Similarly, if upsizing a pipe in the collections system to meet level of service goals under future conditions, system-wide analyses should be conducted first in order to avoid creating capacity issues downstream of the upsized pipe. Adaptation will only be successful if strategies are considered at a broader, systemic scale. Therefore, while these guidelines are required for any new capital project, it is extremely important that resiliency is considered holistically and that this guidance is also considered in existing long-term plans (e.g., the Wastewater Master Plan and the Water Master Plan).

3.5 References

American Society of Civil Engineers (ASCE). (2015). *Adapting Infrastructure and Civil Engineering Practice to a Changing Climate.* American Society of Civil Engineers. https://doi.org/10.1061/9780784479193

Ayyub, B. M. (2014). *Risk Analysis in Engineering and Economics* (2nd ed.). CRC Press. https://www.crcpress.com/Risk-Analysis-in-Engineering-and-Economics-Second-Edition/Ayyub/p/book/9781466518254

Döll, P., & Romero-Lankao, P. (2016). How to embrace uncertainty in participatory climate change risk management – A roadmap. *Earth's Future 5*(1), 18–36. https://doi.org/10.1002/2016EF000411.

Stratus Consulting & Denver Water. (2015). *Embracing Uncertainty: A Case Study Examination of How Climate Change is Shifting Water Utility Planning.* Prepared for the Water Utility Climate Alliance (WUCA), the American Water Works Association (AWWA), the Water Research Foundation (WRF), and the Association of Metropolitan Water Agencies (AMWA) by Stratus Consulting Inc., Boulder, CO (Karen Raucher and Robert Raucher) and Denver Water, Denver, CO (Laurna Kaatz). https://www.wucaonline.org/assets/pdf/pubs-uncertainty.pdf

3.6 Further Readings

American Society of Civil Engineers (ASCE). (2018). *Climate-Resilient Infrastructure: Adaptive Design and Risk Management, MOP 140*. https://doi.org/10.1061/9780784415191

Bhave, A. G., Mishra, A., & Raghuwanshi, N. S. (2014). A combined bottom-up and top-down approach for assessment of climate change adaptation options. *Journal of Hydrology, 518*, 150-161. https://doi.org/10.1016/j.jhydrol.2013.08.039.

Bhave, A. G., Conway, D., Dessai, S., & Stainforth, D. A. (2018). Water resource planning under future climate and socioeconomic uncertainty in the Cauvery River Basin in Karnataka, India. *Water Resources Research, 54*(2), 708-728. https://doi.org/10.1002/2017WR020970

Brown, C., Ghile, Y., Laverty, M., & Li, K. (2012). Decision scaling: Linking bottom-up vulnerability analysis with climate projections in the water sector. *Water Resources Research, 48. https://agwaguide.org/docs/Brown_et_al-2012-Water_Resources_Research.pdf*

Buurman, J., & Babovic, V. (2016). Adaptation Pathways and Real Options Analysis: An approach to deep uncertainty in climate change adaptation policies. *Policy and Society, 35*(2), 137-150. https://doi.org/10.1016/j.polsoc.2016.05.002

Colloff, M., Dunlop, M., & Gorddard, R. (2018). The values-rules-knowledge framework in adaptation decision making: a primer. *CSIRO Land and Water, Canberra.* http://dx.doi.org/10.13140/RG.2.2.13783.11688/1

Dittrich, R., Wreford, A., & Moran, D. (2016). A survey of decision-making approaches for climate change adaptation: Are robust methods the way forward? *Ecological Economics, 122,* 79-89. https://doi.org/10.1016/j.ecolecon.2015.12.006

Goddard, R., Colloff, M. J., Wise, R. M., Ware, D., & Dunlop, M. (2016). Values, rules and knowledge: Adaptation as change in the decision context. *Environmental Science & Policy, 57,* 60-69. https://doi.org/10.1016/j.envsci.2015.12.004

Haasnoot, M., Kwakkel, J. H., Walker, W. E., & ter Maat, J. (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change, 23*(2), 485-498. https://doi.org/10.1016/j.gloenvcha.2012.12.006

Haasnoot, M., Warren, A., & Kwakkel, J. H. (2019). Dynamic Adaptive Policy Pathways (DAPP). In Marchau, V., Walker, W., Bloemen, P., & Popper, S. (Eds.), *Decision Making under Deep Uncertainty* (pp. 71-92). Springer, Cham. https://doi.org/10.1007/978-3-030-05252-2_4

Hallegatte, S., Shah, A., Lempert, R., Brown, C., & Gill, S. (2012). Investment Decision Making under Deep Uncertainty – Application to Climate Change. In *Policy Research Working Papers.* The World Bank. https://doi.org/10.1596/1813-9450-6193

Korteling, B., Dessai, S., & Kapelan, Z. (2013). Using Information-Gap Decision Theory for Water Resources Planning Under Severe Uncertainty. *Water Resources Management, 27,* 1149-1172. https://doi.org/10.1007/s11269-012-0164-4

Kwadijk, J. C.J., Haasnoot, M., Mulder, J. P.M., Hoogvliet, M. M.C., Jeuken, A. B.M., van der Krogt, R. A.A., van Oostrom, N. G.C., Schelfhout, H. A., Velzen, E. H., van Waveren, H., & de Wit, M. J.M. (2010). Using adaptation tipping points to prepare for climate change and sea level rise: a case study in the Netherlands. *Wiley Interdisciplinary Reviews: Climate Change, 1*(5), 729-740. https://doi.org/10.1002/wcc.64

Kwakkel, J. H., Haasnoot, M., & Walker, W. E. (2016). Comparing Robust Decision-Making and Dynamic Adaptive Policy Pathways for model-based decision support under deep uncertainty. *Environmental Modelling & Software, 86,* 168-183. https://doi.org/10.1016/j.envsoft.2016.09.017

Lempert, R. J., Popper, S. W., & Bankes, S. C. (2003). *Shaping the Next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis.* Rand Corporation. https://www.rand.org/pubs/monograph_reports/MR1626.html

Lempert, R. J., Groves, D. G., Popper, S. W., & Bankes, S. C. (2006). A General, Analytic Method for Generating Robust Strategies and Narrative Scenarios. *Management Science, 52*(4), 514-528. https://www.jstor.org/stable/20110530

Lempert, R. J., & Collins, M. T. (2007). Managing the risk of uncertain threshold responses: comparison of robust, optimum, and precautionary approaches. *Risk analysis: An Official Publication of the Society for Risk Analysis, 27*(4), 1009-1026. https://doi.org/10.1111/j.1539-6924.2007.00940.x

Lempert, R. (2013). Scenarios that illuminate vulnerabilities and robust responses. *Climatic Change, 117,* 627-646. https://doi.org/10.1007/s10584-012-0574-6

Parris, A. S., Bromirski, P., Burkett, V., Cayan, D. R., Culver, M. E., John, H., Horton, R. M., Knuuti, K., Moss, R. H., Obeysekera, J., Sallenger, A. H., & Weiss, J. (2012). *Global Sea Level Rise Scenarios for the United States National Climate Assessment.* NOAA Technical Report OAR CPO-1. https://repository.library.noaa.gov/view/noaa/11124

Pahl-Wostl, C., Sendzimir, J., Jeffrey, P., Aerts, J., Berkamp, G., & Cross, K. (2007). Managing Change toward Adaptive Water Management through Social Learning. *Ecology & Society, 12*(2). https://doi.org/10.5751/ES-02147-120230

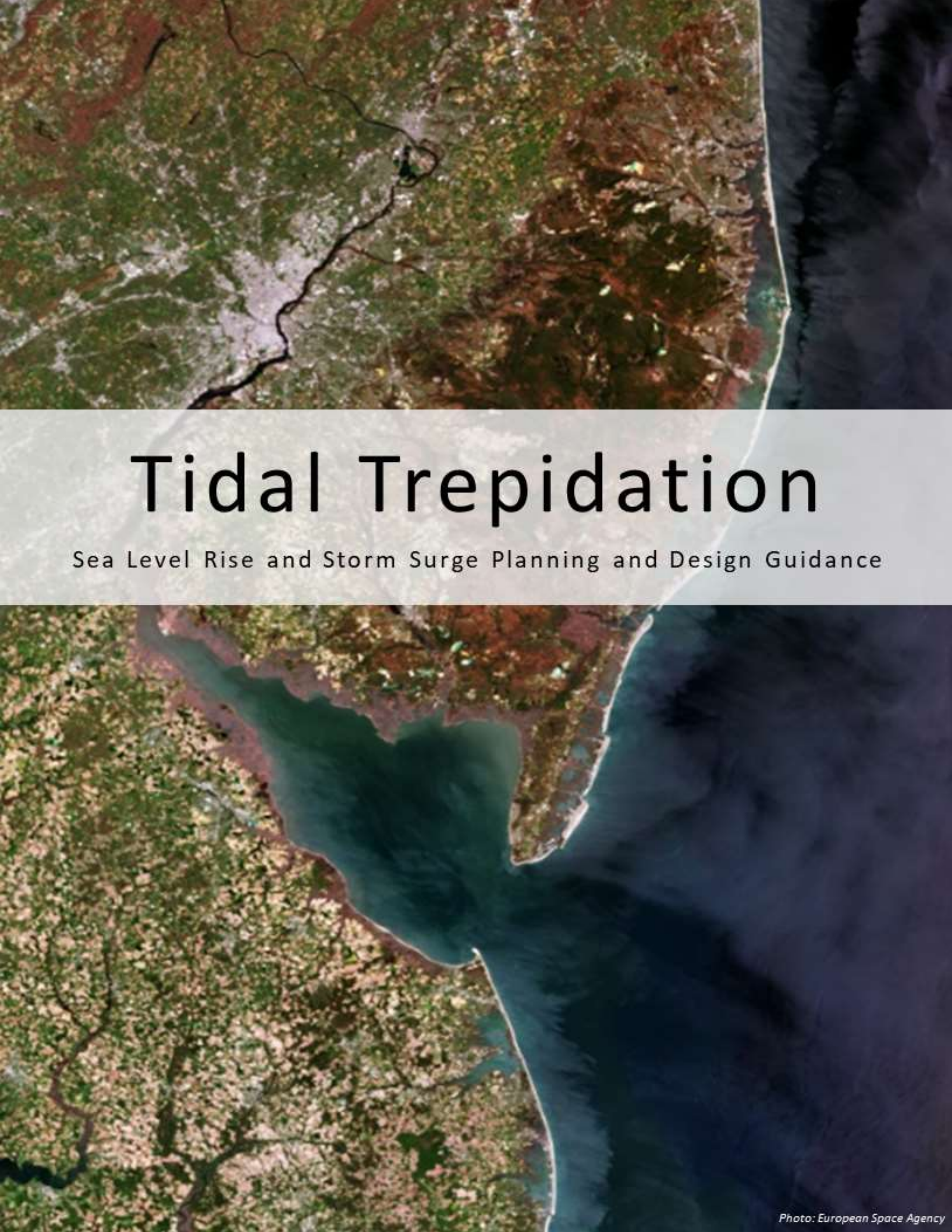
Ray, P. A., & Brown, C. M. (2015). *Confronting Climate Uncertainty in Water Resources Planning and Project Design: The Decision Tree Framework.* The World Bank. https://doi.org/10.1596/978-1-4648-0477-9

Ramm, T. D., Watson, C. S., & White, C. J. (2018). Strategic adaptation pathway planning to manage sea-level rise and changing coastal flood risk. *Environmental Science & Policy, 87,* 92-101. https://doi.org/10.1016/j.envsci.2018.06.001

Renn, O., Klinke, A., & van Asselt, M. (2011). Coping with Complexity, Uncertainty and Ambiguity in Risk Governance: A Synthesis. *Ambio, 40,* 231-246. https://doi.org/10.1007/s13280-010-0134-0

Rosenzweig, C., Solecki, W., Hammer, S. A., & Mehrotra, S. (2010). Cities lead the way in climate-change action. *Nature, 467,* 909-911. http://dx.doi.org/10.1038/467909a

Wise, R. M., Fazey, I., Stafford Smith, M., Park, S. E., Eakin, H. C., Archer Van Garderen, E. R. M., & Campbell, B. (2014). Reconceptualising adaptation to climate change as part of pathways of change and response. *Global Environmental Change, 28,* 325-336. https://doi.org/10.1016/j.gloenvcha.2013.12.002



Tidal Trepidation

Sea Level Rise and Storm Surge Planning and Design Guidance

Photo: European Space Agency

Roadmap

B Background information and justification of information presented
P Relevant to PWD planning processes
D Relevant to an asset or system design

This brief section provides **background information** about sea level rise, both global and local, with emphasis on what has been observed in Philadelphia and how much sea level rise we are projected to see in the future. B

This section provides general information on **how and when it is appropriate (or not appropriate) to use the climate information and tools** provided in this section. B

This section holds the **bulk of applicable information,** such as sea level rise projections and customized tools, to facilitate the integration of future coastal flood risk hazards into PWD's planning and design processes. P D

This section introduces a mandatory design standard for the Department: a design flood elevation for projects and assets in the current and future floodplain. It also introduces an **adaptive management planning** approach and its criteria. P D

CCAP's latest work on evaluating climate change impacts on riverine flooding. B

4.1 Key Terms

Key Term	Acronym	Definition
100-year floodplain	--	The area of land that is inundated by a flood having a 1 in 100 or 1% chance of being equaled or exceeded in any given year. Most often, people refer to the 100-year floodplain established by the Federal Emergency Management Administration (FEMA) as it is used for the Federal Flood Insurance Program. However, the 100-year floodplain can be determined by others (e.g. other governmental departments like the USGS, municipalities, engineering firms and academics) using local data and models.
500-year floodplain	--	The area of land that is inundated by a flood having a 1 in 500 or 0.2% chance of being equaled or exceeded in any given year. Most often, people refer to the 500-year floodplain established by the Federal Emergency Management Administration (FEMA), but the 500-year floodplain can be determined by others (e.g. other governmental departments like the USGS, municipalities, engineering firms and academics) using local data and models.
Absolute sea level	--	Refers to the height of the ocean surface, regardless of whether nearby land is rising or falling.
Adaptive management	--	Adaptive management is an iterative, systematic decision-making process for improving resource and infrastructure-based management in the face of uncertainty. Adjustments are made over time as insights are gained from management outcomes and conditions change.
Annual exceedance probability	**AEP**	The probability of a flood event of a particular magnitude or larger occurring in any given year.
Anticipated useful life	--	An estimated number of years an asset will be in use before needing reinvestment to continue performing its normal function(s). The anticipated useful life assumes regular and adequate maintenance and repairs are implemented. This differs from the design life, which is typically shorter.
Base Flood Elevation	**BFE**	The flood having a one percent chance of being equaled or exceeded in any given year. The base flood is the national standard used by the National Flood Insurance Program (NFIP) and all Federal agencies for the purposes of requiring the purchase of flood insurance and regulating new development.
Climate Change Adaptation Program	**CCAP**	The program at the Philadelphia Water Department working on climate change adaptation.
Coastal inundation (coastal flooding)	--	When normally dry, low-lying land is flooded by seawater, brackish water or freshwater in a tidal river system.
Critical asset	--	An asset whose absence or unavailability would significantly degrade the ability of a utility to carry out its mission or would have unacceptable financial or political consequences for the owner or the community (AWWA J100, 2014).
Datum	--	A base elevation or starting point used as a fixed reference for heights, depths or distance. It is the basis for all geodetic survey work.

Design flood elevation	**DFE**	A new protective elevation for PWD assets to be raised, hardened, or protected. It is higher than current protective elevations found in national and local floodplain regulations.
Federal Emergency Management Agency	**FEMA**	FEMA supports citizens and emergency personnel to build, sustain, and improve the nation's capability to prepare for, protect against, respond to, recover from, and mitigate all hazards.
Flood Insurance Rate Maps	**FIRMS**	The official map of a community on which FEMA has delineated both the special flood hazard areas and the risk premium zones.
Glacial isostatic adjustment	**GIA**	The adjustment process of the earth to an equilibrium state resulting in an ongoing movement of land once burdened by ice-age glaciers.
Highest astronomical Tide	**HAT**	The elevation of the highest predicted astronomical tide expected to occur at a specific tide station over the National Tidal Datum Epoch (NTDE).
Mainstreaming	**--**	In the context of climate change adaptation, the process of providing relevant climate information across all business functions to ensure that climate change impacts and adaptation are a key part of all planning, design, operations and management decisions.
Mean higher-high water	**MHHW**	The average of the higher high water height of each tidal day observed over the National Tidal Datum Epoch.
Mean high water	**MHW**	The average of all the high water heights observed over the National Tidal Datum Epoch.
Mean sea level	**MSL**	The arithmetic mean of hourly heights observed over the National Tidal Datum Epoch.
Mean low water	**MLW**	The average of all the low water heights observed over the National Tidal Datum Epoch.
Mean lower-low water	**MLLW**	The average of the lower low water height of each tidal day observed over the National Tidal Datum Epoch.
National Climate Assessment	**NCA**	An ongoing United States government interagency effort on climate change science conducted under the auspices of the Global Change Research Act of 1990.
National Flood Insurance Program	**NFIP**	A program that aims to reduce the impact of flooding on private and public structures by providing affordable insurance to property owners, renters and businesses and by encouraging communities to adopt and enforce floodplain management regulations.
National Tidal Datum Epoch	**NTDE**	The specific 19-year period adopted by the National Ocean Service as the official time segment over which sea level observations are taken and reduced to obtain mean values for datum definition. The latest NTDE used as a standard across the United States is from 1983-2001.
Nuisance flooding	**--**	See **sunny day flooding**

Permanent inundation	--	This term does not mean that land will be submerged at all times, but refers to land that will be inundated at some point within the regular predicted tide cycle.
Primary planning scenario	--	Ideally, both CCAP sea level rise scenarios are considered in project planning and design. However, when one value must be chosen, the primary planning scenario should be used, which is the NASA (2022) Intermediate-High Scenario.
Sunny day flooding	--	The temporary inundation of low-lying areas, especially streets, during exceptionally high tide events such as those that occur right after the full and new moons (often called *spring* or *king* tides). The term “sunny day” stems from the fact that this flooding is not associated with a storm event.
Surface flooding	--	A pluvial, or surface water flood (also sometimes referred to as ‘urban flooding’), caused when heavy rainfall creates a flood event independent of an overflowing water body.
Storm surge	--	An increase in water elevation above the normal astronomical tide level caused by high sustained winds and low-pressure systems.
Storm tide	--	The total water level during an extreme event that is composed of storm surge on top of high tide.
Sea level rise	SLR	A rise in the average level of the earth’s oceans.
Spring tide	--	A tide just after a new or full moon, when there is the greatest difference between high and low water. Spring tides have nothing to do with the spring season, rather, the word is a reference to the tide "springing forth." Spring tides occur twice each lunar month all year long, without regard to the season.
Temporary flooding	--	Flooding that is not permanent—i.e. is not part of the regular tide cycle—and that occurs due to an extreme event. In this section of the guidance document, temporary flooding refers to flooding caused by storm surge.
Tidal flooding	--	See **sunny day flooding.**
Tidal range	--	Tidal range is the height difference between high tide and low tide.

4.2 Introduction

The rate of sea level rise is increasing, both globally and locally. Since 1880 global mean sea level (GMSL) has increased 8-9 inches and about a third of that occurred in the last two and a half decades (NOAA, 2019). Since the launch of satellites in 1993, which record more accurate **absolute sea levels**, we know the global annual rate of sea level rise has more than doubled in recent decades, increasing from 0.08 inches/year to the current rate of 0.17 inches/year (Willis et al., 2023), and the rate of annual relative sea level rise (SLR) in Philadelphia has increased to ~0.19 inches/year[5].

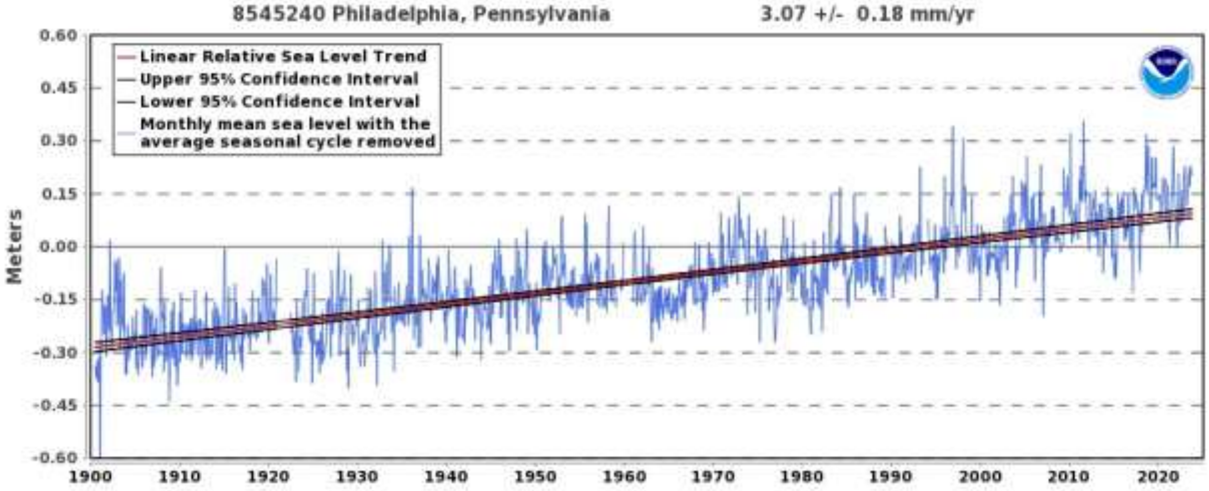


Figure 4-1. Plots show monthly mean sea levels at the NOAA Tide Station #8545240 (1900-2022) without the regular seasonal fluctuations from coastal ocean temperatures, salinity, wind, atmospheric pressure, and ocean currents. The relative sea level trend is also shown with its 95% confidence interval (NOAA, 2022).

Philadelphia is roughly 90 miles from the open ocean, but its two main waterways, the Schuylkill and Delaware Rivers, are tidal[6] (i.e. they are influenced by the ocean and tides and experience sea level rise). Looking at over 120-years of tide level data in Philadelphia, a steady increase in the baseline elevation is observed. Between 1901 and 2022, sea levels in Philadelphia have been rising at a rate of 3.07 mm/year (**Figure 4-1**) or ~0.12 inches/year—a rate that is nearly twice the global average annual rate of 0.06 inches/year for roughly the same time period (1900-2018) (NASA, 2020). The rate of SLR in Philadelphia is higher primarily due to land subsidence (Linn, 2004). While the sea levels are rising, the land beneath Philadelphia—and much of the mid-Atlantic/Northeast region of the U.S.—is sinking in response to the last glacial period, a process called **glacial isostatic adjustment** (GIA).

Furthermore, it is not only the average tide level—or sea level—that is increasing in Philadelphia; the highest tide of each day is also increasing at a faster rate than mean sea level, indicating that our **tidal range** is increasing (**Figure 4-2**). It is thought that this increasing tidal range occurred due to dredging and manmade changes to the floodplain (agriculture and urban development) and changes to the tidal range may continue to occur in the future.

---

[5] *This rate of sea level rise in Philadelphia was determined using a linear model fit to tide level data recorded from 1993 through 2022.*

[6] *The Schuylkill River is tidal up to the Fairmount Dam and the Delaware River is tidal up to Trenton.*

As of 2021, global temperatures have risen by approximately 2°–2.2°F (1.1°–1.2°C) compared to preindustrial levels and are projected to increase to ~5.4°F (3°C) by the end-of-century if the current trajectory continues (IPCC, 2022). According to the latest **National Climate Assessment (NCA)** Report (Crimmins et al., 2023), it is "likely"[7] that global sea level rise will exceed 2 feet by the end-of-century with such warming (Sweet et al., 2022). Failing to curb future emissions will increase the probability of higher emissions scenarios being realized, where GMSL could increase by 3.6-6.9 feet by 2100[8]. Sea level rise alone, in the absence of storm events, will increase the frequency, intensity and depth of coastal flooding in Philadelphia. Extreme events will cause more damage as storm surges occur on top of higher sea levels, increasing the depth of flooding and reaching further inland. As demonstrated by Superstorm Sandy in New York City, damage from storm surge can be catastrophic to wastewater and water infrastructure—damages to wastewater infrastructure alone were estimated to be $100 Million (NYC DEP, 2013).

Using PWD's Primary Planning Sea Level Rise Scenario (see *Section 4.4.a – Sea Level Rise Projections and Future Tide Elevations* for detailed information on sea level rise scenarios) the frequency of today's 100-year **base flood elevation**[9] (BFE) at the Philadelphia tide gauge location, as established by the **Federal Emergency Management Agency (FEMA)**, could increase more than twofold by the 2060s and FEMA's current 100-year special flood hazard area (SFHA)[10] in Philadelphia could increase in extent by approximately 25% by the end of the century. As a utility providing critical services, planning for these changes is important and necessary.

---

[7] *The NCA uses likelihood as a measure of uncertainty expressed probabilistically. This means it is based on statistical analysis of observations, model results and/or expert judgement. "Likely" means greater than or equal to two out of three, or the likelihood of an outcome or result at 66%-100% (Crimmins et al., 2023).*

[8] *Refers to the Intermediate to High sea level rise scenarios that account for low-likelihood, high impact processes such as rapid ice sheet loss (Section 9: Coastal Effects from the 5th National Climate Assessment).*

[9] *The BFE at the Philadelphia tide gauge #8545240 is 9.32 ft. NAVD88.*

[10] *From the FEMA 2015 Flood Insurance Study and Flood Insurance Rate Maps.*

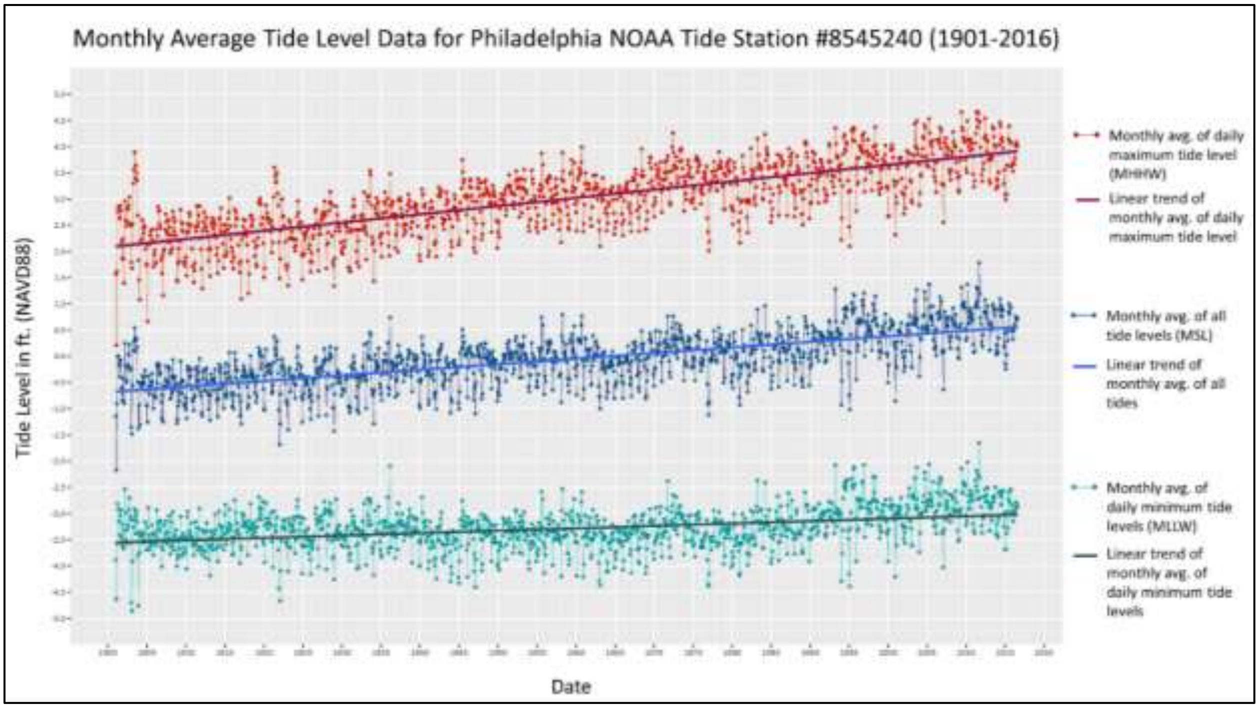


Figure 4-2. Monthly average of daily maximum tide levels (red), monthly average of all daily tide levels (mean sea level) (blue) and monthly average of daily minimum tide levels (teal).

4.3 How This Guidance Applies to PWD

Sea level rise and extreme storms were identified by PWD staff in a CCAP *Vulnerability Survey* as climate change impacts that could result in high consequence scenarios for the Department's physical assets, operations and/or levels of service. CCAP developed an *Inundation Analysis*[11] as an initial, high-level study to understand and estimate the risk that PWD may face due to increases in coastal flood frequency resulting from SLR and storm surge. Projected future water surface elevations for the tidal Delaware and Schuylkill Rivers were examined using three sea level rise scenarios in combination with storm surge for three time periods: the near-term (2030s), mid-century (2060s), and end-of-century (2100+). As with all future climate projections, there is more uncertainty toward the end-of-century scenario compared with the near-term and mid-century scenarios. For planners, designers, and decision makers, assets or investments with long useful lifespans should consider this uncertainty in the planning process (i.e. prioritize flexibility in design).

---

[11] *Note that Phase 1 of the Inundation Analysis contains projections that have since been updated with more recent available data. Please refer to [Section 4.4.a – Sea Level Rise Projections and Future Tide Elevations] for the most up-to-date sea level rise and storm surge projections. Phase I of the CCAP Inundation Analysis looked at risk using sea level rise projections from a group called the Climate & Urban Systems Partnership (CUSP), who worked with climate scientists from Columbia University to develop Philadelphia-specific sea level rise projections. In 2018, CCAP started Phase II of the Inundation Analysis which included adopting new sea level rise projections from NOAA and conducting additional bottom-up analyses to better understand the Department's vulnerabilities and dynamics of the tidal Delaware Bay. In 2023, the sea level rise projections were once again updated based on the most recent projections available in [NASA's Interagency Sea Level Rise Scenario Tool] and the accompanying [2022 Sea Level Rise Technical Report] from the U.S. Sea Level Rise and Coastal Flood Hazard Scenarios and Tools Interagency Task Force.*

The Inundation Analysis informs the guidance outlined here. This guidance is meant to primarily address **surface flooding** in the tidally influenced areas of Philadelphia through a combination of new planning and design requirements and recommendations. There is no prescriptive requirement for most of the information and tools presented in this section. Generally, it is up to planning and design staff to determine how best to incorporate this information into projects, plans and programs. The only exception to this are two new prescriptive planning and design requirements related to sea level rise: PWD's new coastal design flood elevation (DFE) and the associated adaptive management plan requirement, both of which are detailed later in this section.

The Inundation Analysis does not directly address how sea level rise and storm surge may impact PWD's subsurface systems, but a data visualization tool and high-level risk assessment were developed to help identify impacts to the combined sewer collection system, which can be used in further planning analyses and assessments. This guidance does not address how sea level rise may impact water quality, such as increasing salinity levels[12] and impacts to drinking water treatment processes. Water quality issues related to sea level rise and salinity are being studied by the PWD Water Quality Modeling group, which coordinates with CCAP and uses consistent sea level rise projections and climate information.

The guidance and design standards for coastal floodplain management outlined here exceed existing floodplain regulations. However, users should still be familiar with local floodplain regulations as they are required by Philadelphia's participation in the FEMA **National Flood Insurance Program** (NFIP) and required through local ordinance. The planning and design elevations in this guidance document augment existing requirements and should only be considered if they are *higher* than the regulatory standard or the regulatory standard does not currently apply.

a. Example Applications

Below are examples of areas where climate change information—specifically future risk from sea level rise and storm surge—should be considered.

*This guidance is meant **to facilitate the integration of climate change projections into existing planning and design processes at PWD**. Through this process of **mainstreaming** climate information into existing practices, PWD can help ensure that current levels of service can be maintained, and regulatory requirements can be met under future conditions.*

1. **Performing planning assessments**
    - Future tide and storm tide elevations, inundation maps, asset exposure tables and other CCAP tools should be used in planning assessments for all above-grade assets in the current or future floodplain
    - Future tide and storm tide elevations should be used, when possible, in planning and design assessments related to below-grade assets

---

[12] *CCAP coordinates with PWD water quality modelers and consultants who are developing a salinity model. For more information on this effort, please see the PWD Watershed Protection Program website.*

- The **Design Flood Elevation (DFE)** should be used for any preliminary designs that are created during project planning assessments, including the alternatives analysis process
- Future tide and storm tide elevations, inundation maps, and asset exposure tables should be used in flood risk analyses/floodplain management efforts, such as:
    - Facilities-based or system-wide risk assessments
    - Pumping station design or renewal and replacement
    - Storm Flood Relief assessments
- Future tide and storm tide elevations should be used for planning assessments related to receiving water quality regulatory compliance (NPDES Permits)

Mainstreaming Climate Science in PWD's Coastal Flood Risk Assessments

In 2023, CCAP conducted three coastal flood risk assessments for the Northeast, Southeast, and Southwest Water Pollution Control Plants. All three facilities are situated along the tidal Delaware River, making them vulnerable to coastal flooding. The assessments quantify coastal flood risk over time and establish how susceptible the facility is to flood damages under current and future flooding conditions. Future tide and storm tide elevations from the Guidance were applied to determine coastal flood likelihoods and results for various scenarios that include the use of flood mitigation measures. One such example evaluates how effective a site-wide concrete floodwall, built to PWD's Design Flood Elevation, would be in protecting the facility from inundation through the end-of-century given future sea level rise and storm surge. In the planning, design, and decision-making processes, findings from the assessments can be utilized to better understand when certain flood mitigation actions should be prioritized, considering the project's defined level of risk tolerance.

Results from the flood risk assessments also support the 2023 Wastewater Master Plan Update (WWMPU) and provide further insight into mitigation alternatives and flood risk for pre- and post- mitigation flood conditions. As part of the most recent WWMPU process, CCAP has participated in the Working Group and Core Review Committee for the Climate Change Flood Risk Evaluation and provided future sea level rise and storm surge estimates and updated Design Flood Elevations. CCAP has continued to work closely with the Wastewater Master Plan Update (WWMPU) team to integrate the most up to date climate projections and guidance into planning efforts.

2. **Designing above-grade assets**
    - The Design Flood Elevation (DFE) must be used for all designs for new or rehabilitated above-grade assets in the current or future floodplain

3. **Floodproofing existing assets for flood resilience (asset management, operations)**
    - The DFE should be used as a threshold for floodproofing existing assets in the current or future floodplain (e.g. hardening, elevating electrical equipment)

4. **Designing grey, green and nature-based infrastructure**
    - Future tide and storm tide elevations, inundation maps and changes to the groundwater table should be considered for green stormwater infrastructure projects built for Long Term Control Plan Update (LTCPU) compliance
    - Future tide and storm tide elevations, inundation maps and changes to the groundwater table should be considered in nature-based flood mitigation projects, e.g. stream restoration or expansion of the green infrastructure program to address flooding and water quality (MS4 permit)

5. **Evaluating collection system performance**
    - Future tide and storm tide elevations should be used as boundary conditions in Hydrologic & Hydraulic (H&H) models to better understand system performance and to inform which outfalls may need tide gates or pumps

6. **Water Pollution Control Plant hydraulic assessments**
    - Future tide levels and storm tide levels should be used as boundary conditions in models to evaluate flow through PWD's Water Pollution Control Plants (NPDES permits)

It should be noted that CCAP staff is available to help apply the results, information and tools described in this section. Additionally, CCAP has expertise on current floodplain regulations and has developed tools to help users understand how the Inundation Analysis results compare and relate to FEMA's base flood elevations.

4.4 Future Coastal Flood Risk Planning and Design

The goal of this section is to provide an overview of tools and information available to facilitate integration of sea level rise projections and coastal flood risk hazards into PWD's planning and design processes. Future coastal flood risk from SLR and storm surge must be incorporated in all projects in the current or future floodplain and the DFE design standard must be applied. This applies to assessments, plans and projects worked on by in-house staff and those led by consultants.

The sections below will provide useful climate information and tools for project planning and assessments in the following formats:

- **Sea Level Rise Projections and Future Tide Elevations** – Sea level rise projections are used to determine potential tide elevations in Philadelphia for three future time periods. Any flooding associated with future tide elevations is considered *permanent* inundation as it will occur within the predicted tide cycle.
- **Storm Surge and Future Storm Tide Elevations** – Storm surge and storm tide elevations are associated with various sized storms specific to Philadelphia. Any flooding associated with storm surge on top of tide levels (i.e. storm tide) is considered *temporary* inundation as it will only occur during extreme events. Using a combination of sea level rise scenarios and storm surge amounts, storm tide levels are estimated for three future time periods.
- **Forward-Looking Inundation Mapping** – A GIS bathtub model was produced to estimate and visualize the timing and extent of future coastal flooding in Philadelphia.

- **Exposure Analysis and Asset Exposure Tables –** Results are presented for a high-level screening assessment used to determine which PWD assets are most exposed to future sea level rise and storm surge.
- **Changing Flood Frequency Tool** – This tool allows users to input any elevation—such as the elevation of an existing asset, the current protective elevation required by FEMA within the coastal 100-year floodplain, or a potential design flood elevation—and then produces a table that depicts the changing flood frequency (measured as an annual return interval) associated with that elevation over time (through the year 2100) taking into account sea level rise and storm surge probabilities.
- **Interceptor Sewer and Regulators Tool** – This interactive visualization tool allows users to investigate the impact of various sea level rise and storm surge scenarios on PWD's subsurface, combined sewer system drainage infrastructure.

The Dutch Example

The Dutch are leaders in the world when it comes to finding engineering solutions for flood control. With nearly 30% of the country lying below sea level, they have been dealing with flood risk from the sea and storms for hundreds of years. Today, the Dutch government spends $1.3 billion per year on flood protection and water control structures, such as canals and dikes (Kutz, 2018). They are coming to terms with the fact that traditional engineering practices may not always provide the best solutions, especially as they grapple with armored solutions that protect from coastal flooding but hold in riverine flood waters trying to reach the sea. Now they are starting to turn to green solutions that "let water in" and do not attempt to subdue nature. They design assets that benefit communities, like lakes, parks and plazas that also double as enormous reservoirs when the seas rise and rivers spill over.

Flooding from the 1953 North Sea flood devastated the Netherlands and caused an estimated 1,836 deaths and widespread property damage. Following this natural disaster, the Netherlands carried out major studies on flood risk and developed the Delta Works, a system of dams and storm surge barriers.

The Dutch approach to adaptation planning is integrated with other existing planning methods and begins with a comprehensive assessment of the risks, vulnerabilities, and potential benefits and trade-offs associated with different adaptation options. This comprehensive assessment also takes population density and economic centers into account and assigns an appropriate level of protection for different regions of the country. This allows them to prioritize adaptation strategies and define the appropriate level of investments by integrating adaptation planning with spatial planning, resource management and economic analysis.

a. Sea Level Rise Projections and Future Tide Elevations

Two sea level rise scenarios were chosen for infrastructure planning and design[13] at PWD from *NASA's Interagency Sea Level Rise Scenario Tool* in association with the NOAA 2022 Interagency report *Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines*—also referenced here as the **2022 Sea Level Rise Technical Report** (Sweet et al., 2022): The Intermediate-Low and Intermediate-High Scenarios (**Table 4-1** and **Figure 4-3**). Users are encouraged, if they have the time and capacity, to assess risk and examine design alternatives using both sea level rise scenarios, as it is best practice to plan for multiple futures. NASA's Intermediate-High and Intermediate-Low sea level rise scenarios provide a planning envelope (an upper and lower bound) of potential SLR in Philadelphia, representing uncertainty with a plausible high-end scenario and a plausible low-end scenario, respectively. NASA's Intermediate-High sea level rise scenario is the **PWD Primary Planning Scenario. It is recommended that the Primary Planning Scenario for sea level rise, in combination with storm surge, be considered to build resilience to coastal surface flooding in all assessments and analyses.**

For more context on CCAP's selection of sea level rise scenarios and projections, please refer to the NASA 2022 Sea Level Rise Scenarios Justification Document.

Table 4-1. Philadelphia Water Department sea level rise planning scenarios for near-term (2030s), mid-century (2060s), and end-of-century (2100s).

Philadelphia Water Department Sea Level Rise Planning and Design Scenarios		
Year	**PWD Low Scenario (ft.)**	**PWD Primary Planning Scenario (ft.)**
	NASA Int-Low	*NASA Int-High*
2000 (baseline)	0	**0**
Near-term (2030s)	0.69	**0.75**
Mid-century (2060s)	1.48	**2.05**
End-of-century (2100s)	2.43	**5.12**

---

[13] *There are situations or applications where the consideration of the other three sea level rise scenarios may be appropriate. For example, for water quality planning, management and policy decisions, different sea level rise projections may be appropriate given the different risk tolerance, adaptive capacity and planning horizons.*

A NOTE ON SEA LEVEL RISE PROJECTIONS AND THEIR SOURCES

In 2022, the *Sea Level Rise Scenario Technical Report* (Sweet et al., 2022) was released as a product from an interagency effort that included NOAA, NASA, US EPA, USGS, FEMA, USACE, and US DOD (also known as the U.S. Sea Level Rise and Coastal Flood Hazard Scenarios and Tools Interagency Task Force). To accompany this technical report, NOAA and NASA both developed interactive online tools that allow users to easily reference and utilize location-specific sea level rise (SLR) information. PWD's current source of SLR projections is *NASA's Interagency Sea Level Rise Scenario Tool*, referenced in the *"Data and Tools"* portal within the 2022 Technical Report. This tool provides SLR projections for individual tide gauge locations across the United Sates, including *Philadelphia's NOAA tide gauge station 8545240* (located adjacent to the intersection of South Christopher Columbus Blvd. and Washington Ave.), which is referred to as "Philadelphia (Pier 9N)" in the Interagency SLR Scenario Tool. For infrastructure planning and design, this Guidance utilizes two specific SLR scenarios from the Interagency Sea Level Rise Scenario Tool: The Intermediate-Low Scenario and the Intermediate-High scenario. The Intermediate-High Scenario has been selected as **PWD's Primary Planning Sea Level Rise Scenario**. Any tables, graphics, and text that include reference to these SLR projections will cite them as "NASA" projections, but it should be acknowledged that NASA's Sea Level Rise Scenario Tool represents an interagency effort that includes collaboration with NOAA, US EPA, and USGS, as well as Rutgers University.

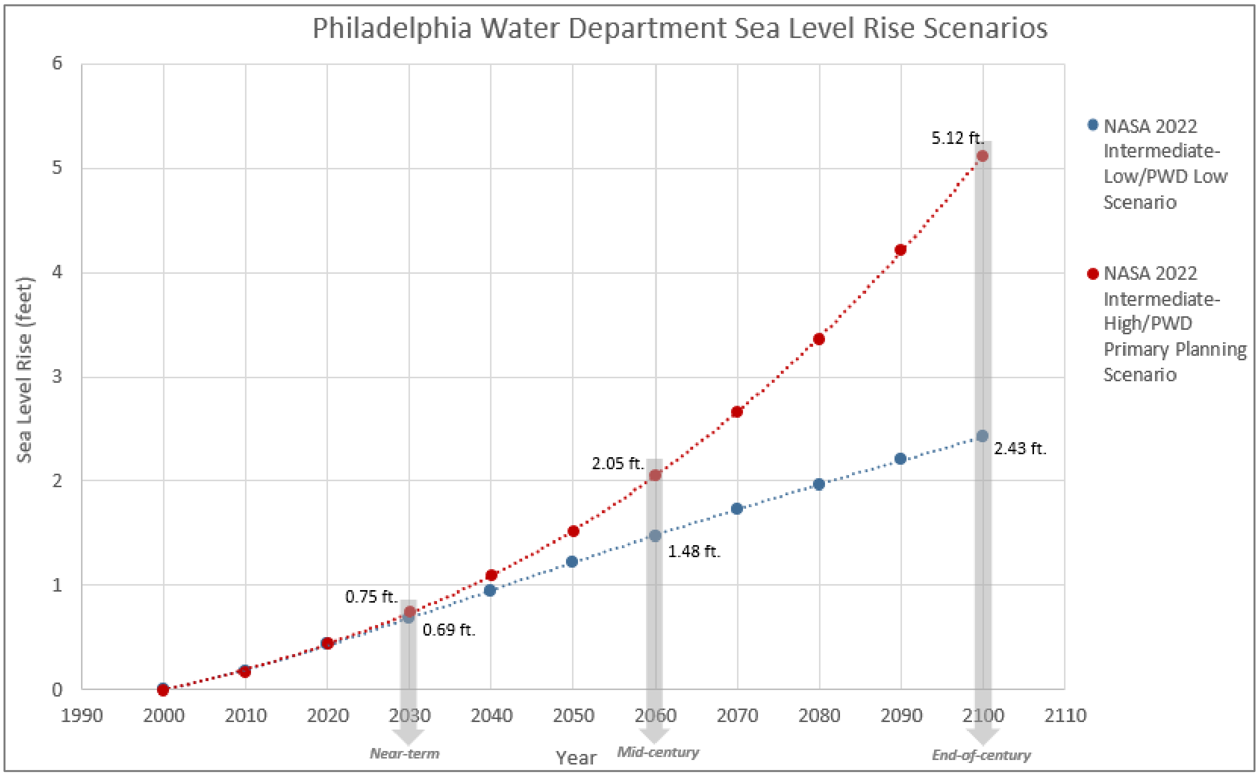


Figure 4-3. PWD sea level rise scenarios with fitted polynomial curves. Values depicted for near-term (2030s), mid-century (2060s) and end-of century (2100).

Tables with estimated annual sea level rise amounts for the years 2000-2150 for both SLR scenarios are also provided in *Appendix B-1* (see example in **Table 4-2**).

Table 4-2. Example of table with annual interpolation of PWD sea level rise scenarios (incomplete), which can be found in Appendix B-1 Sea Level Rise Annual Interpolation Table.

Annual Interpolation of NASA SLR Scenarios		
Year	**PWD Low Scenario (ft.)**	**PWD Primary Planning Scenario (ft.)**
	NASA Int-Low	**NASA Int-High**
2000	0.00	0.00
↓	↓	↓
2022	0.49	0.49
2023	0.51	0.52
2024	0.54	0.55
2025	0.56	0.58
2026	0.59	0.61
2027	0.61	0.64
↓	↓	↓
2075	1.86	3.01
2076	1.88	3.08
2077	1.91	3.15
2078	1.93	3.23
2079	1.96	3.30
2080	1.98	3.38
2081	2.00	3.45
2082	2.03	3.53
2083	2.05	3.61
2084	2.07	3.69
2085	2.10	3.77

When applying the sea level rise scenarios, it is important to add them on top of the correct baseline water elevation. The NASA SLR projections have a baseline year of 2000; therefore, it is necessary to add these sea level rise scenarios on top of Philadelphia's tide levels[14] in the year 2000. NOAA publishes average tide levels for Philadelphia, called tidal datums (**Figure 4-4**). Definitions of tidal datums *can be found here on NOAA's website*. NOAA publishes tidal datums that reference a specific period of time called the **National Tidal Datum Epoch**, which determines the tidal elevations averaged over the period from 1983-2001. CCAP adjusted all the tidal datums provided by NOAA by +0.07 ft. to align with the baseline year (2000), accounting for any changes over time, e.g. any sea level rise that occurred between the NTDE

---

[14] *CCAP uses tide levels from Philadelphia tide station 8545240 from NOAA to represent tide levels in Philadelphia.*

and the year 2000. See the CCAP Memo *Updated Baseline Period Tidal Datums for NOAA Sea Level Rise Projections*[15] for more information about determining the 0.07 ft. conversion factor.

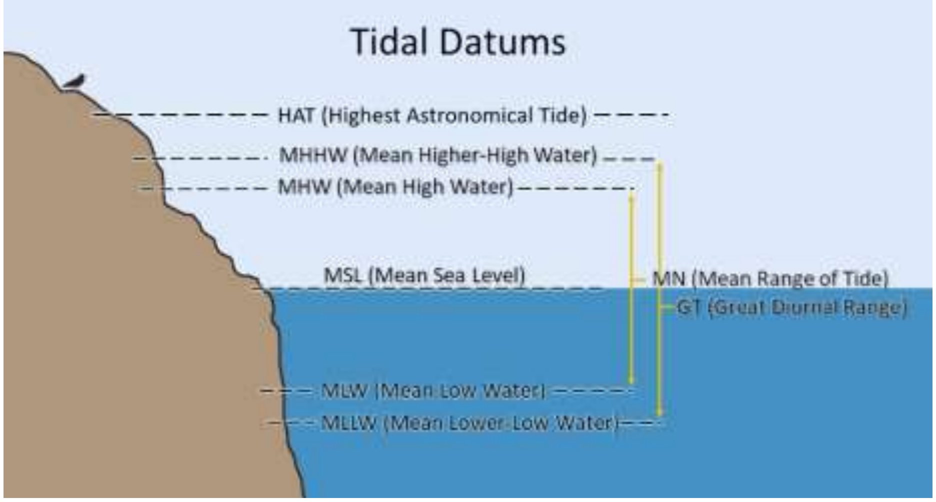


Figure 4-4. Illustration representing the most frequently used tidal datums.

With the correct baseline established, the sea level rise scenarios are added to the tidal datums to estimate future tide elevations that include sea level rise. The future tide elevations for **Mean Lower-Low Water (MLLW)** through **Mean Higher-High Water (MHHW)** represent ***permanent*** **inundation**—as flooding that results from these elevations will occur during the normal predicted tide cycle[16]. CCAP recommends also considering sea level rise (in the absence of storm surge) on top of the **highest astronomical tide (HAT)** as it is guaranteed to occur, even if only once every ~18.6 years[17]. Flooding from sea level rise that occurs during less common and exceptionally high tides--such as the HAT or the **spring tide**--is called **sunny day flooding**, **nuisance flooding** or **tidal flooding.** Sunny day flooding will happen more and more frequently as sea levels rise over time, pushing what were once lower tides above flooding thresholds. **Table 4-3** depicts future tide elevations using the Primary Planning SLR Scenario. Future tide elevations for the PWD Low SLR Scenario can be found in *Appendix B-2 Future Tide & Storm Tide Levels*

---

[15] *This memo references NOAA 2017 SLR projections rather than the updated NASA 2022 SLR projections. However, both sources of SLR projections have a baseline year of 2000; therefore, the information presented in the memo remains applicable.*

[16] *The tide cycle is driven by the gravitational effects of the sun and the moon on the Earth's ocean. As the moon, sun and Earth are in various orientations to one another, there is variation in the tide cycle and periods where tides are generally lower or higher. The East Coast of the United States has a semidiurnal tide cycle with two high and low tides of approximately equal size occurring each lunar day.*

[17] *The Highest Astronomical Tide is the highest predicted tide level that could occur under any combination of astronomical conditions, meaning any orientation of the sun, moon and Earth. It occurs once every ~18.6 years.*

Table 4-3. Philadelphia baseline tidal datums (year 2000) and future tidal datums estimated using the Primary Planning SLR Scenario for the near-term (2030s), mid-century (2060s) and end-of-century (2100+) time periods. All values are in feet, NAVD88.

Tidal Datums	Baseline Year 2000	Future Tidal Datums – Primary Planning Scenario		
		Near-term (2030s)	Mid-century (2060s)	End-of-century (2100)
		+0.75 ft. SLR	*+2.05 ft. SLR*	*+5.12 ft. SLR*
MLLW (mean lower-low water)	-3.03	-2.28	-0.98	2.09
MLW (mean low water)	-2.84	-2.09	-0.79	2.28
MSL (mean sea level)	0.46	1.21	2.51	5.58
MHW (mean high water)	3.26	4.01	5.31	8.38
MHHW (mean higher-high water)	3.66	4.41	5.71	8.78
HAT (highest astronomical Tide)	4.9	5.65	6.95	10.02

To learn more about working with tidal datums and vertical control datums, see the *Tidal Datums AIR Sheet* (Appendix A-1).

b. Storm Surge and Future Storm Tide Elevations

While sea level rise will slowly create new areas that are permanently inundated, exacerbating sunny day flooding, it is arguably ***temporary* inundation** from extreme events with storm surge that causes the most damage. **Storm surge** is an increase in the water elevation caused by high sustained winds and low-pressure systems above the normal, predicted astronomical tide. A **storm tide** is the total water level during an extreme event that is composed of storm surge on top of high tide (**Figure 4-5**).

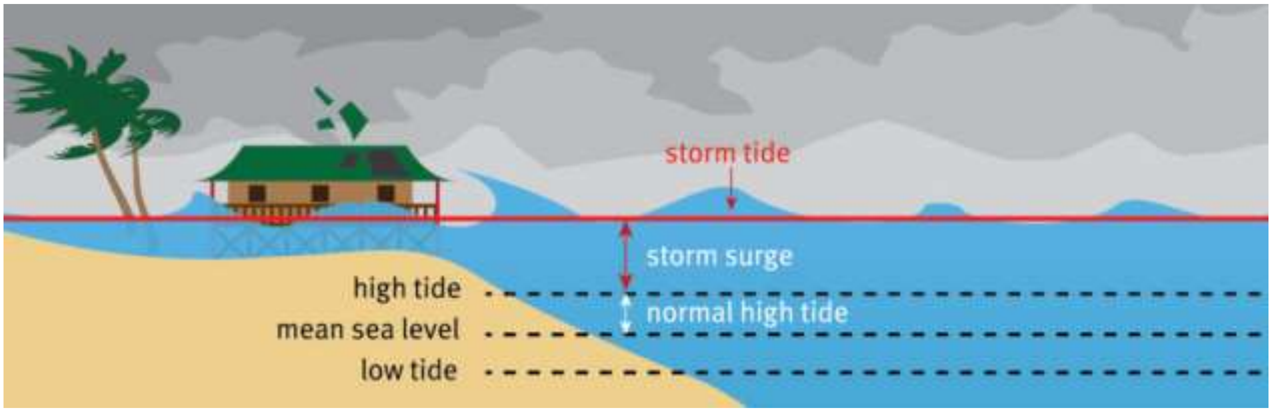


Figure 4-5. Illustration depicting storm surge and storm tide.

Storm surge heights associated with a 1%, 2%, 4%, 10%, 20% and 50% Annual Exceedance Probability (AEP) were taken from NOAA (Sweet et al., 2022). NOAA's analysis assumes that the highest storm tides occur during high tide, so the storm surge height is shown above Mean Higher High Water (the average of the highest daily tides). Estimated storm surge[18] heights associated with each AEP are shown in **Table 4-4**.

---

[18] *The storm surge estimates are based on storm tides that are technically Stillwater elevations. Wave effects are incorporated into design standards using safety factors.*

Table 4-4. Storm surge heights associated with various annual exceedance probabilities for Philadelphia.

Philadelphia Station (NOAA 8545240)			
Return Interval	**Annual Exceedance Probability (AEP)**	**AEP** *as % chance in any given year*	**Storm Surge height (ft.)** *NOAA 2022*
2-year	0.5	50%	2.25
5-year	0.2	20%	2.71
10-year	0.1	10%	3.11
25-year	0.04	4%	3.75
50-year	0.02	2%	4.32
100-year	0.01	1%	4.97

With storm surge amounts associated with various return periods for Philadelphia, it is possible to estimate *temporary* future coastal flooding in Philadelphia by combining storm surge[19] and sea level rise in three future time periods, the 2030s, 2060s and 2100. Note that the future storm tide elevations are determined by placing the associated amount of storm surge on top of **Mean Higher-High Water (MHHW)**, which is the average of the highest tide of each tidal day. CCAP chose to put storm surge on top of MHHW as that water elevation will be experienced on a regular basis; more than 50% of the time, the highest tide of each day reaches or exceeds the MHHW elevation. Furthermore, storm surge in Philadelphia is often experienced during Nor'easters (extratropical storms that form most frequently between September and April), which are generally large and slow-moving, providing more opportunity for storm surge to be experienced over a high tide (Zielinski, 2002). CCAP also considered placing storm surge on top of the **Highest Astronomical Tide (HAT)**, as a way to plan for a worst-case scenario. However, the chance of a rare storm with a low annual exceedance probability falling on the exact day and time of the HAT, which only occurs once every ~18.5 years, is extremely low. It is still good practice to consider flooding from SLR, in the absence of storm surge, on top of HAT, since it is guaranteed to occur.

---

[19] *There is currently no consensus on whether—or the extent to which—climate change will increase storm surge in the future. The values in this guidance associated with storm surge assume it will remain the same in the future. For example, the amount of storm surge associated with a 1% annual chance storm (4.97 ft.) in 2022 is the same amount of storm surge in the 2030s, 2060s and 2100+.*

Table 4-5 depicts future tide levels using the Primary Planning SLR Scenario and future extreme water levels based on storm surge estimates. *Appendix B-2 Future Tide & Storm Tide Levels* provides future tide levels and future extreme water levels for the PWD Low SLR Scenario.

Table 4-5. Baseline, future tide elevations, and future storm tide elevations (above MHHW) in feet, NAVD88.

Future Tide and Storm Tide Levels for Philadelphia *Primary Planning Sea Level Rise Scenario, all values in ft. NAVD88*					
	Baseline (year 2000)	**Near-term (2030s)**	**Mid-century (2060s)**	**End-of-century (2100)**	
		+0.75 ft. SLR	***+2.05 ft. SLR***	***+5.12 ft. SLR***	
MLLW (mean lower-low water)	-3.03	-2.28	-0.98	2.09	***Permanent inundation*** *– occurs within the regular predicted tide cycle*
MLW (mean low water)	-2.84	-2.09	-0.79	2.28	
MSL (mean sea level)	0.46	1.21	2.51	5.58	
MHW (mean high water)	3.26	4.01	5.31	8.38	
MHHW (mean higher-high water)	3.66	4.41	5.71	8.78	
HAT (highest astronomical Tide)	4.9	5.65	6.95	10.02	
Storm tide levels below place storm surge on top of Mean Higher-High Water					
50% annual chance storm (+2.25 ft.)	5.91	6.66	7.96	11.03	***Temporary inundation –*** *occurs during extreme storm events (50%-1% annual chance)*
20% annual chance storm (+2.71 ft.)	6.37	7.12	8.42	11.49	
10% annual chance storm (+3.11 ft.)	6.77	7.52	8.82	11.89	
4% annual chance storm (+3.75 ft.)	7.41	8.16	9.46	12.53	
2% annual chance storm (+4.32 ft.)	7.98	8.73	10.03	13.10	
1% annual chance storm (+4.97 ft)	8.63	9.38	10.68	13.75	

c. Forward-Looking Inundation Mapping

CCAP developed a "bathtub model" in ArcGIS to estimate inundation from future sea level rise and storm surge to better understand PWD's future flood exposure. This tool takes the future water elevations provided in the tables above to estimate and visualize the timing (e.g. mid-century vs. end-of-century) and extent of future coastal flooding in Philadelphia. These inundation maps can be used for:

- Determining whether an asset is within the FEMA BFE area or the FEMA 500-year floodplain
- Determining whether an asset is within estimated future floodplains
- Evaluating project placement to better avoid future flood exposure that may not exist today
- Performing high-level vulnerability assessments for specific projects or systems
- Creating visuals for planning assessments to demonstrate the timing and likelihood of future flooding

The Inundation maps are also a key tool for determining whether the **Design Flood Elevation** applies to your project. The design flood elevation is discussed in detail below in Section V.

- Inundation maps are available to PWD staff through the ArcGIS online CCAP Inundation Mapping Tool: *[LINK REMOVED – for internal PWD access only]*

- Instructions on how to use this tool are provided within the web map and can also be found in the *Design Flood Elevation*[20] *AIR Sheet*
  [LINK REMOVED - for internal PWD use only].

Lastly, CCAP can also provide high-resolution maps in any size and location within the map extent with customized layers for each user. Maps can include high-level asset exposure screening information, which is discussed in further detail below.

d. Exposure Analysis and Asset Exposure Tables

Using the GIS tool described above, a high-level Exposure Analysis was conducted to identify PWD facilities and assets that might be exposed to future coastal flood hazards. The Exposure Analysis is an initial step in evaluating the consequence of flooding on individual assets and systems. Determining the sensitivity of PWD assets and facilities to flooding is another important step to accurately estimate the consequence of inundation to the Department and must be done in coordination with other PWD staff working on asset management, planning and operations.

Using a modified bathtub method to map flood extents, the GIS tool was used to perform an asset screening to identify the timing and likelihood that PWD's structural assets could be exposed to future flooding. Results indicate that several critical assets – including the Baxter Raw Water Basin, multiple structures at the Southwest Water Pollution Control Plant, and two major pumping stations – may become exposed to permanent tidal inundation within the next 70 years. Other major assets may be exposed to flooding much sooner during storm events as sea levels rise over the remainder of the century.

It should be noted that the results of the Exposure Analysis are only as good as the data available; CCAP used all asset data sets that were accessible through PWD's GIS geodatabases. The Exposure Analysis results are coarse but provide a useful starting point for understanding risk and prioritizing which existing facilities and assets should be studied, in-depth, through facilities-based or system-based, asset-by-asset risk assessments. The Exposure Analysis provides inundation maps and asset exposure tables (see example in

---

[20] *The Design Flood Elevation is introduced and discussed in* Section 4-5: *Coastal Design Flood Elevation (DFE).*

Table 4-6) with a breakdown of the likely timing and frequency of flood exposure of existing assets at each of PWD's Water Pollution Control Plants (WPCP), Drinking Water Treatment Plants (DWTP) and pumping stations exposed to current and future coastal flooding.

Building upon results from the initial exposure analysis, CCAP completed three in-depth coastal flood risk assessments for the Northeast, Southeast, and Southwest WPCPs in November 2023. Critical asset elevations (containing architectural, electrical, and mechanical assets) were initially screened against future sea level rise and storm surge scenarios and further evaluated to characterize and quantify flood risk at each of the facilities.

Table 4-6. Sample asset exposure table: Baxter Water Treatment Plant Critical Assets: Timing and Likelihood of Flooding using the PWD Primary Planning Sea Level Rise Scenario from V1.0 of the Climate-Resilient Planning and Design Guidance (NOAA 2017 Intermediate-High SLR Scenario).

Baxter Water Treatment Plant Exposure Table, Primary Planning SLR Scenario			
	2030s	2060s	2100
	SLR Projection[21]: NOAA Intermediate-High (1.18 ft SLR)	SLR Projection: NOAA Intermediate-High (2.89 ft SLR)	SLR Projection: NOAA Intermediate-High (6.4 ft SLR)
Mean Higher-High Water (MHHW)	Torresdale Emergency Intake Bldg.	Torresdale Emergency Intake Bldg.	Torresdale Emergency Intake Bldg. Baxter Effluent House Baxter Intake Building Baxter Raw Water Basin Torresdale Raw Water Pumping Station & Office Bldg.
All storm scenarios below are assumed to occur on top of MHHW			
2-year storm tide (+2.21 ft.)	*Everything above*	*Everything above +* Baxter Effluent House Baxter Intake Building Baxter Raw Water Basin	*Everything above*
5-year storm tide (2.64 ft.)	*Everything above*	*Everything above*	*Everything above*
10-year storm tide (2.99 ft.)	*Everything above +* Baxter Effluent House Baxter Intake Building + *everything above*	*Everything above +* Torresdale Raw Water Pumping Station & Office Bldg.	*Everything above*
25-year storm tide (3.39 ft.)	*Everything above*	*Everything above*	*Everything above*
50-year storm tide (3.66 ft.)	*Everything above +* Baxter Raw Water Basin	*Everything above*	*Everything above*
100-year storm tide (3.9 ft.)	*Everything above*	*Everything above*	*Everything above +* Police Academy Pumping Station

---

[21] *SLR Projections are from NOAA (2017) and have a year 2000 baseline.*

e. Changing Flood Frequency Tool

The Changing Flood Frequency Tool is an Excel-based resource and provides estimates of the changing probability of flooding through the end of the century due to sea level rise and storm surge for any input elevation. As currently designed, the tool combines annual storm surge probability estimates based on the 2022 Sea Level Rise Technical Report (Sweet et al., 2022) for the Philadelphia tide station along with the NASA 2022 sea level rise projections. The intent is to be able to input any elevation related to PWD's coastal assets and the tool will calculate the flood protection level associated with that elevation over time, as sea levels rise, in annual return interval format.

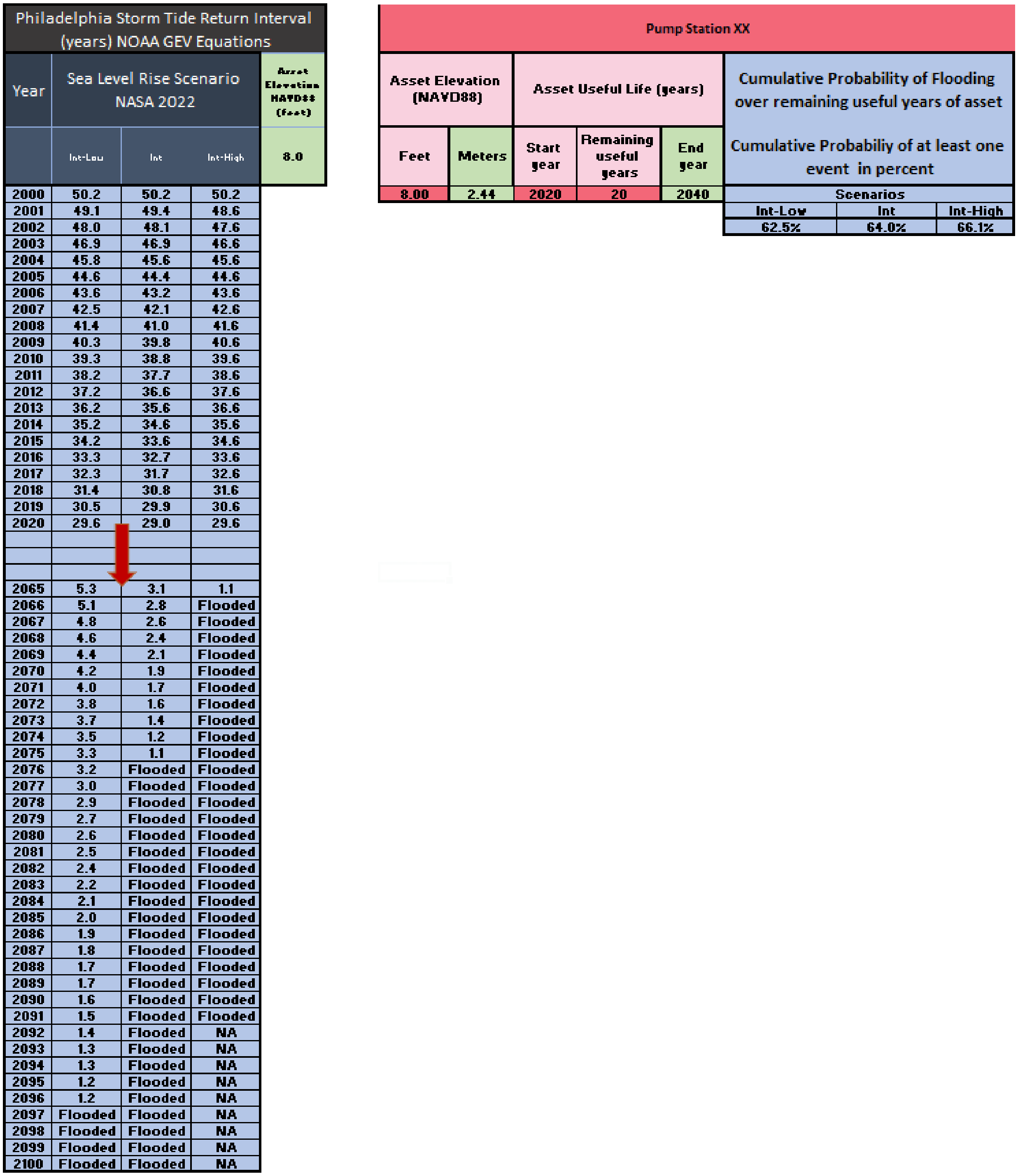
The tool assesses the increasing probability of annual flooding due to sea level rise using three NASA SLR scenarios. The asset elevation must be input relative to feet NAVD88. The tool then converts the elevation to meters and estimates the elevation of the asset above the MHHW elevation (with baseline year 2000). The difference between the input asset elevation (e.g. the lowest entry point) and the current MHHW represents the measure of current protection for *non-storm conditions* but note that the asset is subject to potential flooding due to storm surges. The spreadsheet shows the storm surge probability that will cause flooding of the asset for any year between 2000 and 2100, using NASA's Intermediate-Low, Intermediate, and Intermediate-High SLR scenarios.

It is critical to note that flood risks do not occur on an annual basis, but rather accumulate over time. For this reason, the tool also calculates a *cumulative flood likelihood* which shows the likelihood of flooding at least once over the anticipated useful life of an asset. This is based on the mean annual probability of flooding during its useful life, as calculated from the asset's elevation, the selected sea level rise scenario, and the remaining useful life of the asset. For example, if an asset has a 1% annual flood likelihood (also known as a 100-year flood risk), that asset has a 26% chance of flooding at least once over 30 years.

Figure 4-6 shows an example output of the tool. In blue shaded areas to the left, which depict the tool output, the tool shows the annual probability of flooding (as a return interval in years) for an example asset at an existing elevation of 8.0 ft NAVD88 for three different sea level rise scenarios – NASA Intermediate-Low (PWD's Low scenario), NASA Intermediate, and NASA Intermediate-High (PWD's Primary Planning SLR Scenario).

The red boxes are the input cells, with the example asset elevation at 8.0 feet NAVD88, the start year of the calculation as 2020, and an estimated 20 years of remaining useful life of the asset (through 2040). In the blue boxes to the right, the cumulative flood likelihood over the period 2020 – 2040 (the remaining useful life of the asset) is provided for the three sea level rise scenarios. Note that the table will always include all years between 2000 and 2100, but the cumulative probability is calculated using the start year and end year of the asset's useful life. In the example provided, under the Primary Planning ('Int-High') SLR Scenario, the asset has an estimated 66.1% chance of flooding over the course of its useful life.

The Changing Flood Frequency Tool itself can be accessed by PWD staff at this link *[LINK REMOVED – for internal PWD use only]*.



Philadelphia Storm Tide Return Interval (years) NOAA GEV Equations

Year	Sea Level Rise Scenario NASA 2022			Asset Elevation NAVD88 (feet)
	Int-Low	Int	Int-High	8.0
2000	50.2	50.2	50.2	
2001	49.1	49.4	48.6	
2002	48.0	48.1	47.6	
2003	46.9	46.9	46.6	
2004	45.8	45.6	45.6	
2005	44.6	44.4	44.6	
2006	43.6	43.2	43.6	
2007	42.5	42.1	42.6	
2008	41.4	41.0	41.6	
2009	40.3	39.8	40.6	
2010	39.3	38.8	39.6	
2011	38.2	37.7	38.6	
2012	37.2	36.6	37.6	
2013	36.2	35.6	36.6	
2014	35.2	34.6	35.6	
2015	34.2	33.6	34.6	
2016	33.3	32.7	33.6	
2017	32.3	31.7	32.6	
2018	31.4	30.8	31.6	
2019	30.5	29.9	30.6	
2020	29.6	29.0	29.6	
2065	5.3	3.1	1.1	
2066	5.1	2.8	Flooded	
2067	4.8	2.6	Flooded	
2068	4.6	2.4	Flooded	
2069	4.4	2.1	Flooded	
2070	4.2	1.9	Flooded	
2071	4.0	1.7	Flooded	
2072	3.8	1.6	Flooded	
2073	3.7	1.4	Flooded	
2074	3.5	1.2	Flooded	
2075	3.3	1.1	Flooded	
2076	3.2	Flooded	Flooded	
2077	3.0	Flooded	Flooded	
2078	2.9	Flooded	Flooded	
2079	2.7	Flooded	Flooded	
2080	2.6	Flooded	Flooded	
2081	2.5	Flooded	Flooded	
2082	2.4	Flooded	Flooded	
2083	2.2	Flooded	Flooded	
2084	2.1	Flooded	Flooded	
2085	2.0	Flooded	Flooded	
2086	1.9	Flooded	Flooded	
2087	1.8	Flooded	Flooded	
2088	1.7	Flooded	Flooded	
2089	1.7	Flooded	Flooded	
2090	1.6	Flooded	Flooded	
2091	1.5	Flooded	Flooded	
2092	1.4	Flooded	NA	
2093	1.3	Flooded	NA	
2094	1.3	Flooded	NA	
2095	1.2	Flooded	NA	
2096	1.2	Flooded	NA	
2097	Flooded	Flooded	NA	
2098	Flooded	Flooded	NA	
2099	Flooded	Flooded	NA	
2100	Flooded	Flooded	NA	

Pump Station XX

Asset Elevation (NAVD88)		Asset Useful Life (years)			Cumulative Probability of Flooding over remaining useful years of asset		
Feet	Meters	Start year	Remaining useful years	End year	Cumulative Probabiliy of at least one event in percent		
8.00	2.44	2020	20	2040	Scenarios		
					Int-Low	Int	Int-High
					62.5%	64.0%	66.1%

Figure 4-6. Example of the CFFT output in annual return intervals and cumulative probabilities over the 20-year lifetime of an asset located at an elevation of 8.0 ft. NAVD88.The table is truncated in the figure for practical purposes, showing only years 2000-2020 and the end of century years 2065-2100. The actual spreadsheet shows results for the entire century.

f. Interceptor Sewer and Regulator Dam Analysis Tool

Most tools and information provided in this guidance apply specifically to above-grade assets. However, future tide and storm tide elevations should be considered in subsurface infrastructure planning and design as our drainage system is gravity-fed. Outfalls may need tide gates or pumps in the future to effectively drain the system and maintain current levels of service. Tide gates may also be necessary to reduce the risk of the outfalls acting as conduits for water to flow from the river into neighborhoods and to our treatment plants. In addition to using the future water elevation information above as a boundary condition in analyses, an Interceptor Sewer and Regulator Dam Analysis Tool was developed as an interactive data visualization tool for investigating the impact of sea level rise and storm surge on Philadelphia's Combined Sewer System. In this tool, critical elevations of the regulator (overflow weir, emergency outlet) are compared to projected future tide levels and future storm tide elevations, allowing users to quickly see which systems, regulators and tide gates are at the most risk.

This tool uses updated sea level rise projections as set thresholds and includes a table showing current and future tides and storm tides for easy reference. However, users can add any elevation/threshold they choose and include an annotation, which is then added to the summary tables at the bottom of the webpage.

Results from this analysis indicate that 78 out of the 197 regulators (39%) currently have dam elevations lower than the MHHW 2000 level (3.66ft NAVD88). If MHHW is projected to the 2100s using PWD's Primary Planning scenario, the future water level will be 8.78 ft. NAVD88. Under this projected water level, PWD estimates that the number of regulating chambers with dam elevations below 8.78 ft. would increase to 106, or 53% of all available regulating chambers. Most of the impacted regulators are associated with outfalls that discharge to the Delaware and Schuylkill rivers and most of these regulating chambers have existing tide gates. While tide gates provide backflow prevention, they may also create capacity issues in the combined sewer collecting system during high tides. Pumping—which would increase PWD's carbon footprint—may be necessary in the future to address capacity issues and maintain current levels of service.

Using this tool, PWD performed an initial risk assessment to identify and rank the interceptors and regulator structures most vulnerable to inundation for current day and 2030s conditions. Critical elevations of the regulator structures were compared to projected future normal tide and storm tide levels[22], and further evaluated based on whether a tide gate and/or a flap gate on the Emergency Overflow Outlet were present.

This tool was developed by the PWD H&H modeling team with input from CCAP and is internal to PWD *[LINK REMOVED – for PWD internal use only].*

---

[22] *SLR Projections used in the analysis are from NOAA (2017) and have a year 2000 baseline.*

4.5 Coastal Design Flood Elevation (DFE)

The **coastal design flood elevation** provided in this document is a new PWD design standard which provides a minimum elevation to which built assets in the coastal floodplain must be elevated or protected. For assets in the riverine floodplain, different design guidance is provided in *Section 4.7 A Note on Riverine Flood Resiliency* of this chapter. To determine if your project is in the coastal or the riverine floodplain, use the Design Flood Elevation Screening Tool (can also be accessed in the CCAP Inundation Mapping Tool *[LINK REMOVED – for internal PWD use only]*) and follow the instructions outlined there and within this document.

All new assets as well as existing assets that are being replaced or substantially upgraded must be designed, constructed, or protected (hardened, floodproofed, raised, or relocated) to the design flood elevation (DFE). For example, a new pump that needs to be installed at the DFE could be elevated by placing it on a concrete slab of adequate height. For an existing asset that is being upgraded or replaced and is currently below the DFE, the asset could be floodproofed to the required elevation. A structural barrier, such as a seawall, could be installed to protect the asset from floodwaters.

While the DFE is a new Department-wide design standard, there are special cases where it may not apply. For example, the DFE would not apply to assets that are designed to be temporarily submerged/inundated, such as a wet well or submersible pump, and/or are not sensitive to flooding impacts.

Table 4-7 shows the required coastal design flood elevations based on an asset's criticality and end of useful life. For planned assets with an anticipated useful life that does not extend past 2050, current local floodplain regulations[23] are considered sufficiently protective. For all non-critical assets with a useful life extending past 2050, a DFE of 12 ft. NAVD88 is required. For all critical assets with a useful life extending past 2050, a DFE of 14 ft. NAVD88 is required. Furthermore, all critical assets with an end of useful life exceeding the year 2075 must submit an Adaptive Management Plan (AMP) to CCAP and/or the project Core Review Committee (CRC). The AMP must be developed to ensure the asset is protected to the end of the century and beyond, as well as to ensure efficient implementation of adaptation approaches should future SLR or storm tide elevations trigger the need for additional flood protection. More information on determining which DFE to apply can be found in the subsection below (*a.* Does the DFE apply to your project?) and more detailed information on adaptive management practices can be found in the Adaptive Management Plan AIR Sheet (see Appendix A-1).

The use of a lower protective elevation than the DFEs listed in **Table 4-7** requires that a Project Manager submit justification and seek approval, through consensus, from the CRC (if the project meets the capital planning threshold of $2M) and/or CCAP. More information on this requirement can be found in in the subsection below (*b.* Submission of a Justification for use of a lower DFE).

---

[23] *Philadelphia's Zoning Code: Section 14-704(4) requires structures in the FEMA Special Flood Hazard Area (SFHA) be elevated 18" above the Base Flood Elevation or meet alternate floodproofing design criteria. The City released a Guide for Development in the Floodplain and provides other flood protection resources to reference.*

Table 4-7. PWD Design Flood Elevation (DFE) Table showing DFEs for non-critical and critical assets with useful lives ranging from near-term to end-of-century.

<table>
<tr><th colspan="4">Coastal Design Flood Elevations</th></tr>
<tr><th>Asset Criticality</th><th>Near-term
End of useful life does not extend beyond 2050</th><th>Mid-century
*End of useful life:
2050-2075*</th><th>End-of-century
End of useful life: 2075 +</th></tr>
<tr><td>Non-Critical</td><td>Current floodplain regulations apply</td><td colspan="2">12 ft. NAVD88*
OR
Lower DFE *with an approved Justification*</td></tr>
<tr><td>Critical[24]</td><td>Current floodplain regulations[25] apply</td><td>14 ft. NAVD88*
OR
Lower DFE
with an approved Justification</td><td>14 ft. NAVD88*
+ Adaptive Management Plan (AMP)
OR
Lower DFE
with an approved Justification + AMP</td></tr>
</table>

** If the protective elevation established by local regulations is higher than the required PWD DFE for the asset under consideration, the elevation established by local regulations MUST be applied.*

In almost all cases, the DFE will be higher in elevation than current floodplain regulations which are based on **FEMA Base Flood Elevations (BFEs)** and **FEMA Flood Insurance Rate Maps (FIRMS)** and therefore, provide more flood protection than local floodplain regulations which do not take sea level rise into account. For any instances where the DFE is lower than current floodplain regulations, the higher protective elevation established by local regulations must be used for protecting assets.

To apply this new standard to a specific project or asset, guidance is provided in the following subsections (a-d) and in the Design Flood Elevation AIR sheet**.** *[LINK REMOVED – for internal PWD use only]*

In developing the PWD DFE guidance, CCAP referred to the industry standard for flood resilient design and construction from the American Society of Civil Engineers (ASCE), as well as to guidance and approaches taken by peer cities and other water utilities throughout the U.S. Approaches to DFE guidelines vary significantly as there is no single over-arching standard currently in use. However, the incorporation of local sea level rise projections and/or freeboard is now crucial as utilities must strive to protect critical assets from increasing risks of inundation. The following components have been accounted for in PWD's coastal DFE for protection of critical assets and are also shown quantitatively in **Figure 4-7** below.

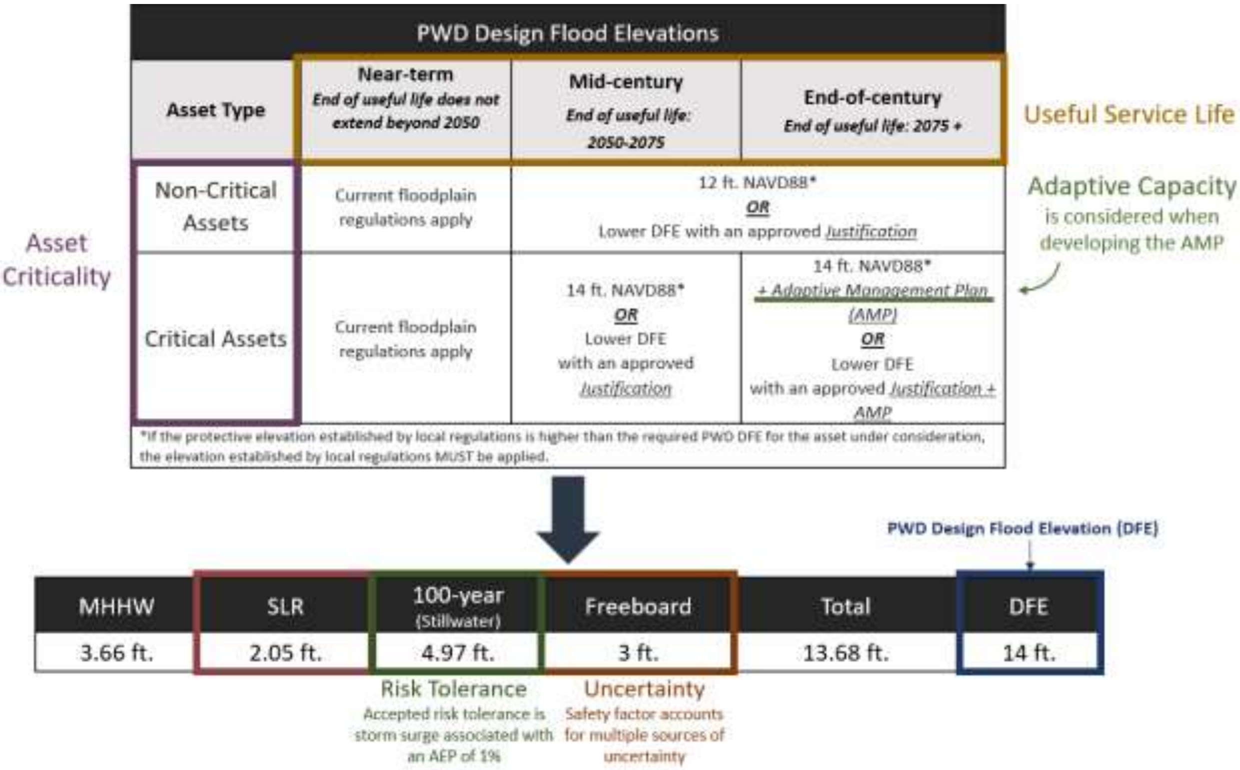
1. Asset criticality: Non-critical versus critical assets.
2. Estimated useful life based on three time periods: Near-term, mid-century, and end-of-century.
3. Baseline tidal conditions (e.g., MHHW).
4. PWD's primary planning sea level rise scenario (i.e., the NASA 2022 Intermediate-High scenario for the 2060s at 2.05 feet of SLR).

---

[24] *All PWD assets are by default assumed to be critical unless justification for non-critical status is documented by the Project Manager and approved by the Core Review Committee (if applicable) and/or CCAP.*

[25] *Refer to Philadelphia Code Section 14-704(4), also included on page 12 of the Guide for Development in the Floodplain.*

5. Local storm surge associated with a 100-year return period, or annual exceedance probability (AEP) of 1%.
6. A safety factor (e.g., freeboard) to account for:
    a. Wind effects
    b. Tidal amplification in the Delaware Bay
    c. Uncertainty associated with climate projections, storm surge estimates, and future local conditions (e.g., ice sheet processes, land use changes, bathymetry changes)
    d. High tides above MHHW
    e. Additional sea level rise by end of the century



PWD Design Flood Elevations

Asset Type	Near-term *End of useful life does not extend beyond 2050*	Mid-century *End of useful life: 2050-2075*	End-of-century *End of useful life: 2075 +*
Non-Critical Assets	Current floodplain regulations apply	12 ft. NAVD88* *OR* Lower DFE with an approved *Justification*	
Critical Assets	Current floodplain regulations apply	14 ft. NAVD88* *OR* Lower DFE with an approved *Justification*	14 ft. NAVD88* *+ Adaptive Management Plan (AMP)* *OR* Lower DFE with an approved *Justification + AMP*

*If the protective elevation established by local regulations is higher than the required PWD DFE for the asset under consideration, the elevation established by local regulations MUST be applied.

MHHW	SLR	100-year (Stillwater)	Freeboard	Total	DFE
3.66 ft.	2.05 ft.	4.97 ft.	3 ft.	13.68 ft.	14 ft.

Figure 4-7. Table of components showing the quantitative breakdown of PWD's coastal design flood elevation (DFE) for critical assets, in feet NAVD88.

a. Does the DFE apply to your project?

Whether or not the DFE applies to your project is determined by its flood vulnerability and risk. The flow chart in **Figure 4-8** outlines the flood vulnerability and risk components (exposure, criticality, and useful life of the asset) used to determine if and how the new DFE applies to your project. Please note that because of the interconnected nature of water, wastewater, and stormwater infrastructure, and the fact that PWD provides critical services deemed essential, by default all assets are assumed to be critical. If you do not believe your project should be considered critical, it is your responsibility to successfully make the case and obtain approval from the Core Review Committee (CRC) and/or CCAP to use the non-critical DFE. The Design Flood Elevation AIR Sheet *[LINK REMOVED – for internal PWD use only]* can help users choose the correct DFE and navigate the online Inundation Mapping Tool *[LINK REMOVED – for internal PWD use only]*, which shows the estimated extents of the current and future coastal floodplains in the City.

When determining the Design Flood Elevation for your project, if you need help working with vertical datums (e.g., converting between City datum, Plant datum, NGVD29, or NAVD88), please refer to the Vertical Control Datums AIR sheet (see Appendix A-1) and/or contact CCAP for further assistance.

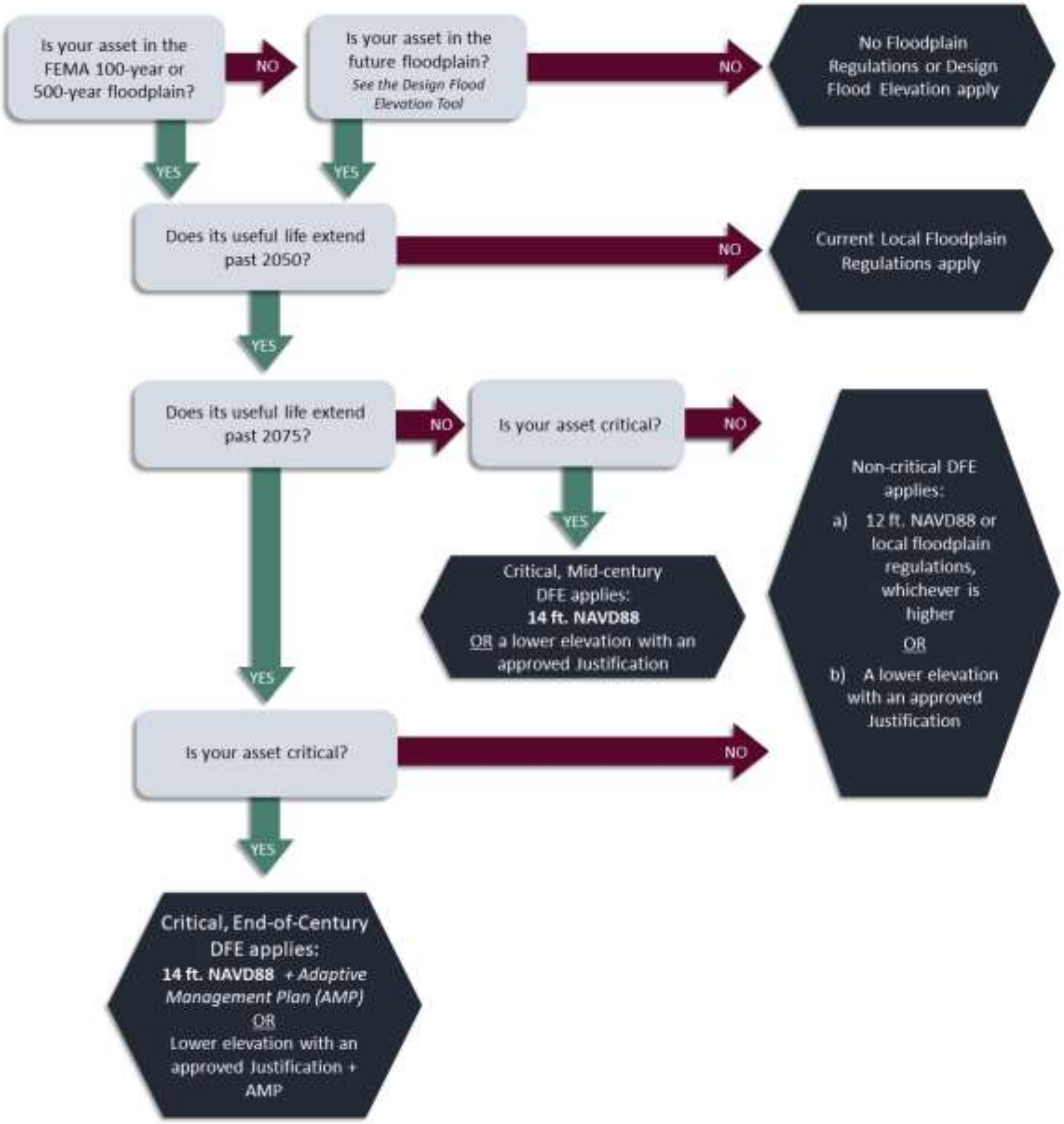


Figure 4-8. Flow chart to determine which Design Flood Elevation applies to a particular project. Note: By default, all PWD projects are assumed to be critical and the non-critical DFE can only be used with approval by the Core Review Committee (if applicable) and/or CCAP.

b. Submission of a Justification for use of a lower DFE

The use of a lower protective elevation than the design flood elevations listed in **Table 4-7** requires that a Project Manager (PM) submit justification and seek approval, through consensus, from the Core Review Committee (if applicable) and/or CCAP. The components of the Justification may vary on a project-by-project basis, as it is up to the PM to show the benefits that PWD may receive by choosing a lower protective elevation for a particular asset. This may include a cost analysis to determine the overall costs to repair or replace the asset (if inundated) compared to costs to implement flood protection measures. A justification could also include an analysis of mitigated annualized losses for different levels of flood protection and projected costs associated with each level of protection. Analyses such as these may show that an asset can be adequately protected for a significant amount of time by using a lower DFE while also minimizing upfront investment costs. However, if the asset is not protected from flood risk based on its entire useful life, repairs and replacement from flood damage could also require significant resources. This is where **adaptive management** comes in—for assets with a useful life that extends beyond 2075, the Justification should be accompanied by an Adaptive Management Plan (AMP). There is an exponential increase in uncertainty in sea level rise projections towards the end-of-century and employing adaptive management practices is key to addressing these uncertainties and increasing PWD's resiliency to future flooding. Considering future conditions in the design process today could have significant cost-savings in the long run under a changing climate.

c. Adaptive Management Plan (AMP) Requirement

While it is encouraged that adaptive management strategies be considered for any project being designed and constructed in the current or future floodplain, **it is a requirement that an Adaptive Management Plan (AMP) be developed for any assets being designed for an anticipated useful life to 2075 or beyond.** An AMP would typically be developed by the Planning and Research Unit and CRC members, if applicable, with support from CCAP. Recommendations from the AMP should be presented to the Design Unit for inclusion as part of the project's Basis of Design. Additional information on developing an Adaptive Management Plan can be found in the Adaptive Management Plan AIR Sheet (see Appendix A-1).

The AMP is a way of documenting the adaptive management strategy that will be employed for a particular asset, ensuring that sufficient flexibility is built into the design to accommodate the potential for higher sea levels and storm surge after 2075. PWD may also consider completing AMPs for an overall facility or system in which a majority of the individual assets need to be protected to the end of the century. This will be determined through evaluation of risk and assets at various levels of inundation within a facility. The AMP shows how the asset (or facility) will be adapted to protect to a higher elevation, if deemed necessary based on observed changes to the environment (specifically, sea levels). This entails establishing thresholds and a monitoring protocol to determine when (and potentially what) adaptation strategies must be implemented to ensure asset or system resiliency. An illustration of the iterative adaptive management process based on the three main phases of planning, doing and learning can be found in **Figure 4-10**.

Figure 4-9. The iterative adaptive management process. Credit: ESSA Technologies, Ltd.

d. AMP Criteria

There is no single methodology that has become a standard for integrating climate risk information into adaptive engineering planning and design practices. Thus, there is a great deal of flexibility in how to approach developing an AMP. Although not an exhaustive list of methods and principles, the information presented in the following sections can serve as a starting point. Instead of requiring a specific type of adaptive planning technique, a set of key elements that should form the basis of the AMP are provided below.

- Estimates of the anticipated useful life of the asset, assets, or facility being designed.
- Identification of current critical flood elevations, if applicable (i.e. elevation(s) at which the asset is vulnerable to flooding from present-day sea levels and/or storm surge) and future critical flood elevations that are based on a range of plausible future sea level rise scenarios.
- Uncertainty characterization using the estimated range of sea level rise corresponding to the anticipated useful life of an asset. CCAP has gathered data and established methods which can be used to aid teams in understanding uncertainty in climate projections and implications for an AMP.
- Estimated cost of asset failure after sea level rise inundation (permanent inundation) and/or storm damage (temporary inundation).
- Identification of one or more adaptation measures to reduce risk in the short and/or long-term depending on the timing of anticipated flood risk. If possible, include associated estimated costs (capital, O&M) for all adaptation measures.
- Development of a monitoring plan to track changing sea levels and storm surge probabilities. This could simply entail periodic review of tide gauge observed data and coordination with CCAP to ensure the most updated SLR projections are being considered.
- Identification of future critical thresholds, or tipping points, that would initiate the design and implementation of additional adaptation measures. The critical threshold should consider the timing of design and implementation to ensure that the flood mitigation measure would be in place before water levels reach the future critical flood elevation. The tipping point for action will be informed by the above-mentioned monitoring plan and take into account costs associated with flood protection measures vs. asset repair/replacement or relocation.

An example AMP outline that provides additional context for how to incorporate the necessary key elements is included below for reference. **Figure 4-10** also refers to the set of components recommended to form the basis of the AMP. Please refer to the Adaptive Management Plan AIR Sheet (see Appendix A-1), which goes further into detail with each AMP component and provides case studies for reference.

Figure 4-10. PWD's Climate Change Adaptation Program overview of suggested components in developing an Adaptive Management Plan (AMP).

1. Asset Characterization and Identification of Critical Flood Elevations

Developing a comprehensive understanding of asset and system vulnerabilities and risks is critical to effective adaptive management planning. The AMP should include an inventory of critical assets with the following components: description of the asset and its function, asset repair or replacement costs, presence of existing protective measures, interdependencies, asset useful service and remaining life, potential flood pathways, overall asset elevation, and critical asset flood elevation. Critical asset flood elevations should generally correspond to elevations at which an asset or system fails due to loss of functionality or the presence of health and safety hazards.

2. Risk Assessment: Identify Uncertainty and Characterize Risk

In terms of future flood risk, a range of plausible sea level rise scenarios should be considered to account for uncertainty in future conditions under climate change. It is recommended that planning assessments consider multiple sea level rise scenarios (e.g., for use in model runs), including PWD's Low SLR Scenario and the PWD Primary Planning SLR Scenario, and probabilities associated with future storm intensity and storm surge events. CCAP evaluated climate scenarios to provide ranges of inundation for different future time periods and developed tools for PWD staff to estimate future coastal flood risk (i.e. Changing Flood Frequency Tool, Inundation Mapping Tool, and an Asset Risk Assessment Data Sheet). Risk is defined as the product of consequence and likelihood/probability. In this context, consequences can be estimated using the cost of flood damage which includes materials and lost services. The likelihood of these consequences can be assumed to be the probability of flooding (i.e. storm surge return intervals).

3. Identification of Adaptation or Protective Measure Alternatives

The adaptive measure(s) being considered should be evaluated using a consistent set of criteria, including benefit-cost ratios, long-term adaptability and flexibility, and operations and maintenance requirements. A final recommendation on the most appropriate adaptive measure(s) to pursue for an asset or facility should be made in consultation with the project CRC (if applicable), the project planning team, the Design Unit and CCAP.

This section will document the development of one or more measures to reduce and/or eliminate the risk of flooding with associated costs to build and maintain. The adaptation or protection measure(s), which may include short and/or long-term solutions depending on the timing of flood risk, should be related to the asset or system's critical flood elevations. Adaptation measures can be designed as successive responses to rising sea levels or as a single measure to reach a predetermined level of protection. In some cases, committing only to short-term actions —with monitoring and tipping points that are established ahead of time to guide future adaptations (see AMP section 4 below) —can reduce unnecessary expenditure and maintain flexibility considering the uncertainty of projections for end-of-century storms and sea level rise.

4. Identification of Future Critical Thresholds (Tipping Points) for Selected Adaptive Measure(s)

Future critical thresholds, or tipping points, correspond to an elevation at which future flood risk approaches a pre-determined acceptable value and further adaptation action is warranted. If applicable for a given asset or system, tipping points should be established based on future flood vulnerability, risk tolerance, level of service goals (for example, protecting an asset up to the 100-year storm event in mid-century), and the protection level provided by any previously implemented adaptation strategy. Tipping points for action will be informed by a monitoring plan that tracks changing sea levels and storm surge probabilities over time. Adaptive management strategies that are triggered once a tipping point is reached will take into account costs associated with fully repairing/replacing an asset versus providing additional flood protection.

5. Monitoring Plan and Adaptation Pathways Map

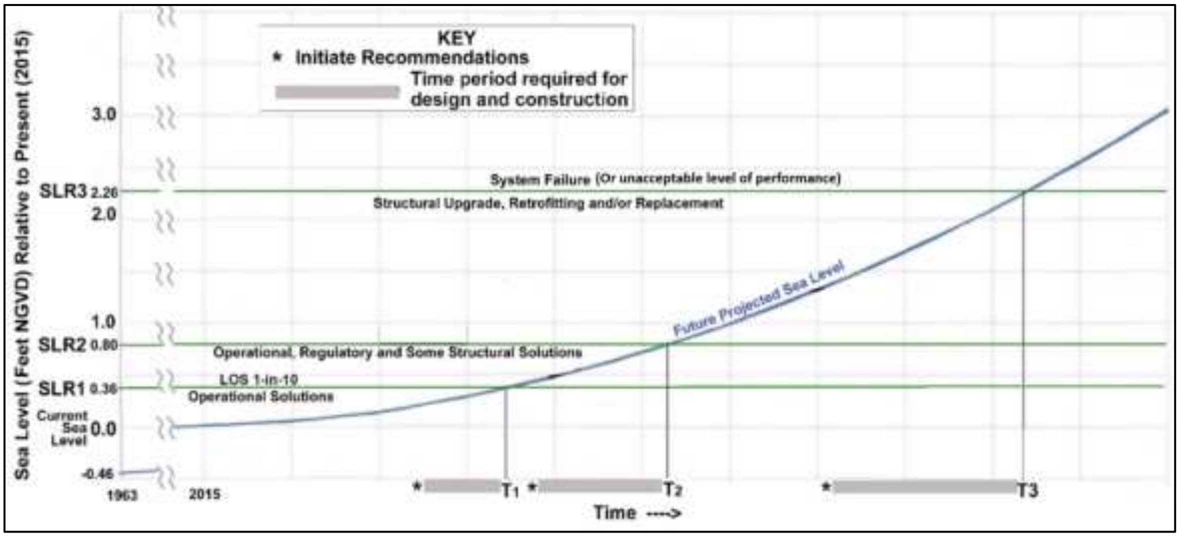


Figure 4-11. South Florida Water Management District's example implementation timeline for selected mitigation strategies (i.e. operation, regulatory, structural). Trigger points and thresholds are identified based on sea level rise (SLR) amounts (i.e. 0.36, 0.80, and 2.26 feet) for the selected SLR scenario (show here as the blue line). The timing for implementation takes into account the estimated design and construction time period of the solution.

A monitoring plan to track updates to measurable climate change impacts and to identify when critical thresholds are met is a key component of an AMP to plan for implementation of adaptive measures. Adaptation pathways maps represent multiple strategies (as identified in Step 3: Identification of Adaptation or Protective Measure Alternatives) that are evaluated and implemented in different stages over time as new information emerges. A well-crafted adaptation pathways map presents not only the possible strategies to implement, but also when and where they could fail (i.e. tipping points and critical thresholds). For example, when monitored flood elevations near the tipping point or threshold, the AMP must detail when adaptive strategies should be implemented while accounting for estimated construction timelines. Adopting this approach also encourages proactive monitoring of climate change impacts to ensure adaptation actions are taken at the appropriate time. It is important to note that the adaptation pathways map and monitoring plan work together in an iterative process as new information becomes available. CCAP is available to support monitoring plans and the tracking of climate science. **Figure 4-12** provides an example from the South Florida Water Management District of an implementation for the selected flood mitigation strategies, taking into account future sea level rise projections with the design and construction time period.

4.6 Applying the Design Flood Elevation Standard: Choosing an Adaptation Strategy

The section above provides information on how to determine *if* the coastal DFE applies to your project/design and *which* DFE applies. Once it is established that a coastal DFE is required, it is up to planning and/or design teams to choose an adaptation strategy or approach to meet the new DFE standard. Sometimes that strategy will only apply to the singular project or asset but other times, it may be more appropriate to develop an adaptation strategy or plan that applies to a larger building, facility or system.

It is also important for planners and designers to ***consider dependencies and vulnerabilities at a system-wide scale****.* ***This may require a facility or system-wide risk assessment to inform the best adaptation strategy*** *and help prioritize resiliency efforts. This will ensure that PWD resources aren't squandered building* ***"islands of resiliency"*** *within an otherwise vulnerable system.*

The most effective flood mitigation method is to relocate existing assets and locate new assets outside of the current and future floodplain. However, as this will often not be an option, elevating the asset to or above the DFE is the next most effective flood mitigation method. When possible, all critical assets—whether existing or new—should be elevated. When relocation or elevation is not feasible or cost-effective, floodproofing is an appropriate, though less effective alternative. More details on adaptation strategies for increasing flood resilience, including considerations for elevating or floodproofing new or existing assets to the DFE, can be found in the Flood Mitigation Strategies AIR sheet (see Appendix A-1). The timing of implementation may also help determine which adaptation strategies are appropriate for the project, and adopting an adaptive management plan acknowledges that flood mitigation measures can be installed over time based on new climate science information and changing conditions. Adaptive management strategies and plans are increasingly recognized as best practices for climate-resilient planning and design. has Adaptive and flexible approaches are essential for utilities to navigate the complex and dynamic challenges presented by climate change and to ensure a high-level of service in the long-term.

Miami-Dade Water and Sewer Department Wastewater Treatment Plant Upgrades

Miami-Dade Water and Sewer Department (WASD) faces a range of climate change impacts and they are particularly vulnerable to flooding from sea level rise and storm surge. WASD's first actions to build resiliency to sea level rise, storm surge and tide effects took place in 2006 and since 2015 all facilities are required to use hardening and resiliency guidelines. WASD also assesses other climate-related impacts on its operations and infrastructure, including inland flooding due to extreme precipitation and rising groundwater and wind from hurricane events. Miami-Dade County requires that all county infrastructure projects consider sea level rise and its potential impacts. As a result, WASD now considers climate change information, particularly sea level rise projections, in all of its Capital Improvement Program projects.

As part of the Capital Improvement Program, WASD developed flood design guidelines for their wastewater treatment plants. They are currently in the process of overhauling all three of their wastewater treatment plants and their system of over 1,000 pump stations. This work will help them address aging infrastructure, meet regulatory compliance for state-wide ocean outfall legislation and build resiliency to climate change. During design upgrades, WASD takes a systematic approach to determine the best design for each asset upgrade. For example, each wastewater treatment plant undergoing upgrades is assessed asset-by-asset using a design flood elevation (DFE).

Miami-Dade WASD Wastewater Treatment Plant.

With over a decade of experience designing and hardening assets, WASD found that the cost to build resilience to sea level rise and storm surge was marginal if projects were already underway through the CIP, adding only ~5% to the total project cost.

More information about the flood design guidelines for the Miami-Dade Water and Sewer Department can be found in the *Water Utility Climate Alliance case study sheet*.

4.7 A Note on Riverine Flood Resiliency

The coastal DFE was developed to protect PWD assets and facilities along the tidal Delaware River. However, as demonstrated by post-tropical storm Ida in September 2021, PWD also has critical assets within the riverine floodplain that are highly vulnerable to flooding. Climate change will increase the intensity and frequency of precipitation, particularly during extreme storm events, which will exacerbate riverine flooding in Philadelphia and surrounding watersheds. In 2022, CCAP developed a method that estimates climate change impacts on future riverine water levels and streamflow for the Schuylkill River (See **Future Changes to Streamflow and Riverine Flood Return Intervals**) As these analyses are developed on a project-by-project basis, it is recommended **that the FEMA 500-year (0.2%-annual-chance) flood elevation be used as a protective elevation for new assets and for protecting and floodproofing existing assets**. FEMA strongly recommends applying, at a minimum, the 500-year flood elevation for planning and design of critical facilities (FEMA, 2007). Under the Federal Flood Risk Management Standard and Executive Order 11988, the 500-year level of protection is required for projects subject to (or to be qualified for) receiving federal funding[26]. The 500-year flood elevations can be found in the flood profiles (at cross sections or based on stream distance) in the *FEMA Philadelphia Flood Insurance Study (2015)* (refer to **Figure 4-13** for an example). To determine whether the riverine 500-year flood elevation applies to a project or facility, the 500-year floodplain should be used as a screening layer. In locations where it is unclear whether the project is within the coastal or riverine floodplain, please consult CCAP or refer to CCAP's Inundation Mapping Tool [LINK REMOVED – for internal PWD use only].

If your project is within the riverine floodplain, CCAP is available for consultation to provide site-specific projections and analysis of changing flood frequencies and flood elevations for areas surrounding the Schuylkill River and other tributaries. In close collaboration with the Water Revitalization Plan group, CCAP developed climate-informed riverine Design Flood Elevations (DFE) at the existing Belmont Raw Water Pumping Station to characterize the level of protection for riverine flooding under future conditions. Similar to the coastal DFE requirement, an **Adaptive Management Plan** is recommended for critical assets in the ground through end-of-century. In the face of more extreme flood events and occurrence of higher riverine flood elevations past mid-century, establishing an Adaptive Management Plan is a proactive and flexible approach to address the complexities and uncertainties associated with long term asset management under a changing climate.

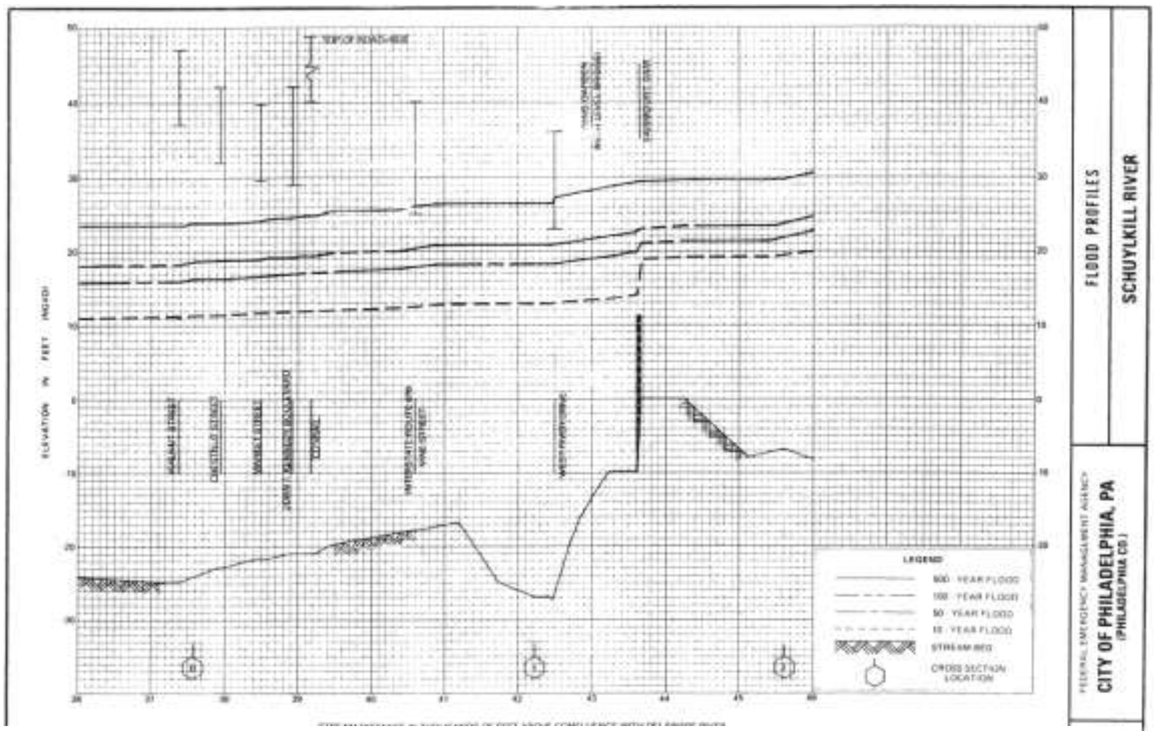


Figure 4-12. Example of a FEMA flood profile within the Flood Insurance Study with flood elevations for the 10, 50, 100 and 500-year return periods.

---

[26] *Under Executive Order 11988, Floodplain Management, Federal agencies funding and/or permitting critical facilities are required to avoid the 0.2 percent (500-year) floodplain or protect the facilities to the 0.2 percent chance flood level.*

4.8 Areas of Future Consideration

There are several areas related to sea level rise, storm surge and climate change that CCAP is planning to research and assess in the future. The research areas, as outlined below, have to do with risks and impacts from sea level rise and storm surge on subsurface infrastructure, the groundwater table, and the compounding impacts from sea level rise/storm surge combined with extreme precipitation events.

- **Subsurface Infrastructure Planning and Design** – Much of this section focuses on above-grade assets vulnerable to surface flooding. However, the risk from sea level rise and storm surge to our stormwater and combined sewer systems is an area that deserves considerable attention. The Interceptor Sewer and Regulator Dam Analysis Tool provides a starting point for this work, but CCAP intends to continue researching this topic and to work with the appropriate PWD staff to develop a plan to assess this unique and challenging vulnerability.
- **Groundwater**: As sea levels rise, so will the groundwater in Philadelphia. This could have implications for GSI systems that rely on infiltration and must be above the groundwater table; the drainage system, which could be impacted by inflow and infiltration from rising groundwater and which could be degraded if brackish or salty water comes in contact with pipes; and flood risk, which could be exacerbated by new areas of the city flooding as rising groundwater breaches the surface or floods more basements and homes.
- **Compound flooding**: To date, CCAP's risk assessments and analyses have focused largely on individual climate impacts (e.g. precipitation changes, temperature changes, sea level rise), but in reality, it is the compound impact of these climate impacts that can cause the most damage. CCAP is interested in studying and assessing compound climate change impacts, specifically flooding impacts from precipitation increases and sea level rise/storm surge. Compound flooding impacts to surface flooding and to drainage systems could be studied using riverine flood models in combination with coastal flood models including H&H models that incorporate higher sea levels and changes to precipitation intensity, duration and frequency. CCAP is involved in this area of research, including through a recently completed NOAA-funded compound flood modeling project (in partnership with Stevens Institute (PI) and Drexel University (co-PI) in the Eastwick neighborhood of Philadelphia.
- **Salinity/Salt Front**: As mentioned previously, CCAP coordinates with the PWD water quality modelling team to better understand the timing and magnitude of risk related to salinity intrusion. This will be an ongoing area of collaboration as the water quality modeling team begins to assess various sea level rise scenarios.
- **Keeping up to date with the climate science**: New scientific models and research findings that investigate the complex processes and dynamics driving global sea level rise (i.e. ice sheet dynamics and the effects of substantial melting) are continually being released by regional, national, and global institutions that are part of the broader climate science community. Staying well-informed with scientific journals, new climate assessment reports, and knowledge exchange with peer utilities is essential for gaining a comprehensive understanding of how future sea level rise and storm surge may be realized. In the evolving field of climate science, CCAP will continue to monitor updates of the latest developments in coastal inundation projections and their impact on Philadelphia and the region.

4.9 References

ASCE. (2018). Climate-Resilient Infrastructure (B. Ayyub, Ed.). American Society of Civil Engineers.

AWWA. (2010). Risk Analysis and Management for Critical Asset Protection (RAMCAP) standard for Risk and Resiliece Management of Water and Wastewater Systems (1st ed.). American Water Works Association.

Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., Merrifield, M. A., Milne, G. A., Nerem, R. S., Nunn, P. D., & others. (2013). Sea level change (Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change). PM Cambridge University Press. http://drs.nio.org/drs/handle/2264/4605

CoastAdapt. (2017). What is a pathways approach to adaptation? https://coastadapt.com.au/pathways-approach

Federal Emergency Management Agency (FEMA). (2007). Design Guide for Improving Critical Facility Safety from Flooding and High Winds. FEMA P-543 Risk Management Series. https://www.fema.gov/sites/default/files/2020-08/fema543_design_guide_complete.pdf

Haasnoot, M., Kwakkel, J. H., Walker, W. E., & ter Maat, J. (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. Global Environmental Change, 23(2), 485–498. https://doi.org/10.1016/j.gloenvcha.2012.12.006

Intergovernmental Panel on Climate Change (IPCC) (ed.) (2023). Mitigation Pathways Compatible with Long-term Goals, in *Climate Change 2022 - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 295-408). Cambridge: Cambridge University Press. doi: 10.1017/9781009157926.005.

Linn, C. (2004). Sea Level Rise Impacts in the Delaware Estuary of Pennsylvania. Regional Planning, 2002, 50.

Maimone, M., & Kulis, P. (2017). Memorandum: Sea Level Rise rate calculation methods and uncertainty. CDM Smith.

Multi-Hazard Mitigation Council. (2019). Mitigation Saves: 2019 Report. National Institute of Building Sciences. https://cdn.ymaws.com/www.nibs.org/resource/resmgr/reports/mitigation_saves_2019/mitigationsaves2019report.pdf

NASA. (2020, August 20). NASA-led Study Reveals the Causes of Sea Level Rise Since 1900 [Feature]. https://climate.nasa.gov/news/3012/nasa-led-study-reveals-the-causes-of-sea-level-rise-since-1900/

NASA. (2022). Philadelphia (Pier 9N). Interagency Sea Level Rise Scenario Tool. Interagency Sea Level Rise Scenario Tool – NASA Sea Level Change Portal

Nerem, R., Chambers, D. P., Choe, C., & Mitchum, G. T. (2010). Estimating mean sea level change from the TOPEX and Jason altimeter missions. Marine Geodesy, 33, 435–446. https://doi.org/10.1080/01490419.2010.491031

NOAA. (2013). EXTREME WATER LEVELS OF THE UNITED STATES 1893-2010 (Technical Report No. 067). https://tidesandcurrents.noaa.gov/publications/NOAA_Technical_Report_NOS_COOPS_067a.pdf

NOAA. (2019, November). Climate Change: Global Sea Level. Climate.Gov. https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level

NYC DEP. (2013, October 29). DEP Releases Resiliency Plan for New York City Wastewater Facilities [Press Release]. https://www1.nyc.gov/html/dep/html/press_releases/13-107pr.shtml#.XsKrWmhKiUk

NYC Dept. of Parks & Recreation. (2017). Design and Planning for Flood Resiliency: Guidelines for NYC Parks. https://www.nycgovparks.org/pagefiles/128/NYCP-Design-and-Planning-Flood-Zone__5b0f0f5da8144.pdf

Sweet, W, Horton, R., Kopp, R. E., LeGrande, A. N., & Romanau, A. (2017). Sea Level Rise. In: Climate Science Special Report: Fourth National Climate Assessment, Volume I [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. (pp. 333–363). U.S. Global Change Research Program.

Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak. (2022). Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD. Retrieved from Global and Regional Sea Level Rise Scenarios for the United States (windows.net)

Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. (2023). Fifth National Climate Assessment. U.S. Global Change Research Program (USGCRP), Washington, DC. Retrieved from https://doi.org/10.7930/NCA5.2023

Williams, Szaro, & Shapiro. (2009). Adaptive Management: The U.S. Department of the Interior Technical Guide (2nd ed.). Department of the Interior. https://edit.doi.gov/sites/doi.gov/files/migrated/ppa/upload/TechGuide.pdf

Willis, J., Hamlington, B., & Fournier, S. (2023). Global Mean Sea Level, Trajectory and Extrapolation (Version 101) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.7702315

Zielinski, G. A. (2002). A Classification Scheme for Winter Storms in the Eastern and Central United States with an emphasis on Nor'easters. Bulletin of the American Meteorological Society, 83(1). https://doi.org/10.1175/1520-0477(2002)083<0037:ACSFWS>2.3.CO;

Storm Ahead

Precipitation Planning and Design Guidance

Photo: c. Melon Images

Roadmap

B Background information and justification of information presented
P Relevant to PWD planning processes
D Relevant to an asset or system design

This brief section provides **background information** about the effect of climate change on precipitation and how that varies across different regions, with emphasis on what has been observed in Philadelphia and precipitation increases we are projected to see in the future. This section also highlights all the applications of precipitation data within PWD. B

This section provides **background information** on the limitations of the Global Climate Model precipitation output and presents results from CCAP's precipitation analysis. This section also provides **justifications** for the use of RCP 8.5. B

This section contains **actionable science** information for precipitation **applications.** These tools, such as the high-resolution future time series, IDF curves, and changing return interval tool, can be used in the planning and design of PWD's assets. P D

This section contains information on a powerful **planning** tool that will help PWD planners explore potential variability in current and future precipitation patterns. P

This section contains information on a method to estimate future riverine flood elevations and an example application that will help **planning and design engineers assess** the potential impact of riverine flooding on projects. P D

This section provides examples of additional applications of future precipitation information to PWD's various initiatives. P D

5.1 Key Terms

Key Term	Acronym	Definition
Annual Exceedance Probability	**AEP**	The probability of a precipitation event of a particular magnitude or larger occurring in any given year.
Climate Change Adaptation Program	**CCAP**	The program at the Philadelphia Water Department working on climate change adaptation.
Critical asset	**--**	An asset whose absence or unavailability would significantly degrade the ability of a utility to carry out its mission or would have unacceptable financial or political consequences for the owner or the community.
Delta Change Factors	**DCFs**	Used in statistical downscaling, a DCF is the ratio between model simulations of current and future climate and is used as a multiplicative factor to obtain future regional or local conditions.
Fifth National Climate Assessment	**NCA5**	The National Climate Assessment (NCA) is a United States government interagency and ongoing effort on climate change science conducted under the auspices of the Global Change Research Act of 1990. NCA5 was released in 2023.
Hydrologic & Hydraulic Model	**H&H Model**	A software simulation of rainfall runoff flow to study the movement of water, including the volume and rate of flow as it moves through a watershed, basin, channel, or man-made structure.
Intensity-Duration-Frequency Curves	**IDF Curves**	Graphical depiction of precipitation frequency estimates in terms of intensity, duration and frequency.
Level of Service/Level of Protection	**LOS**	Quantifiers of the types and amount of services customers receive based on quality levels, service consistency, types of services, and performance levels.
Long-term projections	**--**	Climate projections for the end of the 21st century and beyond.
Mid-term projections	**--**	Climate projections for mid-century, 2050 – 2070.
Near-term projections	**--**	Climate projections for the period 2016 – 2035 (IPCC 2018).
Philadelphia International Airport rain gauge	**PHL rain gauge**	The rain gauge located at the Philadelphia International Airport in Pennsylvania, U.S. Data accessed from NOAA.
Representative Concentration Pathway	**RCP**	Introduced in the IPCC Fifth Assessment Report (AR5), scenarios that provide projections of atmospheric greenhouse gas concentrations while accounting for aerosol emissions concentrations and land use changes.

Return period	**--**	i.e. return interval – the percent chance of a certain size storm occurring in any given year for a specified duration and at a given location.
Risk tolerance/level of risk	**--**	In the context of this guidance document, refers to the level of risk the Department is willing to accept when considering climate change impacts. For an asset or infrastructure system, risk tolerance may be related to understanding how level of service goals may be impacted.
Storm Flood Relief projects	**SFR projects**	On-going since 2005, the Department's program to reduce the occurrence of street and basement flooding that result from inadequate drainage system capacity.

5.2 Introduction and How this Guidance Applies to PWD

In a warming climate, there will be an increase in rainfall intensities because the atmosphere will be able to hold more moisture. According to the Clausius-Clapeyron (C-C) equation, for every 1 ° C of temperature increase, the atmosphere can hold approximately 7% more water (Trenberth et al., 2003). Changes in precipitation will not be uniform across the world as some regions may experience an increase in precipitation intensity, volume and/or frequency while others may experience a decrease in rainfall. Rainfall patterns will also be changing; some regions of the world may start to see longer periods of drought-like conditions in between periods of very intense rainfall, for example (USGCRP, 2017). In the United States, Global Climate Model (GCM) projections vary on a regional scale with the largest increases in the frequency and intensity of extreme precipitation expected in the Northeast region, which includes Philadelphia. Increases will vary by season, with the winter and spring expected to see the largest increases (USGCRP, 2018).

Rainfall in the Philadelphia region is characterized by a large amount of natural variability, making it difficult to determine long-term trends or tease out a climate change signal. Nevertheless, Philadelphia may already be seeing increases in intense rainfall events. **Figure 5-1** illustrates the return intervals of observed rainfall events at the Philadelphia International Airport gauge (PHL) for 1900-2019 in 30-year periods. This period of record is showing an increase in the number of extreme rainfall events over more recent decades.

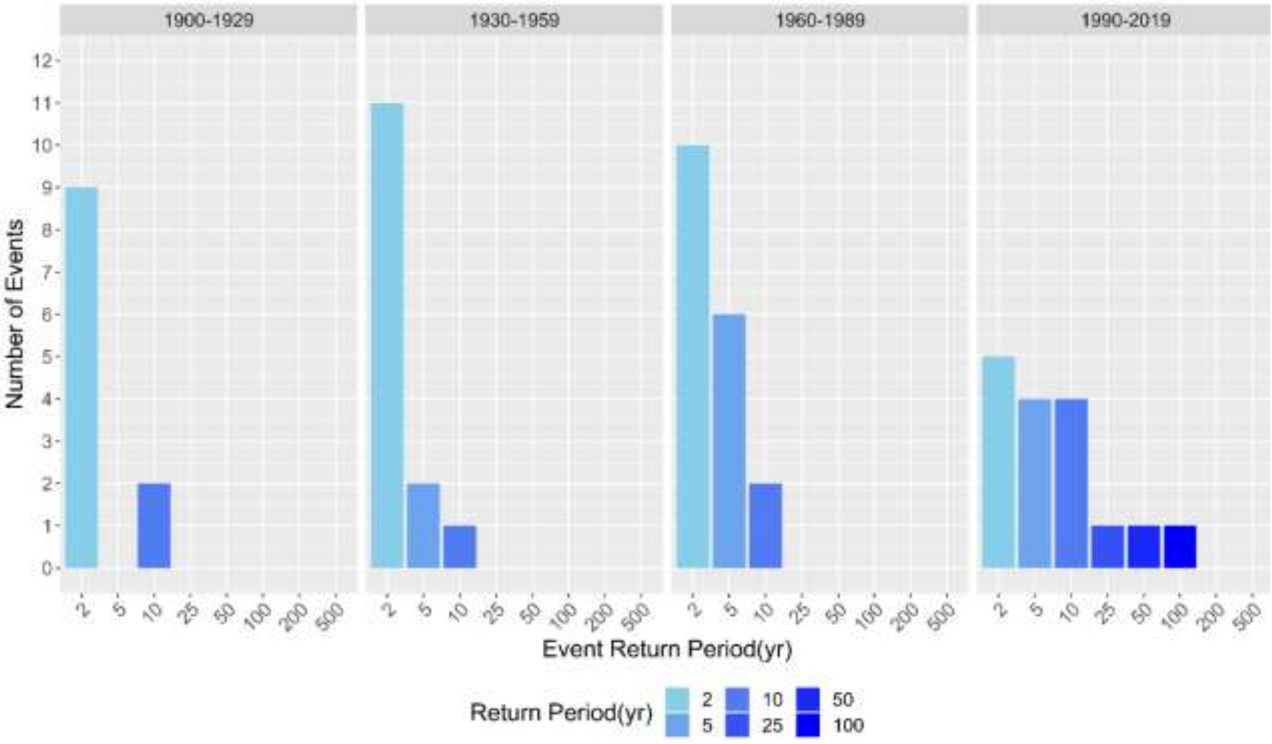


Figure 5-1. Number of events associated with various return periods for a 24-hour event duration. Events are displayed over 30-year periods from 1900 to 2019. (Data source: PHL rain gauge)

According to **Figure 5-1**, there were no extreme rainfall events with a return period of 25 years or higher from 1900-1929, 1930-1959 and 1960-1989. However, in the last 30 years (1990-2019), Philadelphia has experienced one 25-year event, one 50-year event, and one 100-year event. It should be noted that the rainfall data analyzed for **Error! Reference source not found.**comes from the PHL rain gauge. Precipitation exhibits significant spatial variability throughout Philadelphia, as is evidenced when comparing PHL data to PWD rain gauge network data. There are 37 rain gauges in Philadelphia as part of the PWD network. While these gauges do not have a comparable period of record to PHL (most gauges were not operating until 1990), they do provide indication of recent rainfall variability. **Figure 5-2** below shows the spatial variability of rainfall by comparing event return periods recorded at the PHL gauge with select PWD gauges spread throughout Philadelphia for the period 1990-2019. PWD gauges with the longest period of record (i.e. going back to 1990) were selected for **Figure 5-2**.

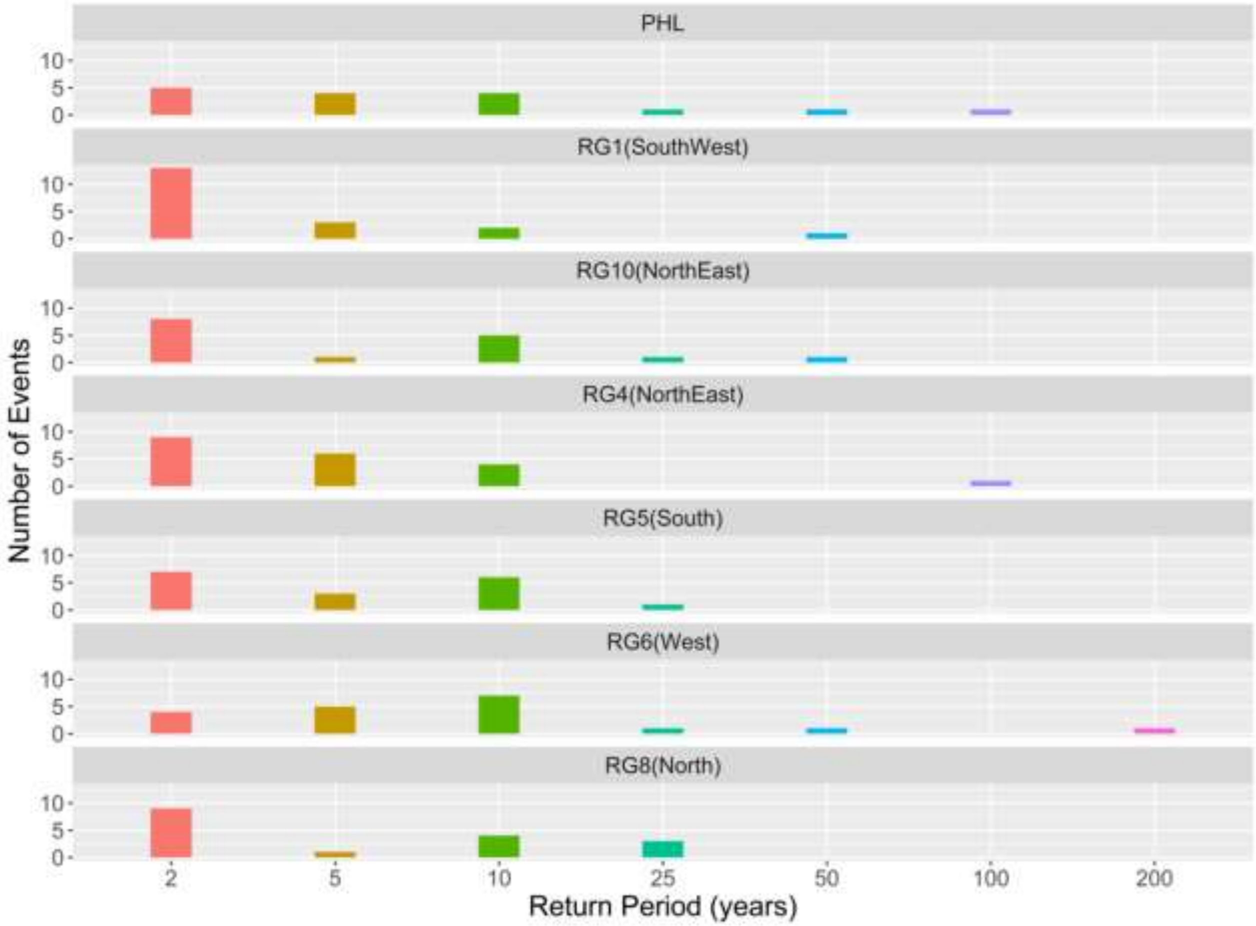


Figure 5-2. Comparison of the number of events associated with various return intervals from 1990-2019 at the PHL rain gauge, Rain Gauge 1 (Southwest Philadelphia), Rain Gauge 10 (Northeast Philadelphia), Rain Gauge 4 (Northeast Philadelphia), Rain Gauge 5 (South Philadelphia), Rain Gauge 6 (West Philadelphia) and Rain Gauge 8 (North Philadelphia).

Error! Reference source not found. shows a map of all 37 rain gauges located in and around Philadelphia. This monitoring network captured a recent example of the spatial variability of precipitation in Philadelphia during a storm event on June 11, 2018. At the 3-hr duration of the event, rain gauges in the Northeast part of the City recorded a 1000-year event while rain gauges in the Southwest part of the City recorded a 1-year event. This observed spatial variability in rainfall may have many contributing factors. For individual storm event variability, the storm characteristics are likely the main contributing factor. For long-term averages, spatial variability may also be impacted by inherent effects associated with gauge placement and functioning.

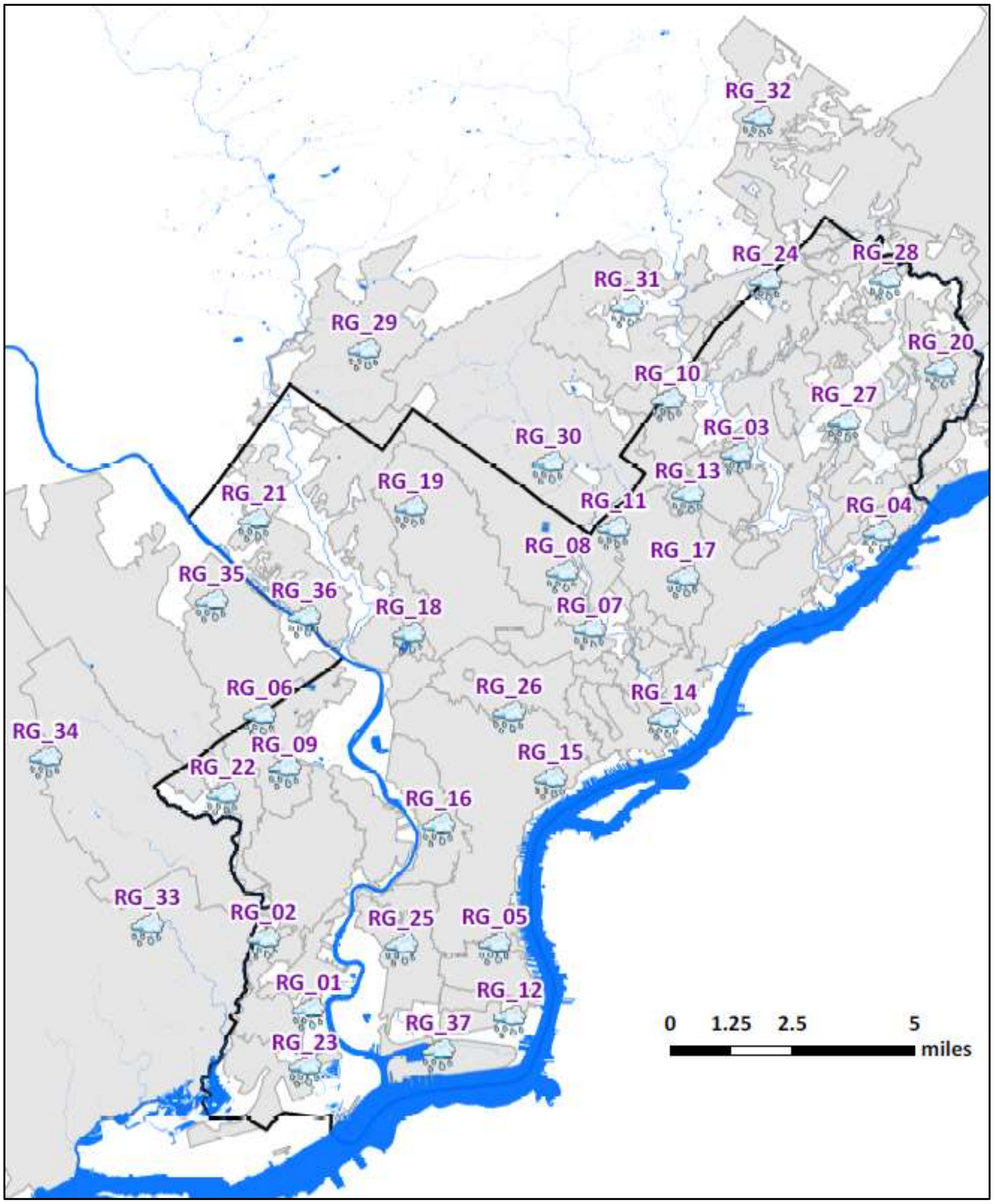


Figure 5-3. Map of the 37 Rain Gauges in PWD's Network.

Future increases in rainfall will have a significant impact on the urban environment and infrastructure across the Philadelphia area. In particular, high intensity rainfall may cause more frequent riverine flooding and infrastructure-based (or urban) flooding as the capacities of surface water bodies and drainage systems are exceeded, respectively. Thus, there is a need to consider precipitation projections to assess the impacts of changing storm size and intensity on the PWD collection system and associated infrastructure. It is important to note that all the precipitation projections and products provided in this section were generated using the long period of record at the PHL rain gauge. This long period of record was critical to be able to estimate low probability events (i.e. events with longer return periods). While the PWD rain gauge network was not included in initial CCAP precipitation analyses, exploring spatial variability in local rainfall is an area for future consideration.

> *The goal of this part of the guidance is to* ***facilitate the integration of precipitation projections in PWD's planning and design processes****. Through this process of mainstreaming climate information in existing practices, PWD can help ensure that current levels of service can be maintained, and regulatory requirements can be met, under future conditions of increasing rainfall.*

As a first step, it is important to consider all the ways in which PWD currently uses precipitation data. Applications that require precipitation inputs at PWD including the following:

1. **Evaluating Collection System Performance**
    - Hydrologic & hydraulic (H&H) models use precipitation time series and design storms to simulate system performance (combined & separate systems)

2. **Performing Planning Assessments**
    - Flood management planning and flood risk analyses
    - Treatment facility assessments
    - Receiving water quality regulatory compliance (NPDES Permits)

3. **Designing Grey, Green and Nature-Based Infrastructure**
    - Standard sewer system design
    - Green stormwater infrastructure (GSI) design
    - Flood mitigation measures
    - Ecological restoration/streambank stabilization

Precipitation projections should be applied by PWD staff as well as consultants working on projects or plans that require precipitation inputs. Additionally, as stated in the User Guide section, PWD project managers should reference PWD's policy requiring use of this Guidance document in any relevant Request for Proposals (RFPs).

5.3 Understanding Future Precipitation Increases

In the United States, the Northeast region, which includes Philadelphia, has seen about a 60% increase in extreme events (defined as events with the top 1% of daily precipitation accumulations) (NCA, 2023). Analysis of climate projections performed by the City of Philadelphia Office of Sustainability indicate that this trend will continue - the City is expected to see higher average total rainfall volumes and intensities than what has been observed in the past (Useful Climate Information for Philadelphia: Past and Future, 2014).

a. Average Precipitation Increases Based on Future Time Series

Increasing rainfall volume and intensity pose many potential risks to PWD, including further stress on the capacity of the City's drainage system and more frequent and severe riverine flooding that could impact PWD facilities and operations.

These risks prompted CCAP to perform additional, in-depth analyses of precipitation projections for Philadelphia using statistically downscaled GCM output[27] that is publicly available through the Bureau of Reclamation (BoR) and a consortium of other scientific agencies (BoR Downscaled Climate Projections).

GCM precipitation output, even once it is statistically downscaled, is in the format of daily totals, which is too low a temporal resolution for direct use in many planning, design and engineering applications, including urban stormwater modeling. Additionally, CCAP's initial analysis revealed that GCM precipitation output for Philadelphia does not accurately represent local precipitation patterns, including storm intensities and durations. To address these limitations, CCAP developed an innovative approach, which has been published in the ASCE *Journal of Water Resources Planning and Management*[28], to transform GCM output into actionable science (Maimone et al., 2019). For PWD stormwater and wastewater planning, actionable science refers to plausible future hourly and sub-hourly precipitation time series that can be applied to hydrologic and hydraulic (H&H) modeling and IDF curve development. (Please refer to Appendix C for tables, figures and supplemental materials).

Based on CCAP's future high-resolution time series generated for a high emissions scenario (Representative Concentration Pathway (RCP) 8.5), Philadelphia can expect that:

- Both precipitation intensities and total volumes to increase.
- Precipitation averages and extremes to both increase.
- Projected increases in precipitation will differ not only by season but also by storm size.
- The frequency of storm events (i.e. the number of wet hours and days per year) will not increase, implying that increases in rainfall will be due to higher intensities.

More specifically, the following results were obtained when comparing observed hourly rainfall timeseries from the PHL gauge (1997-2017) with climate adjusted future PHL hourly time series for the periods 2050-2070 and 2080-2100, using projections from a high emissions scenario (RCP8.5):

- Max event size is projected to increase on average by about 3.7% in 2050-2070 and 9.5% in 2080-2100 while average event depth is projected to increase by about 9.5% in 2050-2070 and 12.7% in 2080-2100
- For the 2050-2070 period, large increases in seasonal total precipitation are expected for Fall, Winter and Spring, with future seasonal averages of 11.8 inches (+10.5%), 10.5 inches (+17.3%) and 11.5 inches (+7.7%), respectively. Though summer precipitation is expected

---

[27] *Statistical downscaling of GCM output involves the use of statistics-based techniques to… 'determine relationships between large-scale climate patterns resolved by GCMs and observed local climate responses. These relationships are applied to GCM results to transform climate model outputs into statistically refined products, often considered to be more appropriate for use as input to regional or local climate impacts studies.' (NOAA GFDL, 2020)*

[28] *If you cannot access this article through ASCE, please contact the CCAP.*

to increase less compared to other seasons, it shows the largest variability across seasons due to an increase in extreme events. This variability can be seen in **Figure 5-4** below.

- For the 2080-2100 period, large increases in seasonal total precipitation are expected for Fall, Winter and Spring, with future seasonal averages of 11.66 inches (+9.6%), 10.98 inches (+22.2%) and 12.33 inches (+15.2%), respectively. Though summer precipitation is expected to increase less compared to other seasons, it shows the largest variability across seasons due to an increase in extreme events. This variability can be seen in **Figure 5-4** below.
- The 90th percentile storm event is expected to increase, on average, by about 10.1% in 2050-2070 and 13.7% in 2080-2100, while the 10th percentile storm event is expected to increase, on average, by 2.9% in 2050-2070 and 4.5% in 2080-2100.

Note that these results are likely an underestimation since they are based on GCM precipitation projections which are limited in simulating extreme events. Results that present better estimates of changes in extreme events are shown in *b. Projections for Future Design Storms and IDF/DDF Curves.*

Figure 5-4 shows the seasonal precipitation for current, mid-century, and end-of-century time periods.

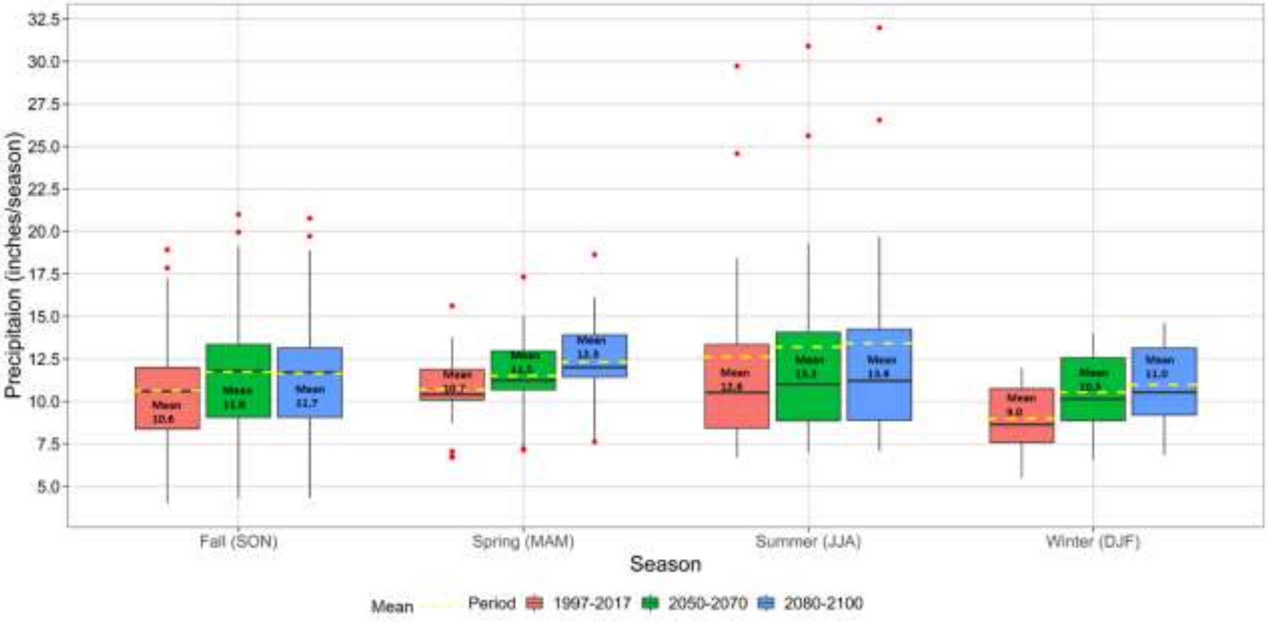


Figure 5-4. Seasonal precipitation for observed PHL gauge data (1997-2017) and climate-adjusted future time periods for mid (2050-2070) and end-of-century (2080-2100). The lower and upper values in the box plot correspond to the first and third quartiles (the 25th and 75th percentiles). The red dots represent outlier values, the black lines represent the median, and the dashed yellow lines represent the mean.

Table 5-1 below provides additional results obtained from comparing the baseline PHL gauge data (1997-2017) with climate-adjusted future time series for the periods 2050-2070 and 2080-2100.

Table 5-1. Statistical parameters for the PHL 1997-2017 observed time series compared to the PHL 2050-2070 and 2080-2100 projected (i.e. climate-adjusted) time series.

Time Period	Average Annual Total (in./yr.)	Max. Annual Total (in./yr.)	Min. Annual Total (in./yr.)	Mean Event Depth (in./event)	Max. Event Depth (in./event)	Max Intensity (in./hr.)	Mean Intensity (in./hr.)
1997-2017	43.01	64.33	30.41	0.41	8.27	1.36	0.06
2050-2070	47.10	70.22	33.22	0.45	8.58	1.55	0.07
2080-2100	48.49	72.28	34.50	0.46	9.06	1.52	0.07
% Change 2050	9.5%	9.2%	9.2%	9.5%	3.7%	14.0%	7.6%
% Change 2080	12.7%	12.4%	13.4%	12.7%	9.5%	11.7%	9.7%

b. Event-Based Extreme Precipitation Increases

In addition to inaccurately representing local precipitation patterns, the GCMs also do not simulate extreme events very well. Consequently, projections for future extreme rainfall events are likely underestimated due to model limitations. There is no established and consistent method to handle the models' inability to model extreme precipitation, so CCAP tried to address this issue by developing three event-based methods (low, medium and high), which have been published in the *Journal of Water and Climate Change*. The CCAP Low method uses the GCM precipitation outputs to develop DCFs based on the largest wet days in a 20-year period. The CCAP Medium and High methods use the more reliable temperature projections from the GCMs and the C-C and Super C-C principles to develop DCFs. for each decade between 2020 and 2090. The standard C-C principle used in generating DCFs for the CCAP Medium method applies a 7% increase in precipitation per 1°C of warming, while the Super C-C principle used in the CCAP High method applies precipitation increases of 7-12% per 1°C of warming. All three methods utilized an ensemble of the IPCC's Coupled Model Intercomparison Project 5 (CMIP5) models under a high emission scenario (RCP8.5). The DCFs generated for all three methods were applied on a decadal basis to a baseline period of 1900-2022 and used to generate estimates of future extreme precipitation depths and intensities for various durations. More information on these results can be found in section 5.4 below.

CCAP also developed a tool to assess future changes in the return interval of storms for all the three extreme precipitation projection methods. The results of this tool will help inform level of service considerations when planning and designing projects. CCAP will continue to research and update the results as the science regarding extreme precipitation evolves. (Please refer to Appendix C for tables, figures and supplemental materials).

Table 5-2 below provides future changes in extreme precipitation using CCAP's High method for the 2080s decade.

Table 5-2. Percent change in extreme precipitation events for the 2080s decade under CCAP's High method.

	Average Recurrence Interval					
Duration	**2-y**	**5-y**	**10-y**	**25-y**	**50-y**	**100-y**
1-hour	52.1%	53.7%	55.4%	57.1%	58.8%	60.5%
2-hour	49.2%	51.1%	52.9%	54.8%	56.6%	58.5%
3-hour	46.4%	48.4%	50.4%	52.4%	54.4%	56.4%
6-hour	43.5%	45.7%	47.9%	50.1%	52.2%	54.4%
12-hour	40.6%	43.0%	45.4%	47.7%	50.1%	52.4%
24-hour	37.8%	40.3%	42.8%	45.4%	47.9%	50.4%

All the precipitation projections presented in this section of the guidance are based on an ensemble of GCMs and represent results for a high emission scenario only (RCP8.5). It is best practice to use a model ensemble with multiple GCMs since no single GCM can be said to be the most accurate and there is a wide range of possible future outcomes depending on the GCM being considered. Generally, it is also best practice to use GCM output from more than one emissions scenario given future uncertainties. However, CCAP determined that for the purposes of this guidance, projections corresponding to RCP8.5, a high emissions scenario, will be provided. Projections related to other, lower, emissions scenarios can be provided upon request. The primary reasons for focusing on RCP8.5 projections have to do with the characteristics of precipitation in the Philadelphia region as well as assumptions regarding PWD's risk tolerance. More specifically:

- **Precipitation in the Philadelphia region is characterized by a high level of natural variability.** CCAP determined that for precipitation, natural variability is the dominant source of uncertainty until at least mid-century and remains significant through the end-of-the century. When compared to natural variability, emissions scenarios have a relatively low impact on future precipitation, making it less critical to consider multiple scenarios than with other climate parameters, such as air temperature, that are highly influenced by emissions scenarios.
- **PWD provides critical services through the operation and maintenance of critical infrastructure, so a low tolerance for risk is appropriate.** Some of PWD's assets and infrastructure are highly vulnerable to increasing rainfall, furthering the justification for using projections from a high emissions scenario. Additionally, since PWD infrastructure has a long useful service life, high emissions scenario projections should be considered through the end-of-the century. CCAP's general approach given the criticality of the services provided, has been to "plan for the worst and hope for the best."

5.4 CCAP Precipitation Products

The information and tools developed by CCAP aim to facilitate the use of rainfall projections in evaluating and adapting to climate risks, helping to ensure PWD maintains current levels of service and continues to meet regulatory requirements. To this end, it was necessary for CCAP to generate products and information that can directly inform planning and design processes at PWD**.** The precipitation products CCAP developed are:

- ✓ **High resolution (hourly, sub-hourly) future time series**
- ✓ **Future IDF curves (low, medium, high)**
- ✓ **Changing return interval tool**

More information on each precipitation product can be found below.

a. Projections for High Resolution Future Time Series

A basic requirement of urban stormwater modeling applications, specifically, hydrologic and hydraulic (H&H) modeling, is high resolution precipitation inputs. CCAP has developed hourly and sub-hourly time series and can provide these for use by PWD staff. These 20-year time series for mid-century (2050-2070) and end-of-century (2080-2100) conditions under a high emissions scenario are currently available, but time series for other emissions scenarios and future timeframes can be generated upon request. As stated above, the future time series are based on precipitation output from an ensemble of CMIP5 GCMs.

b. Projections for Future Design Storms and IDF/DDF Curves

Intensity-duration-frequency, or IDF curves, and Depth-duration-frequency, or DDF curves, are fundamental tools used in event-based infrastructure design. They can also be used to provide information on extreme storm events for flood risk management planning purposes. IDF and DDF curves characterize the magnitude of rainfall corresponding to different duration events (typically ranging from minutes to hours) for various return periods. Frequency estimates can be expressed as rainfall intensity (inches/hour) or rainfall totals (inches over the duration of an event). Using the event-based extreme precipitation methodology mentioned above, CCAP generated three sets of IDF and DDF curves for each decade from the 2020s -2090s under a high emissions scenario. The DCFs were generated and applied on a decadal basis and referenced to a baseline period of 1900-2022.

Examples of IDF and DDF curves are shown in **Figure 5-5** and **Figure 5-6**, respectively.

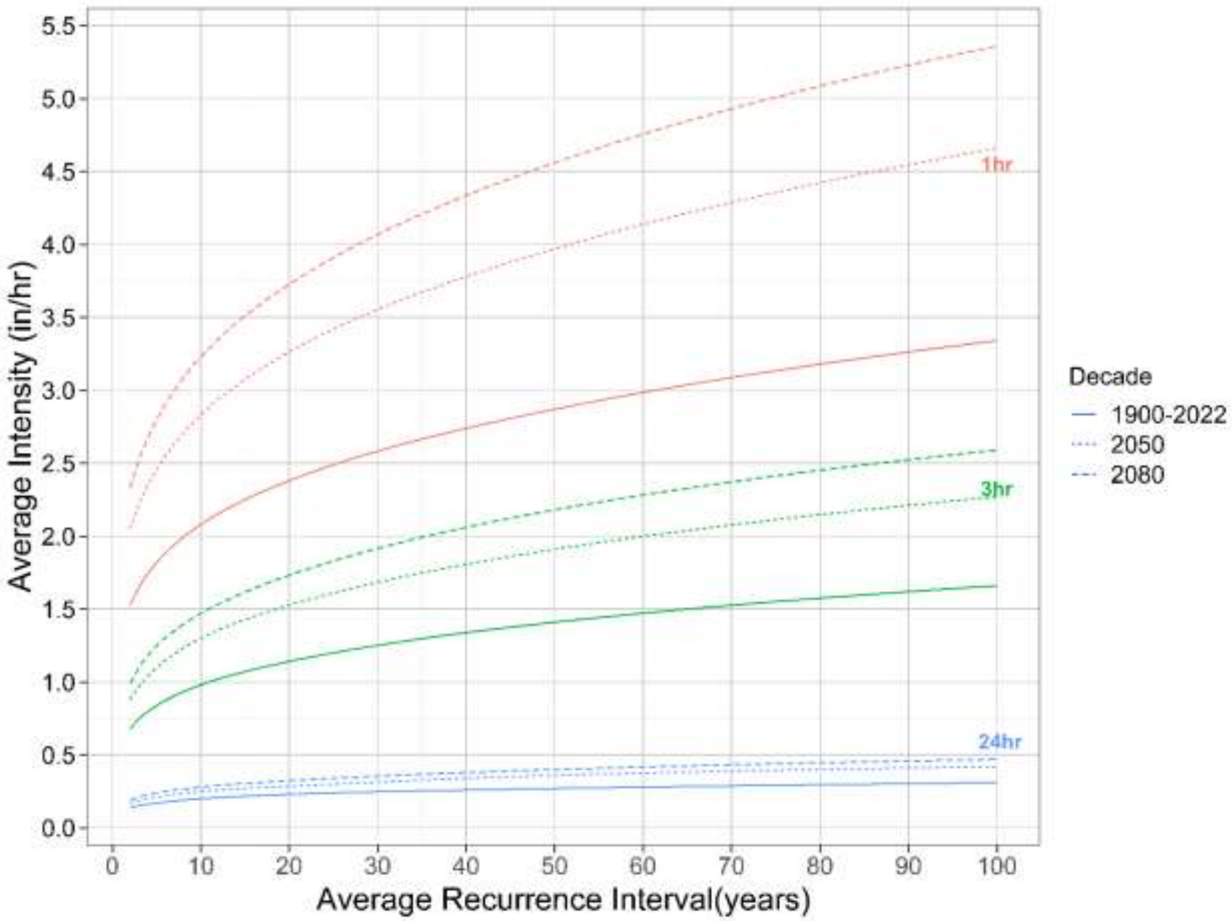


Figure 5-5. Intensity-Duration-Frequency (IDF) curves created using the CCAP High method for different duration storm events generated from observed PHL data (1900-2022 and climate adjusted future conditions for 2050 and 2080 periods under RCP8.5).

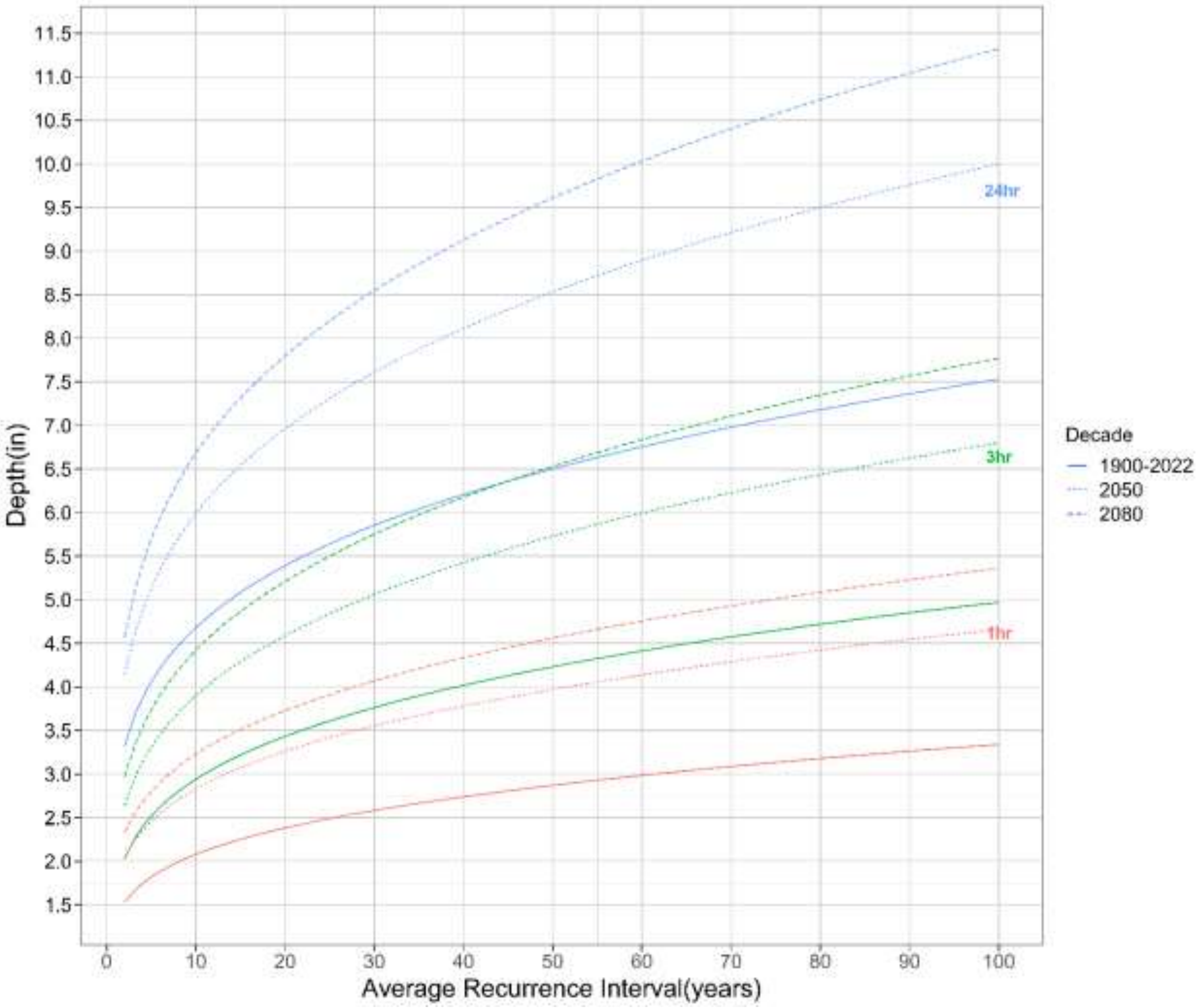


Figure 5-6. Depth-Duration-Frequency (DDF) curves created using the CCAP High method for different duration storm events generated from observed PHL data (1900-2022 and climate adjusted future conditions for 2050 and 2080 periods under RCP8.5).

As mentioned previously, detailed information on the methods to develop CCAP precipitation products can be found in online publications from the ASCE Journal of Water Resources Planning and Management and the Journal of Water and Climate Change.

c. Future Changes to Storm Return Intervals

In order to assess future changes to return intervals of events, CCAP developed a tool for 2-yr to 100-yr return intervals and durations ranging from 2-hr to 24-hr under the CCAP Low, Medium and High extreme precipitation methods on a decadal basis. The results of this tool can be very helpful in providing information on extreme storm events for flood risk management planning purposes. **Table 5-3** illustrates how the precipitation event associated with a 100-year return interval is already significantly lower (i.e. more frequent) than the baseline period (1900-2022) and will continue to decrease (become more frequent) in the coming decades. CCAP can provide results for other return interval storms upon request.

Table 5-3. The change in return interval of the 24-hr, 100-year storm compared to the baseline period (1900-2022) under the CCAP low, medium, and high extreme precipitation approaches (results represent conditions under a high emissions scenario).

Change in Return Interval for 24-hr 100-yr Event			
Average Recurrence Interval			
Decade	**Low**	**Medium**	**High**
2020	73	62	51
2030	69	57	44
2040	68	51	38
2050	65	41	27
2060	56	36	22
2070	53	29	16
2080	49	28	14
2090	48	23	7

5.5 Stochastic Rainfall Generator

In addition to these three precipitation products, CCAP also developed a simple yet powerful stochastic rainfall generator that utilizes the high-resolution time series to explore potential variability in current and future precipitation patterns. As GCM output and statistical downscaling methods do not effectively capture precipitation variability, this tool allows for an exploration of variability in future time series for planning and design purposes. For example, the stochastic rainfall generator can be used to inform scenario-based risk assessments to evaluate a range of plausible current and/or future conditions.

PWD staff who are interested in exploring future precipitation variability may reach out to CCAP. CCAP can provide guidance and assist PWD teams with running the rainfall generator and interpreting output.

5.6 Future Changes to Streamflow and Riverine Flood Return Intervals

The increase in intensity and frequency of precipitation, particularly during extreme storm events, is directly correlated with an increase in overland riverine flooding events. In September 2021, heavy rain from Hurricane Ida caused several flooding events as the Schuylkill River overtopped its banks and flood waters compromised PWD infrastructure. To evaluate how future flooding from the Schuylkill River will be impacted by climate change, CCAP developed a method that estimates future flood elevations and return intervals based on a combination of existing FEMA cross section information and runoff volumes calculated using GCM precipitation output. Results from the analysis show that Hurricane Ida represents a 30-year flood event and will be categorized as a 6-year flood by the end of century under a high-emissions scenario. Similar increases are expected to occur for even larger flooding (i.e. less probable) events in the coming years. **Table 5-4** below is summary of current and future streamflows and flood elevations through 2080 at the Belmont Raw Water Pumping Station for the 10-year, 50-year, and 100-year flood events. For projects impacted by riverine flooding, CCAP can provide site-specific flood elevations and streamflows for future conditions. Increasing flooding risks from large rainfall events should continue to be addressed both at PWD, by evaluating current and future risks to infrastructure, facilities and employee safety, and on a citywide scale through the Flood Risk Management Task Force.

Table 5-4. Streamflows and associated Schuylkill River elevations adjacent to the Belmont Raw Water Pumping Station (BRWPS) for RCP8.5.

Streamflows and Associated Schuylkill River Elevations at the Belmont Raw Water Pumping Station for RCP8.5						
	Flood Return Interval					
	10-year		50-year		100-year	
Decade (year)	Flow (cfs)	Elevation (ft) NAVD88	Flow (cfs)	Elevation (ft) NAVD88	Flow (cfs)	Elevation (ft) NAVD88
2020	91,969	23.1	136,711	28.9	159,082	32.3
2040	95,169	23.5	141,467	29.6	164,616	33.2
2060	97,731	23.8	145,275	30.1	169,047	33.9
2080	113,308	25.7	168,431	33.8	195,992	38.8

5.7 Applying Precipitation Projections to PWD Initiatives

As outlined in the introduction to this guidance, when applying climate change projections to any infrastructure project, there are several factors that must be considered, including:

- the anticipated useful service life of the project;
- the exposure to specific climate change impact(s), in this case increasing precipitation, that will affect the ability of the project to meet its objectives;
- the vulnerability of the project to climate change impact(s), considering both adaptive capacity[29] and sensitivity[30] to plausible climate change scenarios;
- the criticality of the project to PWD's core services and overall mission and objectives; and,
- the general view that PWD, in relying on critical infrastructure to provide core services, has a low risk tolerance[31] when it comes to climate risks.

Providing detailed information on planning and risk assessment approaches is not within the scope of this version of the guidance document. *Uncertainty Futures: Planning Under Deep Uncertainty*, and *d.* AMP Criteria of this document contain relevant information on adaptive planning approaches. Please note, however, that precipitation projections must be considered in the planning and design of new assets, or the renewal and replacement of existing assets, that are vulnerable to increasing rainfall. There is currently no prescriptive method on how PWD should apply precipitation projections, but a few tangible

---

[29] ***Adaptive capacity*** *is defined as the ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences (IPCC, 2018). An asset or system with a high adaptive capacity will be able to practically adapt over time and maintain current functions and/or levels of service as the climate changes.*

[30] ***Sensitivity,*** *sometimes called elasticity, is the degree to which an asset or system is affected by or responds to a climate impact/hazard (i.e. it is a way of characterizing how tolerant to or susceptible to harm the asset or system is to climate change).*

[31] ***Risk tolerance****, in the context of this guidance document, refers to the level of risk the Department is willing to accept when considering climate change impacts. For an asset or infrastructure system, risk tolerance may be related to understanding how level of service goals may be impacted.*

examples of how CCAP precipitation products can inform PWD initiatives are outlined below. Graphics are included for the precipitation products that are most relevant to each example.

a. Maintaining or Improving Levels of Service in the Collection System

Urban stormwater and wastewater utilities strive to maintain a certain level of service throughout the collection system. In order to maintain or improve current levels of service in future conditions, precipitation projections need to be considered. A standard practice for assessing collection system performance is to apply a design storm that is characterized by intensity, duration and frequency. CCAP's latest extreme precipitation analysis allows decadal future IDF curves to be generated for 5min-24hr durations and return intervals of 2yr-100yr.

For example, if a system is being designed to meet a 5-year level of service under current conditions, a 5-year future IDF curve could be used to determine the design intensity to ensure current levels of service are maintained. **Figure 5-7** below illustrates a 5-year IDF curve based on data at the PHL rain gauge from 1900-2022 for different durations and future time periods. Future IDF curves based on the CCAP High extreme precipitation method are also included for mid-century (2050) and end-of-century (2080) conditions under RCP8.5. In comparing these three curves, intensities are increasing for all durations into the future. For example, for a 5-year, 1-hour duration event, the intensity increases from 1.82 inches/hour to 2.46 inches/hour in mid-century and 2.80 inches/hour at the end of the century under a high emissions scenario.

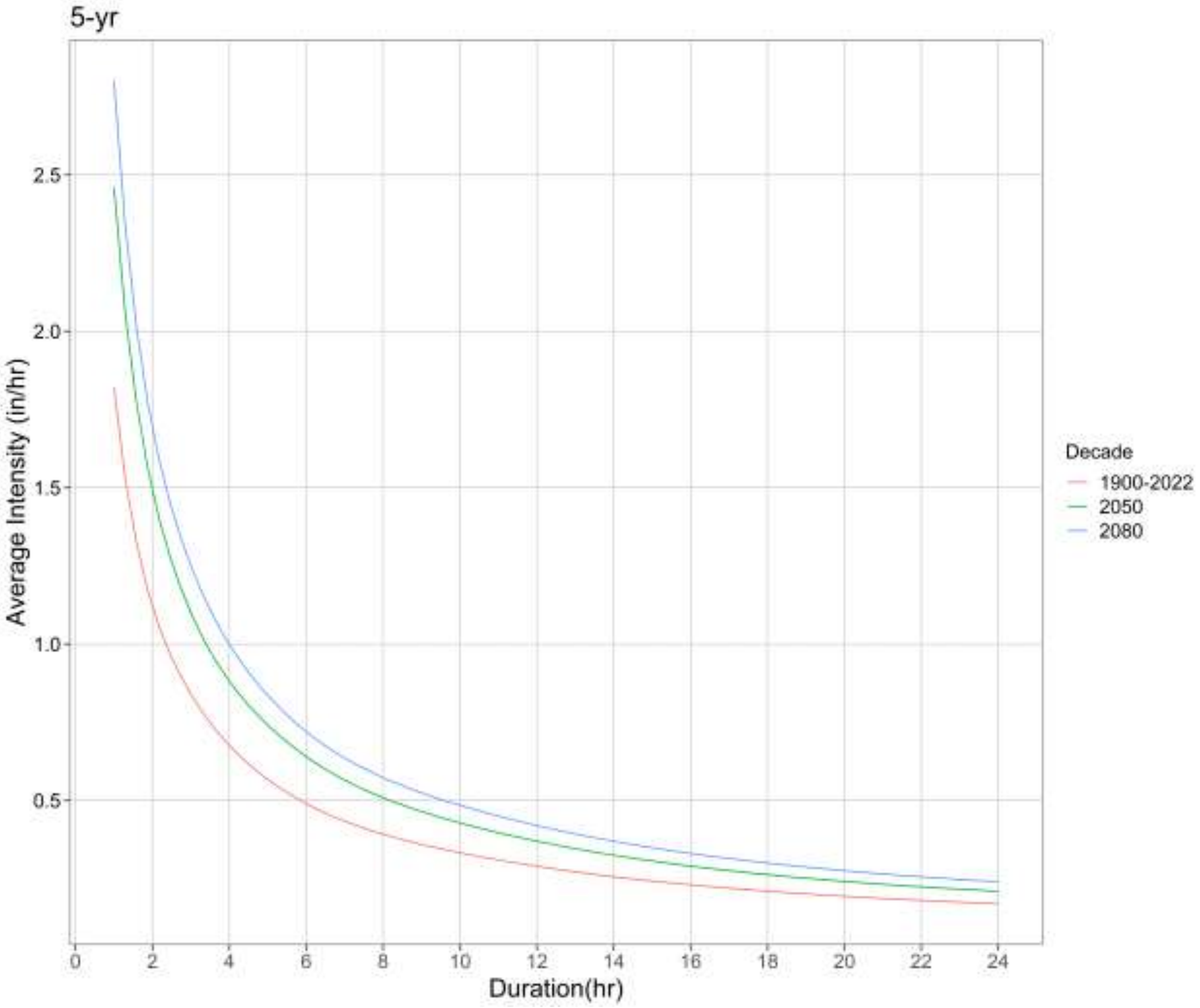
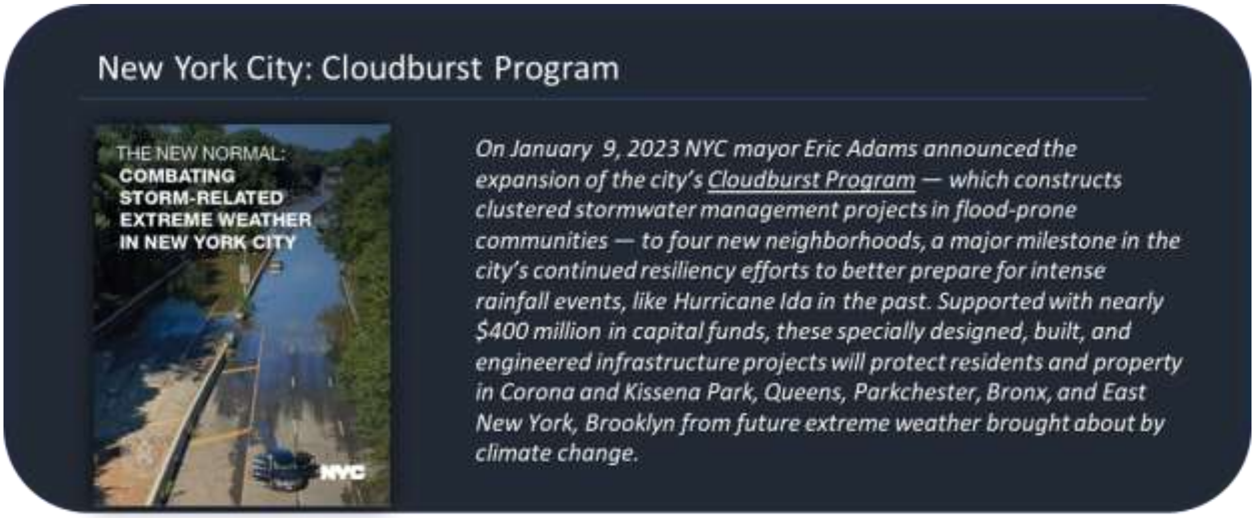


Figure 5-7. Intensity-Duration-Frequency (IDF) curves for a 5-yr recurrence interval based on observed PHL data (1900-2022) and future projections from the CCAP High extreme precipitation method for 2050 and 2080 periods under RCP8.5.

The implication of increasing precipitation intensities is that maintaining levels of service will require either increasing the capacity of the collection system or supplementing current capacities with source control solutions like Green Stormwater Infrastructure (GSI). New York City's recently updated Climate Resiliency Design Guidelines states the need to supplement its existing sewer system using above-ground approaches to meet level of service goals (NYC, 2019).



New York City: Cloudburst Program

THE NEW NORMAL:
COMBATING STORM-RELATED EXTREME WEATHER IN NEW YORK CITY
NYC

On January 9, 2023 NYC mayor Eric Adams announced the expansion of the city's Cloudburst Program — which constructs clustered stormwater management projects in flood-prone communities — to four new neighborhoods, a major milestone in the city's continued resiliency efforts to better prepare for intense rainfall events, like Hurricane Ida in the past. Supported with nearly $400 million in capital funds, these specially designed, built, and engineered infrastructure projects will protect residents and property in Corona and Kissena Park, Queens, Parkchester, Bronx, and East New York, Brooklyn from future extreme weather brought about by climate change.

Additional information on aligning stormwater management strategies with level of service goals using case study examples from NYC, Copenhagen and Phoenix can be found in the Cloudburst Management Examples AIR Sheet (see Appendix A-1). As with the Copenhagen case study, which was featured through a Water Utility Climate Alliance (WUCA) project, meeting level of service goals not only applies to standard sewer system design, but also flood risk management projects that, in some instances, seek to alleviate flooding impacts from more extreme storm events. The same CCAP precipitation products, including future time series and future IDF curves, can be applied to flood risk management analyses.

Water Utility Climate Alliance (WUCA)

The Water Utility Climate Alliance (WUCA) was formed in 2007 to provide leadership and collaboration on climate change issues affecting the country's water agencies. The organization comprises 12 of the nation's largest water and wastewater providers. WUCA members supply drinking water for more than 50 million people throughout the United States. PWD joined WUCA in 2018 and has been an active member of the alliance through participation in monthly calls, staff meetings and General Manager summits, as well as training workshops. PWD also participates in multiple WUCA committees, such as the CMIP6 Committee, the Equity Committee, and the Stormwater/Wastewater Committee.

While both flood risk management and sewer planning typically involve the use of IDF curves, there are additional products specific to PWD's current planning and design practices that are also available for use. To this end, Appendix C contains climate-adjusted precipitation products that, in addition to IDF curves, include future rainfall constants and tables outlining future frequency estimates for sub-hourly and hourly rain event durations for various return periods at the Philadelphia International Airport (PHL) rain gauge. A step-by-step example of how climate-adjusted precipitation products can be applied to PWD's current design of storm flood relief projects can be found in the Future Design Storms AIR Sheet (see Appendix A-1).

Regardless of the exact method used, scenarios representing current as well as future conditions should be used to evaluate the performance of project alternatives and/ or design interventions related to sewer planning and flood risk management applications.

b. Meeting Receiving Water Quality Requirements

Under the Clean Water Act (CWA), PWD is obligated to reduce pollutant loads to receiving waters from Water Pollution Control Plants (WPCPs) and the separate and combined sewer systems. While current water quality-based regulations do not explicitly require climate change to be considered, climate impacts, including increasing rainfall, have the potential to make it harder for PWD to meet existing regulatory requirements. It is therefore imperative that PWD consider climate change in the planning and design of projects and programs for which regulatory compliance is a primary driver.

National Pollutant Discharge Elimination System (NPDES) Permits

PWD has both a Municipal Wastewater NPDES permit that encompasses our Water Pollution Control Plant (WPCP) effluent and combined sewer overflow (CSO) requirements, as well as a NPDES Stormwater Permit for discharges from our Municipal Separate Storm Sewer System (MS4). Pollutant loads that enter receiving waters from the collection system are directly dependent on precipitation patterns. In combined sewers, the pollutant load is dependent on the intensity and duration of rainfall events, which may adversely affect the wastewater treatment process and impact the frequency and volume of combined sewer overflows (CSOs). In separate sewers, all stormwater is routed directly to receiving waters and any increase in precipitation will increase pollutant loads.

For separate sewers, precipitation increases might need to be considered to evaluate PWD's future ability to meet NPDES permit requirements. For combined sewers, continuous simulation using high resolution precipitation data and PWD's H&H models is needed to understand system performance, as is described in the Long-Term Control Plan Update (LTCPU) section below. *See **Appendix C** for these projections.*

Long Term Control Plan Update (LTCPU)

Per the Environmental Protection Agency's (EPA's) National CSO Program, PWD developed a Long-Term Control Plan Update that is the basis of the Department's Green City, Clean Waters (GCCW) program. GCCW is focused on the design and implementation of green stormwater infrastructure (GSI) that will manage stormwater at the source, before it enters the collection system, thereby reducing CSOs and enabling PWD to achieve NPDES permit compliance and meet CWA requirements. To evaluate the performance of our combined sewer system and GSI infrastructure, continuous simulation using H&H models is needed. Continuous simulations of urban drainage systems require hourly or sub-hourly precipitation time series. The method CCAP developed to generate high resolution future time series can provide the necessary inputs for H&H simulations that assess system performance, and potential changes to overflows, under future climatic conditions. In addition, the stochastic rainfall generator can be used to evaluate variability in these future time series.

Total Maximum Daily Load (TMDL)

The designation of Total Maximum Daily Loads (TMDLs) in receiving water bodies is another regulatory mechanism used to restore impaired water bodies and ensure CWA goals can be met. TMDLs define a maximum amount of a pollutant that can enter a specific receiving water body while still enabling water quality standards to be met. In certain instances, a TMDL will be assigned to a parameter that is influenced by precipitation patterns, as is the case with the Wissahickon siltation TMDL. For this TMDL, streambank erosion, which is directly affected by extreme precipitation events, is a major source of suspended solids. The PWD ecological restoration team uses stream restoration measures to reduce streambank and streambed erosion. To ensure the long-term resilience of these restoration efforts, increases in precipitation must be considered.

c. Green Stormwater Infrastructure (GSI) Design

In Philadelphia Green Stormwater Infrastructure (GSI) design is highly constricted by space constraints due to the dense urban environment and underground utilities. Currently design guidelines target the capture of a 1.5" storm as the most cost-effective measure to achieve water quality compliance goals. These guidelines, however, make it challenging to apply CCAP's latest extreme precipitation results and recommendations since the most significant increases in precipitation are projected to occur on the larger (i.e. less frequent) storms while projected increases of smaller storms like the 1.5" storm, will be less significant. CCAP's future IDF curves could also be used to inform potential cloudburst management projects, should PWD choose to pursue such strategies in the future.

d. Flood Emergency Preparedness at PWD

Philadelphia experiences different types of flooding due to precipitation including riverine and urban (or infrastructure-based) flooding. Urban flooding occurs when the sewer system capacity is exceeded and is directly related to the level of service guidance provided above. This type of flooding typically results from short-duration, intense events, otherwise known as cloudbursts.

Riverine flooding is a direct consequence of increasing flow volumes typically from longer-duration or high-volume rainfall events that impact large portions of a watershed. While it is understood that GCMs cannot simulate extreme rainfall events accurately, recent CCAP analyses indicate that large rainfall events may increase in volume by almost 70% at the end of the century under a high emissions scenario.

5.8 Areas of Future Consideration

There are several areas of research and analysis related to precipitation data, projections and impacts that CCAP may pursue in the future. Any new information generated through these efforts has the potential to inform the precipitation products presented in this guidance section. The research areas, as outlined below, have to do with extreme storm (or precipitation) events, the spatial variability of rainfall in Philadelphia, impacts from compound flooding and regulatory compliance risks.

- **Spatial Variability of Rainfall** – Rainfall in Philadelphia is not only highly variable over time, but also over space, or geographic extent. Initial analyses suggest that the PHL rain gauge is not seeing as high an increase in precipitation as PWD's overall 37-gauge network (Nemtuda et al., 2019). This network of gauges could be further analyzed to better understand recent rainfall trends. Additionally, CCAP's latest extreme precipitation methods could be applied to gauges in the PWD network to draw comparisons to results from the PHL gauge.
- **GCM Update** - As of this version of the guidance, the GCM ensemble used by CCAP is comprised of 9 models from the IPCC's Coupled Model Intercomparison Project 5 (CMIP5). In a continued effort to ensure the best available guidance is included in this document, CCAP will be exploring updates to the projections and analyses in this document using output from the sixth phase of the Coupled Model Intercomparison Project (CMIP6). Results of this effort will be shared in a future version of this guidance.
- **Compound Flooding –** To date, CCAP's risk assessments and analyses have focused largely on individual climate impacts (e.g. precipitation changes, temperature changes, sea level rise), but in reality, it is the compound effect of these climate impacts that can cause the most damage. CCAP is interested in studying and assessing compound climate change impacts, specifically flooding impacts from precipitation increases and sea level rise/storm surge. Compound flooding impacts to surface flooding and to drainage systems could be studied using riverine flood models in combination with coastal flood models and H&H models that incorporate higher sea levels and changes to precipitation intensity, duration and frequency. CCAP is involved in this area of

research, including through a recently completed NOAA-funded compound flood modeling project (in partnership with Stevens Institute (PI) and Drexel University (co-PI) in the Eastwick neighborhood of Philadelphia.

- **Regulatory Compliance Risks** – GCM projections have the potential to inform planning analyses related to compliance risks, including potential changes to flood frequency return periods, pollutant loads to receiving waters, expected flows at Water Pollution Control Plants (WPCPs) and the frequency of combined sewer overflows (CSOs).

5.9 References

Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections. (n.d.). Gdo-Dcp.ucllnl.org. Retrieved December 9, 2023, from https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/ *Accessed July 30, 2020.*

Maimone, M., Malter, S., Rockwell, J., & Raj, V. (2019). Transforming Global Climate Model Precipitation Output for Use in Urban Stormwater Applications. *Journal of Water Resources Planning and Management, 145*(6). https://doi.org/10.1061/(asce)wr.1943-5452.0001071

Maimone, M., Malter, S., Tsega Anbessie, & Rockwell, J. (2023). Three methods of characterizing climate-induced changes in extreme rainfall: a comparison study. *Journal of Water and Climate Change, 14*(11), 4245–4260. https://doi.org/10.2166/wcc.2023.420

Mita, K., Orton, P. M., Montalto, F., Saleh, F., & Rockwell, J. (2023). Sea Level Rise-Induced Transition from Rare Fluvial Extremes to Chronic and Compound Floods. *Water, 15*(14), 2671–2671. https://doi.org/10.3390/w15142671

Nemtuda, M., Anbessie, T., Lennon, E. (2019). 2018 Rainfall Analysis.

New York City (NYC) Mayor's Office of Recovery and Resiliency. (2019). Climate Resiliency Design Guidelines, Version 4.1.

Philadelphia Water Department Climate Change Adaptation Program (PWD CCAP). (2018). Characterizing and Addressing Uncertainty in Climate Change Adaptation Planning at the Philadelphia Water Department.

Program, U. S. G. C. R. (2023). *Fifth National Climate Assessment*. Nca2023.Globalchange.gov. https://nca2023.globalchange.gov/chapter/2#key-message-2

Reidmiller, D. R., Avery, C. W., Easterling, D. R., Kunkel, K. E., Lewis, K. L. M., Maycock, T. K., & Stewart, B. C. (Eds.). (2018). Impacts, Risks, and Adaptation in the United States: The Fourth National Climate Assessment, Volume II. https://doi.org/10.7930/nca4.2018

Stock, C. (n.d.). Climate Model Downscaling. Www.gfdl.noaa.gov. https://www.gfdl.noaa.gov/climate-model-downscaling/

Trenberth, K. E., Dai, A., Rasmussen, R. M., & Parsons, D. B. (2003). The Changing Character of Precipitation. *Bulletin of the American Meteorological Society*, *84*(9), 1205–1218. https://doi.org/10.1175/bams-84-9-1205

Useful Climate Information for Philadelphia: Past and Future. (2014). https://www.phila.gov/media/20160505145605/Useful-Climate-Science-for-Philadelphia.pdf

Wuebbles, D. J., Fahey, D. W., Hibbard, K. A., Dokken, D. J., Stewart, B. C., & Maycock, T. K. (Eds.). (2017). Climate Science Special Report: Fourth National Climate Assessment, Volume I. https://doi.org/10.7930/j0j964j6

Getting Heated

Air Temperature Planning and Design Guidance

Photo: Michael Burkholder

Roadmap

B	Background information and justification of information presented	**P**	Relevant to PWD planning processes	**D**	Relevant to an asset or system design

This section provides **background information** on local and global trends related to air temperature changes due to climate change and its relevance to Philadelphia and PWD, specifically. The section outlines areas where **increasing temperatures could impact PWD's essential services** and includes results of an analysis to assess **potential impacts to personnel safety**. **B** **P**

This section provides the **projections of temperature increases** for use in PWD's planning, design, and operations of drinking water and wastewater systems. This includes average and extreme temperature values based on recent trends and projections. **P** **D**

This section outlines the **products and reports** created by CCAP to assess the impacts of increasing temperatures on PWD's assets. The section also provides **recommendations on how temperature projections can be applied** to PWD initiatives going forward. **P**

6.1 Key Terms

Key Term	Acronym	Definition
Average Annual Temperature	--	Average of the daily minimum and daily maximum temperature for each year over a current or future time period.
Average Monthly Temperature	--	Average of the daily minimum and daily maximum temperature for each month over a current or future time period.
Code Red	--	The City of Philadelphia declares a Code Red when the heat index reaches 95°F for at least three consecutive days.
Current Period	--	Jan. 1, 1995 through Dec. 31, 2014
Mid-Century Period	--	Jan. 1, 2050 through Dec. 31, 2069
End-Of-Century Period	--	Jan. 1, 2080 through Dec. 31, 2099
Extreme Heat	--	The World Meteorological Organization defines a heat wave as five or more consecutive days of prolonged heat in which the daily maximum temperature is higher than the average maximum temperature by 5°C (9°F) or more. Other measures generally are related to temperatures in excess of 95°F.
Heat Health Emergency	--	The City of Philadelphia declares a Heat Health Emergency under the following conditions: • Activated May through June when the heat index reaches 101°F or higher for two consecutive days, or 98°F for three or more consecutive days; • Activated July through September when the heat index reaches 106°F for two consecutive days or 103°F for three or more consecutive days. During a Heat Health Emergency, the City halts utility shutoffs for residential non-payment, activates HeatLine and mobile teams, and activates cooling centers.
Heat Index	--	The heat index, also known as the apparent temperature, is an index calculated for shady, light wind environmental conditions using air temperature and relative humidity as inputs. It represents what the temperature feels like to the human body. (National Weather Service).
Heat Wave	--	Five or more consecutive days of prolonged heat in which the daily maximum temperature is higher than the seasonal or monthly average maximum temperature by 5°C (9°F) or more. (World Meteorological Organization).

The Importance and Impacts of Air Temperature to PWD

Long term global and local temperature data are the most consistent and easily tracked indicators of climate change. Temperature projections are also the primary and most accurate of the Global Climate Model (GCM) outputs. Global and US average temperatures have been increasing for over a century, with much of the increase occurring over the past 40 years. According to the NOAA 2022 Global Climate Summary, the combined land and ocean temperature has increased at an average rate of 0.08°C (0.14°F) per decade since 1880; however, the average rate of increase since 1981 (0.18°C / 0.32°F) is more than twice as great (NOAA, 2022). In recent years, there has also been a significant increase in record breaking temperatures related to climate change. Notably, according to combined NOAA and NASA data, the last ten years (2014-2023) ranked as the ten warmest years on record since 1881, with 2023 ranking as the warmest year on record with a temperature anomaly of +1.4°C (+2.52°F) above a baseline period of 1881 to 1910 (Climate Central, 2024). As shown in **Figure 6-1**, recent increasing observed temperature trends for the Philadelphia area align with GCM output for the time period between 1955 and 2022.

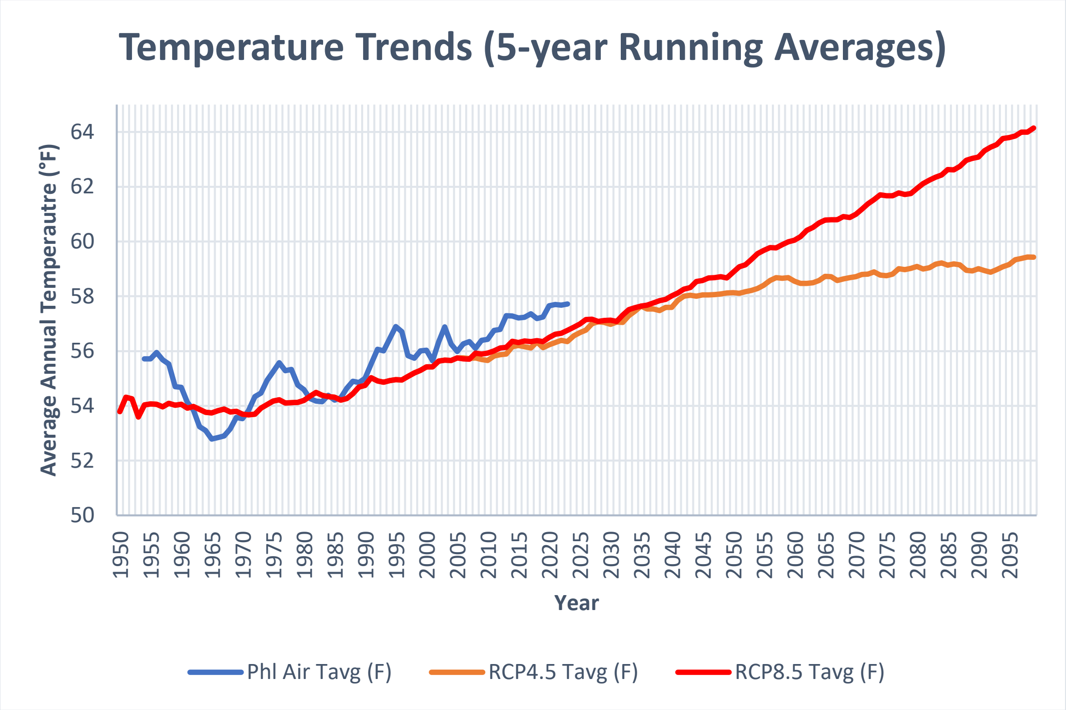


Figure 6-1. Comparison of 5-year running average temperature trends for the Philadelphia area. The blue line represents the temperature trend based on observed data recorded at the Philadelphia International Airport for years 1955 to 2022, whereas the orange and red lines represent the temperature trends based on downscaled CMIP5 GCM output for Philadelphia using the RCP4.5 and RCP8.5 scenarios, respectively, for years 1950 to 2095.

The report *Growing Stronger: Towards a Climate Ready Philadelphia* (ICF International, 2015) presented a trend analysis of annual average temperatures in Philadelphia suggesting a roughly 2.5°F increase over the period 1948 through 2014. The northeastern US has shown particularly high increases relative to global temperature changes and Philadelphia is no exception to this trend. The Northeast region has been observed to have the fastest winter warming across the U.S. since 1970, along with the Great Lakes region (Climate Central, 2023). On average, winter has warmed by 4.6°F in the Northeast region from 1970 to

2022, with fewer annual nights below freezing, shorter cold spells, and a rise in warmer-than-normal winter days (Climate Central, 2023).

For the Philadelphia Water Department (PWD), a summary of observed temperature trends and Global Climate Model (GCM) projections is useful as the basis for assessing and preparing for any potential impacts relevant to PWD's water, wastewater and stormwater system planning, design, and operations.

The goal of the next section is to provide projections of temperature increases for use in PWD's planning, design, and operation of drinking water, wastewater and stormwater systems. Temperature projections should also be considered in PWDs Source Water Protection Program, watershed analyses and ecological restoration efforts. To conclude this section, some of the ways in which increasing temperature could impact PWD core services and personnel safety are considered.

a. Drinking Water

Temperature can affect every aspect of the treatment and delivery of potable water. As air temperature increases, so will the temperature of PWD's sources of drinking water – the Delaware and Schuylkill Rivers. The Safe Drinking Water Foundation[32], as well as other references noted below, provide the following information on drinking water treatment and temperature.

- **Enhanced Chemical and Physical Processes** - When chemical treatment is involved, generally the rates of chemical reactions increase with increasing water temperature because the temperature dependence of most chemical reactions stems from the activation energy associated with them. In addition, the relative concentrations of reactants and products in chemical equilibria can also change with temperature.
    - The efficiency of one of the key water treatment steps, coagulation, is greatly dependent on temperature. As temperature increases, the viscosity of water decreases and the rate of sedimentation increases, making the system more efficient.
    - Working with Escherichia coli (E. coli), Butterfield et al. (1943) observed a five-fold increase in the bactericidal effectiveness of chlorine between 2°C to 5°C (36°F and 41°F) and 20°C to 25°C (68°F and 77°F). The National Research Council (US) Safe Drinking Water Committee (1980) references the Butterfield et al. (1943) study. It remains one of the only studies on this subject, but the actual study text is no longer available. According to the guidance published by the Safe Drinking Water Committee (1980), Butterfield studied percentages of inactivation as functions of time for *E. coli, Enterobacter aerogenes, Pseudomonas aeruginosa, Salmonella typhi,* and *Shigella dysenteriae.* They used different levels of free chlorine at pH values ranging from 7.0 to 10.7 and two temperature ranges: 2°C to 5°C and 20°C to 25°C. Generally, they found that the primary factors governing the bactericidal efficacy of free available chlorine and combined available chlorine were:
        - The time of contact between the bacteria and the bactericidal agent, i.e., the longer the contact time, the more effective the chlorine disinfection process;

---

[32] *SDWF Water Temperature Fact Sheet:* *https://www.safewater.org/fact-sheets-1/2018/8/15/water-temperature-fact-sheet*

- The temperature of the water in which contact is made, i.e., the lower the water temperature, the less effective the chlorine disinfecting activity; and
- The pH of the water in which contact is made, i.e., the higher the pH, the less effective the chlorine disinfection process.

Zhang et al. (2021) studied the inactivation effect of free chlorine, monochloramine, and chlorine dioxide on ammonia oxidizing bacterium (AOB). This was done under different temperatures (8°C, 26°C, and 35°C) and pH (6.0, 7.0, and 8.7) conditions. Genera *Nitrosomonas* and *Nitrosospira* represented the dominant AOB. They concluded that the inactivation effect of *Nitrosomonas europaea* (a type of AOB) by the three disinfectants increases with increasing temperature.

Finally, the Centre for Affordable Water and Sanitation Technology has on their website (CAWST.org) a temperature table showing that the required contact time for inactivation of pathogens increases from half an hour for temperatures of 25°C or higher, to 1.5 hours for a temperature range of 5°C – 15°C.

Although chlorine disinfection efficacy is aided by increased temperature, it breaks down more quickly in the distribution system under warmer conditions. Thus, during the summer months, PWD often needs to use more chlorine to maintain the required chlorine residual.

- **Disinfection By-Product Formation** - It has been found that water temperature is perhaps the single most important factor influencing seasonal variation in disinfection byproduct (DBP), specifically trihalomethane (THM) concentrations in finished water. Stevens et al. (1976) demonstrated that the rate of formation of chloroform, one of the four types of THMs, in raw water treated with a chlorine dose of 10 mg/L increased threefold between 3°C and 25°C (37°F and 77°F).

- **Conveyance Pipe Corrosion** - Mullen et al. (1974) showed the effect of temperature on the corrosion of cast iron in water produced and distributed by the Middlesex Water Company of New Jersey. This study clearly demonstrated that the corrosion of water conveyance pipes increased as a function of temperature, with a good correlation between the average monthly raw water temperature and the measured corrosion rate. In the absence of corrosion inhibitors, the corrosion rate increased four-fold over the temperature range of 3°C to 26°C. The use of sodium hydroxide to adjust the pH reduced this increase to a factor of two over the same temperature range.

- **Lead Service Line Leaching** – Many water systems exhibit higher lead levels in tap water in the summer than in the winter. Although temperature is a key factor in explaining seasonality in lead release, it certainly may not be the only factor or the most significant factor. Additionally, in some cases, higher temperatures do not invariably increase lead in water. In one study, even within the same potable water system served by a single, centralized treatment plant, soluble lead release from pure-lead service lines showed a strong correlation with temperature in only 4 of 8 homes studied, whereas the other homes had no correlation (Masters et al., 2016).

- **Taste & Odor** - The aesthetic objective for water temperature is 59°F (15°C) because most consumers complain about tap water taste and odor issues at about 66°F (19°C) or higher. The intensity of taste is greatest for water at room temperature and is significantly reduced at lower temperatures. It is also possible that micro fungi can grow inside the internal plumbing systems of buildings, leading to complaints of musty, earthy, or moldy tastes and odors if the temperature rises above approximately 61°F (16°C) (Safe Drinking Water Foundation).

b. Source Water and Regulatory Compliance Planning

PWD performs planning related to source water quality and receiving water quality. These planning assessments should include temperature changes related to climate change in future planning applications. For example:

- Climate change impacts affect certain planning and analysis activities of PWD’s Source Water Protection Program. (More information on PWD’s Source Water Assessments and Protection plans can be found here.) One potential planning application is the tracking of changing raw water quality at water supply intakes. Both algae growth and taste and odor issues are related to warmer water temperatures in the Delaware and Schuylkill Rivers.

- Temperature increases combined with drought tend to mean that people use more water, and evaporation in the source watershed increases, reducing water availability downstream. Generally, PWD has adequate supplies even during droughts, but this issue should be explored with regard to the Delaware River and Schuylkill River intakes.

- Another potential application is to assess the impact of increased river and stream temperature on receiving water quality regulatory compliance (NPDES Permits) primarily related to temperature impacts on dissolved oxygen levels.

c. Wastewater Treatment

Temperature is a critical parameter to monitor for biological wastewater treatment systems. Seasonal variations in temperature can influence the makeup of microbial communities and shifts in temperature due to climate change may require changes to wastewater treatment operation. Each microbial species is characterized by a minimum, optimum, and maximum temperature that will support growth. Mesophiles are microorganisms which comprise most of the species commonly found in wastewater treatment processes. They grow within the range of 10 to 45°C (50 to 115°F), with an optimum of approximately 30 to 35°C (85 to 95°F) (Water Environment Federation, 1994). At the upper end of this spectrum and beyond, bacteria slow down and eventually cease to function at all.

Shahzad et al. (2015) discuss solids retention time (SRT), which is a critical component of the activated sludge process, and its variation with the ambient temperature for a full-scale municipal activated sludge plant. SRT (in days) is the average time the activated-sludge solids are in the system and is an important design and operating parameter for the activated-sludge process. The plant's observed effluent quality, and thereby its overall removal efficiency, was evaluated in terms of measuring standard biochemical parameters. The results indicate that significant improvement in effluent quality can be obtained by varying SRT depending on temperature variation.

d. Maintaining Safe Working Conditions

Higher temperatures or longer, more frequent periods of heat may result in greater occupational heat stress, potentially leading to more cases of heat-related fatigue and illnesses[33] (e.g., heat syncope, heat exhaustion, or heat stroke). Exposure to increased temperature can also result in reduced cognitive function and increased risk of injury or lapses in safety. With a warming climate and more frequent extreme weather events predicted, heat exposure and heat stress are becoming a prominent employee safety issue, yet there are few regulatory standards currently in place to protect workers from climate change-related hazards (Kiefer et al., 2016). However, the U.S. Occupational Safety and Health Administration (OSHA) acknowledges the safety threat posed by a warming climate, stating heat as the leading cause of death among all weather-related phenomena. OSHA has therefore initiated the process to propose the creation of a regulatory standard for protection of workers from extreme heat, and has published an Advance Notice of Proposed Rulemaking (ANPRM) for Heat Injury and Illness Prevention in Outdoor and Indoor Work Settings.

While there is currently no standard for working in hot environments, OSHA maintains that employers have a duty to protect workers from recognized serious hazards in the workplace, including heat-related hazards.[34] Protections may include (1) providing adequate water, rest, and shade, (2) allowing new employees time to build tolerance for working in the heat, and (3) training employees in heat illness prevention. The National Institute for Occupational Safety and Health (NIOSH) has published a sample work/rest schedule that provides guidance on rest breaks required for temperatures ranging from 90°F to 112°F, with recommended adjustments based on humidity and environmental conditions as well as work intensity levels.[35] For example, if the temperature reading is 95°F on a partly cloudy day *(Partly cloudy/overcast: Add 7°F)* with a humidity level of 65% *(60% humidity or more: Add 9°F)*, the total adjusted temperature sums to 111°F, for which the NIOSH work/rest schedule advises extreme caution for work of all intensity levels. It is worth noting that humidity levels commonly exceed 60% in the Philadelphia area and are therefore particularly important to consider for the health and safety of outdoor workers in our region.

The temperature adjustment presented in the NIOSH Work/Rest Schedule is similar to calculating the heat index (e.g., the "apparent temperature"), which entails combining the effects of humidity and temperature to measure the temperature perceived by the human body. The NOAA National Weather Service (NWS) Heat Index Chart[36], **Figure 6-2**, presents a method for easily calculating the heat index provided the temperature and relative humidity. For example, if the temperature is 90°F and the relative humidity is 50%, the heat index will be 95°F.

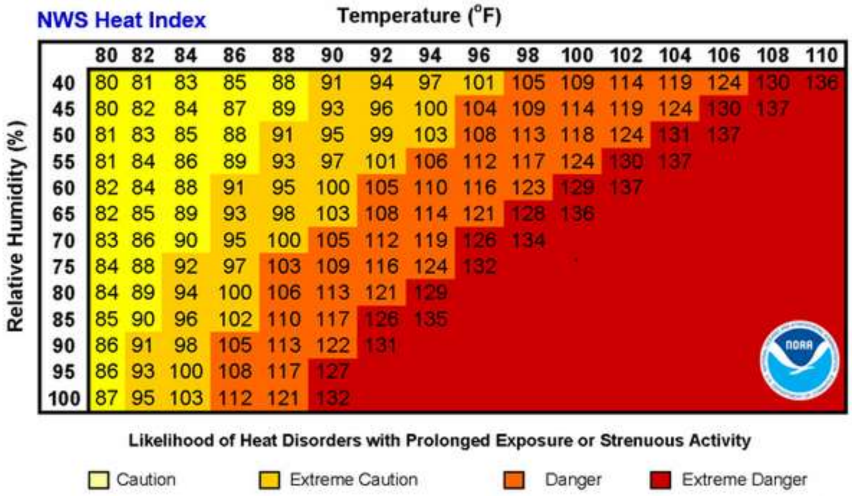
---

[33] *NSC 5-Minute Safety Talk – Heat-related illness*

[34] *Hazard Alert: Extreme Heat Can Be Deadly to Workers*

[35] *NIOSH Work/Rest Schedule: Heat Stress: Work/Rest Schedules (cdc.gov)*

[36] *NOAA Heat Index: Heat Forecast Tools (weather.gov)*



NWS Heat Index

Temperature (°F)

Relative Humidity (%)	80	82	84	86	88	90	92	94	96	98	100	102	104	106	108	110
40	80	81	83	85	88	91	94	97	101	105	109	114	119	124	130	136
45	80	82	84	87	89	93	96	100	104	109	114	119	124	130	137	
50	81	83	85	88	91	95	99	103	108	113	118	124	131	137		
55	81	84	86	89	93	97	101	106	112	117	124	130	137			
60	82	84	88	91	95	100	105	110	116	123	129	137				
65	82	85	89	93	98	103	108	114	121	128	136					
70	83	86	90	95	100	105	112	119	126	134						
75	84	88	92	97	103	109	116	124	132							
80	84	89	94	100	106	113	121	129								
85	85	90	96	102	110	117	126	135								
90	86	91	98	105	113	122	131									
95	86	93	100	108	117	127										
100	87	95	103	112	121	132										

Likelihood of Heat Disorders with Prolonged Exposure or Strenuous Activity

☐ Caution ☐ Extreme Caution ☐ Danger ☐ Extreme Danger

Figure 6-2. NOAA National Weather Service (NWS) Heat Index Chart based on temperature and relative humidity for shady, light wind environmental conditions.

The heat index values shown in **Figure 6-2** were created for shady, light wind conditions. As shown in the NIOSH Work/Rest Schedule example, the heat index may increase substantially in partly cloudy *(+7°F)* or full sun *(+13°F)* conditions. Use of the heat index is straightforward and a great first step, but its drawback lies in its simplicity as it only accounts for temperature and humidity. Both NIOSH and OSHA now recommend the use of wet bulb globe temperature (WBGT) to monitor environmental heat in the workplace. WBGT accounts not only for air temperature and humidity, but also for radiant heat and air movement, which are specified by OSHA as primary factors that contribute to heat stress in workers. Additional information on the use of WBGT can be found at OSHA.gov.

OSHA and NIOSH provide guidance on using a heat index to determine when extra precautions are needed at a worksite to protect workers from heat-related illness[37]. Their guidance is shown **in Table 6-1**. The heat indices are divided into four intervals based on risk levels ranging from "Lower (Caution)" to "Very High to Extreme." Note these risk levels vary from those presented in the NWS Heat Index Chart, **Figure 6-2**, as the OSHA recommendations in **Table 6-1** have been modified for use at worksites.

Table 6-1. OSHA heat index-associated risk levels and protective measures for worksites.

Heat Index	Risk Level	Protective Measure
Less than 91°F	Lower (Caution)	Basic heat safety and planning
91° to 103°F	Moderate	Implement precautions and heighten awareness
103° to 115°F	High	Additional precautions to protect workers
Greater than 115°F	Very High to Extreme	Triggers even more aggressive protective measures

---

[37] *NIOSH (2016) Criteria for a Recommended Standard: Occupational Exposure to Heat and Hot Environments, Appendix C: Table C-1*

As climate change progresses, resulting in increases to both temperature and relative humidity, heat indices associated with high risk levels to outside workers are projected to occur more frequently in the future. CCAP has performed an analysis to estimate the increased risk to outdoor workers by mid- and end-of-century based on OSHA's heat index-associated risk levels (**Table 6-1**). This analysis utilizes temperature projections based on statistically downscaled CMIP5 global climate model (GCM) output (Localized Constructed Analogs (LOCA)) for Philadelphia. The emissions scenarios used for this analysis were two representative concentration pathways (RCPs) including RCP4.5 and RCP8.5, representing an intermediate emissions scenario and a high emissions scenario, respectively. To calculate observed and projected heat indices, median relative humidity values for the Philadelphia area for each emissions scenario and time period were calculated using Multivariate Adaptive Constructed Analogs (MACA) CMIP5 relative humidity projections averaged across 18 GCMs. These were validated by a comparison with measured relative humidity values from the Philadelphia Airport gage for the period 2010 to 2014. The heat stress analysis was performed relative to a 1995 to 2014 baseline using observed temperatures from the Philadelphia Airport.

The results based on the RCP4.5 emissions scenario are included in

Table 6-2, which shows the projected days per year that fall within each of OSHA's heat index-associated risk levels for three time periods: current (1995-2014), mid-century (2050-2069), and end-of-century (2080-2099). The number of moderate risk level days (Heat Index of 91°F to 103°F) per year is estimated to increase from 31 days to 50 days by mid-century and 52 days by end-of-century. The number of high risk level days (Heat Index of 103°F to 115°F) per year is estimated to increase from 3 days to 11 days by mid-century and 13 days by end-of-century. The results based on the RCP8.5 emissions scenario are included in **Table 6-3** and show larger increases in the frequency of moderate to very high to extreme risk level days than those under the RCP4.5 emissions scenario. Notably, under the RCP8.5 emissions scenario the number of high risk level days (Heat Index of 103°F to 115°F) per year is estimated to increase from 3 days to 19 days by mid-century and 40 days by end-of-century. The number of very high to extreme risk level days (Heat Index Greater than 115°F) per year is estimated to increase from 0 days to 1 day by mid-century and 8 days by end-of-century.

Table 6-2. Projected days per year that fall within each of OSHA's heat index-associated risk levels for three time periods. The observed days per year are based on daily maximum temperatures measured at the Philadelphia International Airport from 1995 to 2014. Projections are based on the ***RCP4.5*** *emissions scenario for the CMIP5 9 GCM Ensemble.*

Heat Index	**Observed PHL Airport** 1995-2014	**GCM Current** 1995-2014	**GCM Mid-Century** 2050-2069	**GCM End-of-Century** 2080-2099	**Risk Level (OSHA)**
Days per year between 80°F to 90°F	77	78	70	69	Lower (Caution)
Days per year between 91°F to 103°F	31	31	50	52	Moderate
Days per year between 103°F to 115°F	3	3	11	13	High
Days per year greater than 115°F	0	0	0	0	Very High to Extreme

Table 6-3. Estimated days per year that fall within each of OSHA's heat index-associated risk levels for three time periods. The observed days per year are based on daily maximum temperatures measured at the Philadelphia International Airport from 1995 to 2014. Projections are based on the ***RCP8.5*** *emissions scenario for the CMIP5 9 GCM Ensemble.*

Heat Index	**Observed PHL Airport** 1995-2014	**GCM Current** 1995-2014	**GCM Mid-Century** 2050-2069	**GCM End-of-Century** 2080-2099	**Risk Level (OSHA)**
Days per year between 80°F to 90°F	77	78	58	53	Lower (Caution)
Days per year between 91°F to 103°F	31	32	57	53	Moderate
Days per year between 103°F to 115°F	3	3	19	40	High
Days per year greater than 115°F	0	0	1	8	Very High to Extreme

The City of Philadelphia's Department of Public Health and Office of Emergency Management (OEM) have defined three levels of excessive heat warnings that will be declared when temperatures meet or exceed defined temperature values as shown in **Table 6-4**. The three excessive heat warnings currently in use by the City are (1) Heat Caution, (2) Heat Health Emergency, and (3) Code Red. For example, a Code Red event is declared during very hot weather events that entail three or more consecutive days with a heat index greater than or equal to 95°F. Each excessive heat warning was developed for a specific purpose, as stated in **Table 6-4**. While the primary intention was to protect residents of Philadelphia during extreme heat events, particularly vulnerable populations, these notifications may also serve as warnings to increase protections for PWD's outdoor workers.

Table 6-4. Excessive heat warnings issued by The City of Philadelphia, as defined by Philadelphia's Department of Public Health and Office of Emergency Management. Listed are definitions for each heat warning and the purpose for which they were developed.

	Heat Caution	**Heat Health Emergency**	**Code Red**
Definition	Activated Under the Following Scenarios: 1. In May through June when heat index (HI) is at least 95°F for 2 consecutive days <u>OR</u> 93°F for 3 or more consecutive days. 2. In July through September when HI is at least 98°F to 105°F for 2 consecutive days <u>OR</u> 95°F to 102°F for 3 or more consecutive days.	Activated Under the Following Scenarios: 1. In May through June when heat index (HI) is at least 101°F for 2 consecutive days <u>OR</u> 98°F for 3 or more consecutive days. 2. In July to September when HI is at least 106°F for 2 consecutive days OR 103°F for 3 or more consecutive days.	Declared when the heat index (HI) reaches 95°F for 3 or more consecutive days.
Purpose	Triggers homeless services partners to determine whether a Code Red will be issued and initiates public messaging to vulnerable populations.	Halts utility shutoffs for residential non-payment and activates cooling centers, the City's HeatLine, and mobile teams.	Code Reds are explicitly for the protection of homeless individuals.

CCAP performed an analysis to predict how the occurrence of Code Red events and Heat Health Emergencies may change as the climate in Philadelphia warms. As with the analysis performed using OSHA's heat index-associated risk levels (

Table 6-2 and **Table 6-3**), this analysis utilized temperature and relative humidity (RH) projections for Philadelphia based on statistically downscaled LOCA CMIP5 temperature projections and MACA CMIP5 median relative humidity projections.

The results of the Code Red analysis are shown in

Table 6-5, which includes the observed (PHL INTL Airport) and projected (GCM) average annual frequency of Code Red events in the Philadelphia area, as well as the average duration (in days) for a typical Code Red event. Additionally, the maximum duration (in days) for all observed and projected Code Red events was determined to better understand the changes that may be expected by mid- and end-of-century. Based on observed air temperature data measured at the Philadelphia Airport between 1995 to 2014 and MACA median RH hindcast data for the same time period, Code Red events occur, on average, approximately twice per year and last an average of 4 days, with a maximum observed duration of 15 days that occurred during the summer of 1995. As shown by the "GCM Current" columns for both RCP4.5 and RCP8.5, the global climate model hindcast data aligns well with the observed data for Philadelphia.

Table 6-5. Annual average frequency, average duration, and maximum duration of Code Red Events (at least 3 consecutive days with heat indices greater than or equal to 95°F) in the Philadelphia Area. Includes projected annual frequencies and durations for three time periods (current, mid-century, and end-of-century) and two emissions scenarios (RCP4.5, RCP8.5). LOCA projections are based on the CMIP5 9 GCM Ensemble.

	Observed PHL Airport 1995-2014	**GCM Current RCP4.5** 1995-2014	**GCM Mid-Century RCP4.5** 2050-2069	**GCM End-of-Century RCP4.5** 2080-2099	**GCM Current RCP8.5** 1995-2014	**GCM Mid-Century RCP8.5** 2050-2069	**GCM End-of-Century RCP8.5** 2080-2099
Annual Average Frequency *(Events per Year)*	2	2	5	5	2	7	8
Average Code Red Event Duration *(Days)*	4	4	5	6	5	7	9
Maximum Code Red Event Duration* *(Days)*	15	10	20	23	11	31	50

**The maximum code red event duration is the average of the maximum durations across the LOCA 9 model ensemble.*

Under the high emissions scenario (RCP8.5), Code Red events are projected to increase to approximately 7 events per year by mid-century and last an average of 7 days, with a maximum projected duration of 31 days. By the end of the century under the same scenario, Code Reds are projected to increase to 8 events per year and span an average of 9 days, with a maximum projected duration of 50 days. Results for the intermediate emissions scenario (RCP4.5) are likewise shown in

Table 6-5. The results indicate a substantial increase in Code Red event frequencies and durations by mid-century for both the RCP4.5 and RCP8.5 emissions scenarios, pointing to a need for heightened awareness on maintaining safe working conditions as the potential for heat exposure and heat stress increases. Notably, the projected frequencies and durations of Code Red events using the intermediate (RCP4.5) emissions scenario do not change considerably from mid-century to end-of-century. A similar trend was observed for the previous analysis performed using OSHA risk levels and the RCP 4.5 emissions scenario with results shown in

Table 6-2. This is due to a larger increase in projected temperatures between now and mid-century when compared to the increase between mid-century and end-of-century under the RCP4.5 emissions scenario, which corresponds to a projected peak in annual greenhouse gas emissions in 2040 followed by a decrease in emissions (Climate Central, 2017). In contrast, under the high emissions scenario (RCP8.5), temperatures and Code Red events continue to increase considerably between mid- and end-of-century.

The results of the Heat Health Emergency (HHE) analysis are presented in **Table 6-6** and

Table 6-7. As introduced in **Table 6-4**, HHEs are activated during the months of May through June when heat indices reach 101°F or greater for two or more consecutive days or 98°F or greater for three or more consecutive days, *OR* during the months of July to September when heat indices reach 106°F or greater for two or more consecutive days or 103°F or greater for three or more consecutive days. **Table 6-6** shows the observed (PHL INTL Airport) and projected (GCM) average annual frequency of HHEs during the months of May through June in the Philadelphia area, as well as the average duration (in days) for a typical HHE. Additionally, the maximum duration (in days) for all observed and projected HHEs was determined. Results are similarly shown in

Table 6-7 for observed and projected HHEs activated during the months from July to September.

For the months of May through June (**Table 6-6**), based on observed air temperature data measured at the Philadelphia Airport between 1995 to 2014 and MACA median RH hindcast data for the same time period, HHEs occurred approximately zero times per time period *(May/June)* and lasted an average of 3 days, with a maximum observed duration of 4 days. Under the intermediate emissions scenario (RCP4.5), both the mid-century and end-of-century projections show an increase in HHEs to approximately 1 event per time period *(May/June)* lasting an average of 4 days, with a maximum projected duration of 8 days. Results for the high emissions scenario (RCP8.5) are similarly presented, with a projected increase in HHEs to 3 events per time period *(May/June)* by the end of the century, lasting an average of 5 days and with a maximum projected duration of 15 days.

Table 6-6. Annual average frequency, average duration, and maximum duration of Heat Health Emergencies in the Philadelphia Area during the months of **May to June***. Includes projected annual frequencies and durations for three time periods (current, mid-century, and end-of-century) and two emissions scenarios (RCP4.5, RCP8.5). LOCA projections are based on the CMIP5 9 GCM Ensemble.*

	Observed PHL Airport 1995-2014	**GCM Current RCP4.5** 1995-2014	**GCM Mid-Century RCP4.5** 2050-2069	**GCM End-of-Century RCP4.5** 2080-2099	**GCM Current RCP8.5** 1995-2014	**GCM Mid-Century RCP8.5** 2050-2069	**GCM End-of-Century RCP8.5** 2080-2099
Annual Average Frequency *(Emergencies per Year, May-Jun)*	0.2	0.3	1	1	0.3	2	3
Average Heat Health Emergency Duration *(Days)*	3	3	4	4	4	5	5
Maximum Heat Health Emergency Duration* *(Days)*	4	4	8	8	5	11	15

**The maximum code red event duration is the average of the maximum durations across the LOCA 9 model ensemble.*

In a similar manner,

Table 6-7 presents both the observed and projected annual average frequencies and durations of HHEs for the months of July to September. Under the intermediate emissions scenario (RCP4.5), HHEs are projected to increase to approximately 1 event per time period *(July to September)* by mid-century and last an average of 4 days, with a maximum projected duration of 10 days. By the end of the century under the same scenario, the projected average frequency increases to 2 events per time period *(July to September)* while the average and maximum durations remain the same. Results for the high emissions scenario (RCP8.5) are similarly presented, with a projected increase in HHEs to 5 events per time period *(July to September)* by the end of the century, lasting an average of 7 days and with a maximum projected duration of 30 days.

Table 6-7. Annual average frequency, average duration, and maximum duration of Heat Health Emergencies in the Philadelphia Area during the months of ***July to September****. Includes projected annual frequencies and durations for three time periods (current, mid-century, and end-of-century) and two emissions scenarios (RCP4.5, RCP8.5). LOCA projections are based on the CMIP5 9 GCM Ensemble.*

	Observed PHL Airport 1995-2014	**GCM Current RCP4.5** 1995-2014	**GCM Mid-Century RCP4.5** 2050-2069	**GCM End-of-Century RCP4.5** 2080-2099	**GCM Current RCP8.5** 1995-2014	**GCM Mid-Century RCP8.5** 2050-2069	**GCM End-of-Century RCP8.5** 2080-2099
Annual Average Frequency *(Emergencies per Year, Jul-Sep)*	0.3	0.3	1	2	0.4	3	5
Average Heat Health Emergency Duration *(Days)*	3	4	4	4	4	5	7
Maximum Heat Health Emergency Duration *(Days)*	4	5	10	10	5	13	30

**The maximum code red event duration is the average of the maximum durations across the LOCA 9 model ensemble.*

Together, the results for both time periods (May/June and July to September) indicate a substantial increase in annual Heat Health Emergency frequencies and durations by mid- and end-of-century, with a potential to increase to 3 HHEs annually by the end of the century under the RCP4.5 scenario and 8 HHEs annually by the end of the century under the RCP8.5 scenario. Further, both scenarios show the potential for far longer HHE durations than those typically experienced in the Philadelphia area.

It is also worth noting that a similar trend to that observed for the OSHA heat index-associated risk level analysis and Code Red analysis is once again observed here for the intermediate emissions scenario (RCP4.5) wherein the projected HHE frequencies and durations do not increase substantially between mid-century and end-of-century due to a projected peak in annual greenhouse gas emissions in 2040 followed by a decrease in emissions under the RCP4.5 scenario (Climate Central, 2017). The next section (Section 6.3 – Understanding Future Temperature Increases*)* will discuss projected temperature trends in greater detail.

The City has published an Extreme heat guide to provide information on who is most at risk to heat-related illnesses, tips on staying safe in very hot weather, some background on the changing climate and what that means for Philadelphia, as well as several additional resources including OSHA's guide to Working in Outdoor and Indoor Heat Environments. It is also recommended to sign up for ReadyPhiladelphia, the City of Philadelphia's notification system for emergencies or severe weather alerts, including weather alerts from the National Weather Service and Heat Health Emergency and Code Red event alerts from the City.

Heat Impacts on Infrastructure & Personnel: A Miami-Dade Water and Sewer Department (WASD) Case Study

The Water Utility Climate Alliance (WUCA) and the Association of Metropolitan Water Agencies (AMWA) sponsored a study on heat impacts to water utility infrastructure and personnel for five water utilities throughout the U.S. Each utility performed this analysis using Resilient Analytics (RA), a data analytics software that specializes in helping organizations protect against the impacts of climate change. WASD found that relative to a 1990 to 2009 baseline, by 2070 they will see temperatures resulting in 13 additional weeks over 90°F, 4.5 additional weeks over **95°F, and one day over 100°F every three years.** Under the RCP 8.5 emissions scenario, WASD found the risk of workplace accidents and injuries to increase by as much as 5% by 2070 if they do not implement adaptation strategies to protect employee exposure to heat stress. One adaptation strategy noted is the use of work/rest cycles. WASD suggested flexing outdoor personnel schedules to begin earlier in the morning to offset productivity losses incurred by implementing work/rest cycles. Annual savings to WASD under this scenario ranged from $32,000 to $241,000 in 2030 and $76,000 to $869,000 in 2070 depending on the standard work/rest cycle implemented.

Water Utility Climate Alliance

ASSOCIATION OF
METROPOLITAN
WATER AGENCIES

6.2 Understanding Future Temperature Increases

Statistically downscaled global climate model (GCM) temperature output is available for Philadelphia. Of the three primary climate change impacts of concern (temperature, precipitation, sea level rise), temperature projections are considered to be the most accurate.

Temperatures have been increasing for over a century and the data show that these increases have accelerated over the past 30 years. Looking towards the future, data are replaced by output from ensembles of Global Climate Models (GCMs). PWD's air temperature analysis uses the two future emissions scenarios available for statistically downscaled (Localized Constructed Analogs (LOCA)) projections: RCP4.5 and RCP8.5. Like sea level rise, temperature projections are highly sensitive to emissions scenarios, which makes it critical to use multiple scenarios to evaluate the effects of increasing temperature to PWD's services. Daily temperature data from the Philadelphia International Airport Gauge (PHL), which has a long period of record available, are used to compare GCM output to recent observed data. Three 20-year time periods were selected to show the potential increases in temperature over time using mean and extreme daily temperatures:

- Current Period: Jan. 1, 1995 through Dec. 31, 2014 (LOCA output and PHL data)

- Mid-century: Jan. 1, 2050 through Dec. 31, 2069 (LOCA output)
- End-of-century: Jan. 1, 2080 through Dec. 31, 2099 (LOCA output)

a. Projections of Annual Average and Monthly Average Temperatures

Annual average temperature projections provide a means to illustrate the general trend in temperature increases. Annual averages are presented for PHL and output from an ensemble of 9 GCMs, giving a mean, minimum, and maximum annual average. In addition, the trend in annual average temperature is provided, comparing the Philadelphia gauge data with current GCM output future projections through end of century. Finally, monthly average temperatures are provided for current and future time periods to provide insight into seasonal differences. **Table 6-8** through **Table 6-9** and **Figure 6-3** provide this information for RCP4.5, and **Table 6-10** through **Table 6-11** and **Figure 6-4** provide the same information for RCP8.5. The column representing temperature increase is the difference between GCM current model output and end-of century projections.

Table 6-8. Annual Average Temperature Projections (°F) using PHL data and LOCA output (RCP4.5) for three time periods. LOCA projections are based on the 9 GCM Ensemble (CMIP5).

	Observed PHL Airport 1995-2014	**GCM Current** 1995-2014	**GCM Mid-Century** 2050-2069	**GCM End-of-Century** 2080-2099	**Temperature Increase by End of Century (°F)**
Annual Average Mean	56.41	55.61	58.46	59.06	3.45
Annual Average Minimum	53.73	54.86	57.95	58.51	3.65
Annual Average Maximum	58.89	56.91	59.11	59.64	2.73

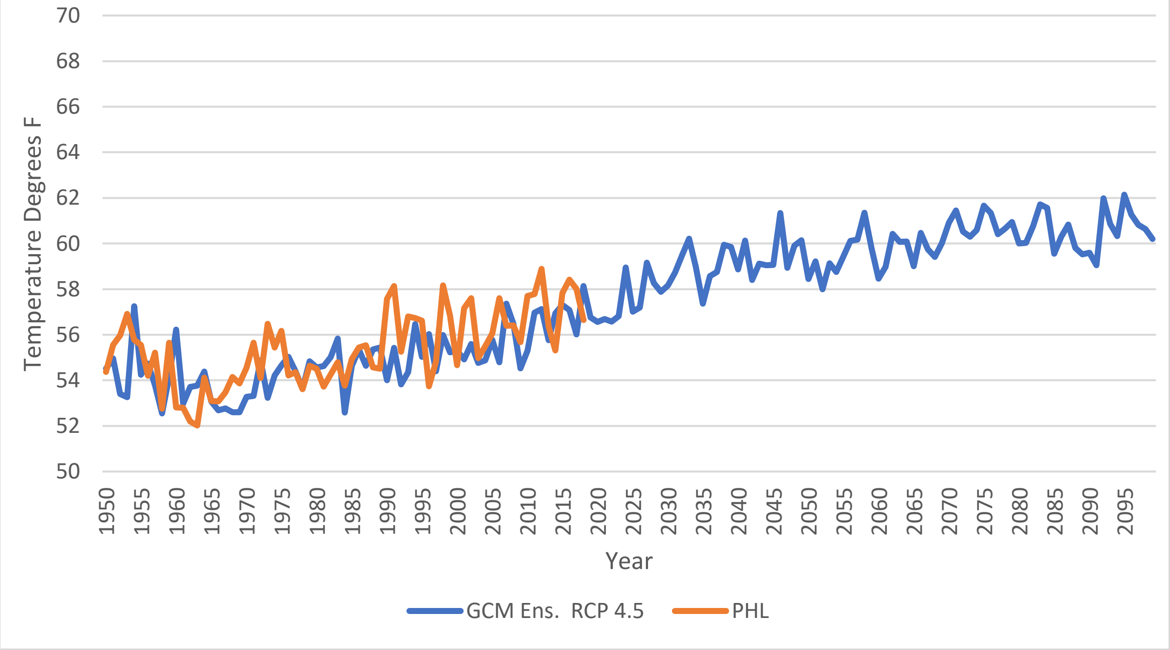


Figure 6-3. Annual Average Temperature trend based on LOCA output (RCP4.5) for 1950 through 2099 and actual trend based on observed Philadelphia Airport Gauge (PHL) data for 1950 through 2018.

Table 6-9. Monthly average air temperature projections using PHL and LOCA output (RCP4.5) for three time periods.

Month	**Observed PHL Airport** 1995-2014	**GCM Current** 1995-2014	**GCM Mid-Century** 2050-2069	**GCM End-of-Century** 2080-2099	**Temperature Increase by End of Century (°F)**
1	33.80	33.06	36.05	36.43	3.37
2	35.85	35.62	38.54	38.80	3.18
3	44.16	43.37	46.11	46.73	3.36
4	54.63	53.42	55.69	56.62	3.20
5	64.29	63.31	66.15	67.12	3.81
6	73.62	72.80	75.71	76.16	3.36
7	78.56	77.71	80.93	81.50	3.79
8	77.03	75.89	79.24	79.90	4.01
9	69.96	68.83	72.29	72.61	3.78
10	58.23	57.96	60.65	61.38	3.42
11	47.37	47.93	50.00	50.69	2.77
12	38.28	37.38	40.15	40.81	3.44

Table 6-10. Annual Average Temperature Projections (°F) using PHL data and LOCA output (RCP8.5) for three time periods. LOCA projections are based on the 9 GCM Ensemble (CMIP5).

	Observed PHL Airport 1995-2014	**GCM Current** 1995-2014	**GCM Mid-Century** 2050-2069	**GCM End-of-Century** 2080-2099	**Temperature Increase by End of Century (°F)**
Annual Average Mean	56.41	55.70	60.18	63.25	7.54
Annual Average Minimum	53.73	54.86	59.17	62.22	7.36
Annual Average Maximum	58.89	56.73	61.38	64.65	7.92

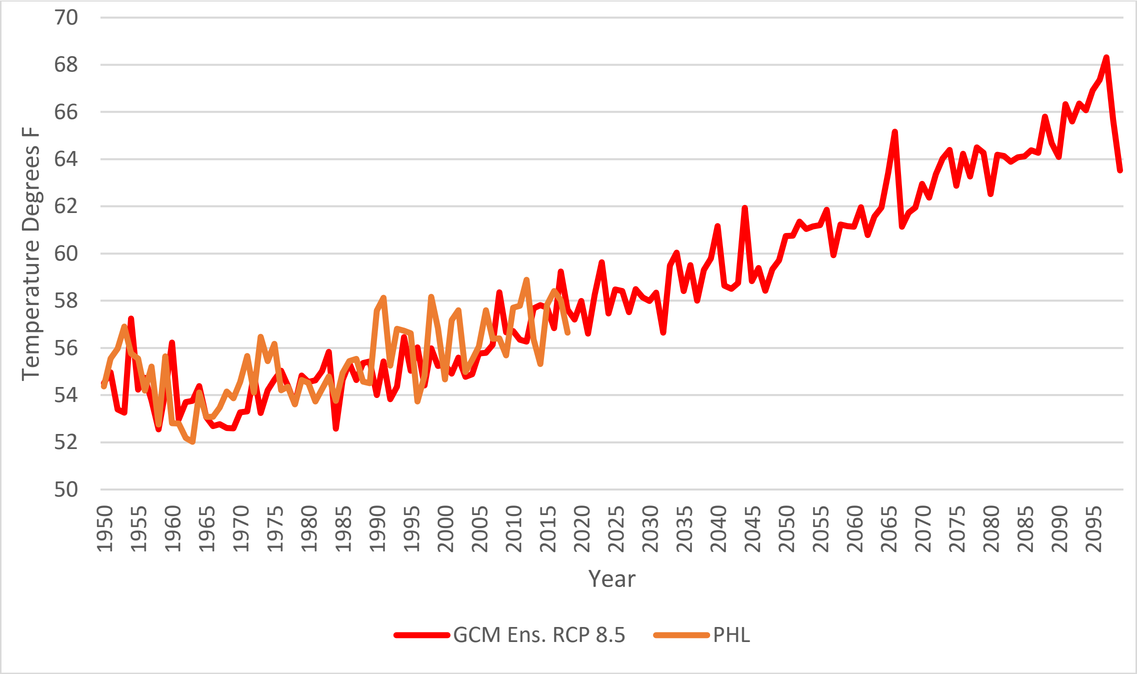


Figure 6-4. Annual average temperature trend based on LOCA output (RCP8.5) for 1950 through 2099 and actual trend based on observed Philadelphia Airport Gauge (PHL) data for 1950 through 2018.

Table 6-11. Monthly average temperature projections using observed Philadelphia Airport Gauge (PHL) data and LOCA output (RCP8.5) for three time periods.

Month	**Observed PHL Airport** 1995-2014	**GCM Current** 1995-2014	**GCM Mid-Century** 2050-2069	**GCM End-of-Century** 2080-2099	**Temperature Increase by End of Century (°F)**
1	33.80	33.19	37.36	40.19	7.00
2	35.85	35.75	40.19	42.85	7.10
3	44.16	43.85	46.91	49.51	5.67
4	54.63	53.57	57.92	60.69	7.12
5	64.29	63.43	67.82	71.62	8.19
6	73.62	72.75	77.87	80.88	8.13
7	78.56	77.74	83.09	86.40	8.65
8	77.03	76.12	81.33	85.00	8.88
9	69.96	68.87	74.00	77.53	8.66
10	58.23	58.05	62.39	65.89	7.84
11	47.37	47.90	51.69	54.35	6.45
12	38.28	37.23	41.63	44.03	6.80

b. Projections of Extreme Summer Temperatures

When considering temperature changes, extreme summer heat, which is often made worse by the heat island effect in cities, is of great importance for human health. “Heat Wave” is a flexible and relative term with no official definition. The World Meteorological Organization defines a heat wave as five or more consecutive days of prolonged heat in which the daily maximum temperature is higher than the average maximum temperature by 5°C (9°F) or more (*Heat Wave*, 2023). But the average maximum temperature is not defined.

The National Weather Service has created a de facto basic heat wave definition through the development of criteria for the issuance of heat watches and warnings. These criteria involve nationwide standards but allow deviations for individual stations based on local conditions (National Weather Service [NWS], n.d.). This results in the loosely defined NWS definition of a heat wave as the following: “A period of abnormally and uncomfortably hot and unusually humid weather. Typically, a heat wave lasts two or more days.”[38]

Robinson (2001) worked with heat stress factors to define a heat wave as a period of at least 48 hours during which neither the overnight low nor the daytime high falls below the NWS heat stress thresholds (80° and 105°F, respectively).

With no firm definition of a heat wave, **Table 6-12** and **Table 6-13** provide several measures of extreme heat relevant to Philadelphia weather, all using the daily T_{max} values from the Philadelphia Airport gauge as well as the 9 GCMs. The two tables represent projections related to RCP4.5 and RCP8.5.

---

[38] *National Weather Service (NWS) heat wave definition, as found in: https://forecast.weather.gov/glossary.php?letter=h*

Table 6-12. Extreme summer heat values for the current period, mid-century, and end-of-century using daily maximum temperature values from the PHL Airport gauge and the 9 GCM Ensemble under RCP4.5 (CMIP5).

	Observed PHL Airport 1995-2014	**GCM Current** 1995-2014	**GCM Mid-Century** 2050-2069	**GCM End-of-Century** 2080-2099	**Temperature/Duration Increase by End of Century (°F/Days)**
Hottest Daily Temperature of Period (°F)	103	104.09	107.21	108.00	3.91
Number of Days over 20-year period Above 95°F	131 (1.8%)	113 (1.5%)	323 (4.4%)	385 (5.3%)	273
Number of Days over 20-year period Above 100°F	10	11	68	91	80
Number of Days over 20-year period Above 105°F	0	0	5	10	9
Number of Days over 20-year period Above 110°F	0	0	0	0	0
Summer Heat Waves					
Highest 5-day Average Summer High (°F)	98.4	99.76	103.50	104.91	5.14
Highest 7-day Average Summer High (°F)	97.14	98.20	102.03	103.62	5.41

Table 6-13. Extreme summer heat values for the current period, mid-century, and end-of-century using maximum temperature values from the PHL Airport gauge and the 9 GCM Ensemble under RCP8.5 (CMIP5).

	Observed PHL Airport 1995-2014	**GCM Current** 1995-2014	**GCM Mid-Century** 2050-2069	**GCM End-of-Century** 2080-2099	**Temperature/Duration Increase by End of Century (°F/Days)**
Hottest Daily Temperature of Period (°F)	103	103.89	111.31	113.75	9.86
Number of Days over 20-year period Above 95°F	131 (1.8%)	122 (1.7%)	570 (7.8%)	1050 (14.4%)	928
Number of Days over 20-year period Above 100°F	10	13	148	412	399
Number of Days over 20-year period Above 105°F	0	1	21	112	111
Number of Days over 20-year period Above 110°F	0	0	2	22	22
Summer Heat Waves					
Highest 5-day Average Summer High (°F)	98.4	100.56	107.50	110.11	9.55
Highest 7-day Average Summer High (°F)	97.14	99.33	105.73	108.84	9.51

6.3 CCAP Temperature Products

The purpose of these guidelines is to help ensure that PWD proactively protects employee health and safety, maintains current levels of service and continues to meet regulatory requirements under future conditions of increasing temperatures. The tables in Section 6.3 provide the basic temperature information on recent trends and projections, both in terms of averages as well as extreme values. In addition, CCAP can provide daily temperature time series for the period 1950 through 2099 for various emissions scenarios. Additional studies have been conducted to assess extreme cold impacts on drinking water intake infrastructure as well as the impact of increasing air temperature on source water temperature.

a. Applying Temperature Projections to PWD Initiatives

The following potential applications and tools can be considered.

- Preparation of worker safety guidelines during heat waves using recommendations from NIOSH and OSHA.
- Water treatment chemical application rates and supply costs under future temperature conditions using the air-water temperature analyses.
- Estimates of changes in raw water quality due to algae blooms related to increased stream temperature.
- Estimates of THM levels in finished water under increased water temperatures.
- Impacts of increasing water temperatures on dissolved oxygen levels in streams and rivers as they relate to water quality standard compliance.
- Assessment of changes to future drought conditions using precipitation and temperature projection time series.
- Impacts of increasing temperatures on plant selection in Green Stormwater Infrastructure (GSI) systems.

6.4 Future Areas of Consideration

While increasing precipitation and sea level rise were identified as priority climate impacts for CCAP to evaluate given their many potential, high consequence impacts to PWD core services, there are several air temperature-related impacts that warrant further analysis, including those identified in the CCAP Vulnerability Survey and outlined below. Future versions of this guidance may include more specific recommendations or requirements related to planning, designing and operating systems that are vulnerable to high heat. In addition, employee health and safety should remain a paramount concern as temperatures rise.

- **Water supply impacts (quantity):** Warming air temperatures could increase the rate of evaporation in PWD source watersheds, potentially exacerbating low flow conditions during drought periods.
- **Water supply impacts (quality):** Higher air and water temperatures may decrease dissolved oxygen (DO) concentrations in PWD source and receiving waters. Additionally, increasing levels of pollutants (sediments, nutrients, pathogens, bacteria, etc.) that can result from intense precipitation or low flow conditions can couple with higher water temperatures to produce algal blooms and other negative water quality conditions.
- **Drinking water treatment process:** Increases in water temperature could affect chemical dosing. For example, a higher water temperature could necessitate a higher chlorine dose to compensate for increased degradation rates. In addition to higher chemical costs and possible T&O complaints from customers receiving more chlorinated water, there may also be regulatory and water quality implications, such as increased disinfection byproduct (DBP) levels.
- **Electrical equipment reliability:** Extreme high temperatures and heat waves can stress or damage electrical equipment and cause power outages, both on site and in the greater Philadelphia region, threatening structures and processes that rely on electricity.

While increasing temperatures are projected under climate change, CCAP acknowledges that extreme cold temperatures are also a concern for PWD Operations. To address this, CCAP performed research on the potential for extreme cold conditions in our region in the future. Analyses were also performed to better characterize extreme cold conditions under which substantial operational challenges occur, most notably icing at the Baxter Drinking Water Treatment Plant Intake. Results of these research efforts and analyses have been shared with relevant PWD staff.

As of this version of the guidance, the GCM ensemble used by CCAP is comprised of 9 models from the IPCC's Coupled Model Intercomparison Project 5 (CMIP5). In a continued effort to ensure the best available guidance is included in this document, CCAP will be exploring updates to the projections and analyses in this document using output from the sixth phase of the Coupled Model Intercomparison Project (CMIP6). Results of this effort will be shared in a future version of this guidance.

6.5 References

Butterfield, C.T., Wattie, E., Megregian, S. & Chambers, C.W. (1943). Influence of pH and Temperature on the Survival of Coliforms and Enteric Pathogens When Exposed to Free Chlorine*. Public Health Reports, 58*(51), 1837-66. doi:10.2307/4584715

City of Philadelphia Mayor's Office of Sustainability and ICF International. (2015, November). *Growing Stronger: Toward A Climate-Ready Philadelphia.* City of Philadelphia, Mayor's Office of Sustainability. https://www.phila.gov/documents/growing-stronger-toward-a-climate-ready-philadelphia/

Climate Central. (2024, January 12). *2023: Earth's Hottest Year on Record.* 2023: Earth's Hottest Year on Record | Climate Central

Climate Central. (2023, November 22). *2023 Winter Package.* 2023 Winter Package | Climate Central

Climate Central. (2017, August 3). *More Hot Days Are Coming With Climate Change. Our Choices Will Decide How Many.* https://www.climatecentral.org/report/climate-change-hot-days-21667

Heat Wave. (2023, December 27). Britannica. Retrieved December 27, 2023, from https://www.britannica.com/science/heat-wave-meteorology

ICF International. (2014, August). *Useful Climate Information for Philadelphia: Past and Future.* City of Philadelphia, Mayor's Office of Sustainability. https://www.phila.gov/media/20160505145605/Useful-Climate-Science-for-Philadelphia.pdf

Kiefer, M., Rodríguez-Guzmán, J., Watson, J., van Wendel de Joode, B., Mergler, D., & Soares da Silva, A. (2016). Worker health and safety and climate change in the Americas: issues and research needs. *Pan American Journal of Public Health, 40*(3), 192–97.

Masters, S., Welter, G.J., & Edwards, M. (2016). Seasonal Variations in Lead Release to Potable Water. *Environmental science & technology, 50*(10), 5269-5277. doi:10.1021/acs.est.5b05060

Mullen, E.D. & Ritter, J.A. (1974). Potable-Water Corrosion Control. *Jour. AWWA*, *66*(8), 473-479. doi:10.1002/j.1551-8833.1974.tb02080.x

National Research Council (US) Safe Drinking Water Committee. (1980). *Drinking Water and Health: Volume 2.* National Academies Press (US). doi:10.17226/1904

National Weather Service (NWS). (n.d.) *During a Heat Wave.* Retrieved December 27, 2023, from https://www.weather.gov/safety/heat-during

Robinson, P.J. (2001, April 1). On the Definition of a Heat Wave. *Journal of Applied Meteorology and Climatology, 40*(4), 762-775. doi:10.1175/1520-0450(2001)040<0762:OTDOAH>2.0.CO;2

Safe Drinking Water Foundation. (n.d.). *Water Temperature*. https://www.safewater.org/fact-sheets-1/2018/8/15/water-temperature-fact-sheet

Shahzad, M., Khan, S.J., & Paul, P. (2015). Influence of Temperature on the Performance of a Full-Scale Activated Sludge Process Operated at Varying Solids Retention Times Whilst Treating Municipal Sewage. *Water*, *7*(3), 855-867. doi:10.3390/w7030855

Stevens, A.A., Slocum, C.J., Seeger, D.R., & Robeck, G.G. (1976). Chlorination of organics in drinking water. *Jour. AWWA*, *68*(11), 615-620. doi:10.1002/j.1551-8833.1976.tb02506.x

Wuebbles, D.J., Fahey, D.W., Hibbard, K.A., DeAngelo, B., Doherty, S., Hayhoe, K., Horton, R., Kossin, J.P., Taylor, P.C., Waple, A.M., & Weaver, C.P. (2017). *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. U.S. Global Change Research Program. doi:10.7930/J0DJ5CTG.

Zhang, Y., Qiu, J., Xu, X., & Zhou, L. (2021). Disinfection Kinetics of Free Chlorine, Monochloramines, and Chlorine Dioxide on Ammonia-Oxidizing Bacterium Inactivation in Drinking Water. *Water, 13*(21), 3026. doi:10.3390/w13213026

7 The Broader Context

While this document is focused on a very critical aspect of ensuring PWD's long-term resilience – mainstreaming the use of climate change information in the planning and design of our infrastructure systems – the much broader context of climate resiliency work includes additional strategies, solutions and considerations that can at times be hard to quantify and do not always relate to physical infrastructure. Below are some of the topics and issues related to the broader climate resiliency context. It will be important for PWD to consider these topics in parallel with implementation of PWD's Climate-Resilient Planning & Design Guidance.

- **PWD and Citywide Policy Changes** – As climate change exacerbates infrastructure and resource management challenges we already face, broader policy changes will likely be needed to maintain levels of service and consistently increase resilience across city systems and sectors.
- **Citywide and Regional Coordination**: Beyond considering resilience at an asset, system or facility/treatment plant scale, it is also important that, when needed, PWD's adaptation strategies are coordinated with other City departments and regional planning bodies such as the Delaware Valley Regional Planning Commission (DVRPC). For example, if PWD decides that hardening the shoreline is the best option for protecting the SW WPCP from coastal inundation risks, planning and design of the hardening measures should be coordinated with the Philadelphia International Airport, which is directly adjacent to the plant and also highly vulnerable to coastal flooding. Through such coordination, there is an opportunity to leverage resources and amplify efforts. As PWD adaptation strategies are developed, CCAP will look to coordinate with other city agencies and regional planning bodies, including the Office of Sustainability, the Philadelphia Department of Public Health, the Philadelphia International Airport, the Delaware Valley Regional Planning Commission and the Delaware River Basin Commission. Additionally, CCAP and other teams within PWD specifically address flood risk and related coordination needs through the Citywide Flood Risk Management Task Force.
- **Climate Change Impacts and Equity** – CCAP is aware that climate change disproportionately impacts certain Philadelphia residents and neighborhoods. Climate change is a threat multiplier and will exacerbate existing inequalities. Much of CCAP's work aims to help PWD maintain current levels of service throughout the City, ensuring that critical services are reliably available to all Philadelphians. However, there is more work to be done in this space and CCAP is interested in continuing to explore this topic and environmental justice issues with City, regional and national partners.
- **Visuals, communication tools and staff education**: Communicating about climate change and mainstreaming climate information can be challenging. Without an understanding of climate change and how it will impact our lives, people may not be willing to change work protocols or invest in adaptation efforts. PWD, through CCAP and other Public Affairs and communications-based teams, should consider ways to further engage and educate PWD staff, staff from other city departments, regional partners, students, staff from other utilities across the nation, and the general public.
- **Adaptation Strategy vs. GHG Accounting**: Certain adaptation strategies that help us cope with a changing climate may ultimately be maladaptive and exacerbate climate change by increasing

our greenhouse gas (GHG) footprint. For example, if additional pumping becomes necessary for flood mitigation or for maintaining levels of services, it will add to PWD and the City’s GHG footprint. Moving forward, CCAP will consider ways to avoid or at least reduce GHG increases resulting from adaptation strategies.

Appendix A

Appendix A-1 Additional Information and Resources (AIR) Sheets

List of CCAP Resources:

Location	Title	Description	Type	Link to Resource
Uncertainty	**Adaptive Management Plan AIR Sheet**	This Additional Information & Resources (AIR) Sheet provides an overview of Adaptive Management Planning as a process to evaluate and apply information learned over time to improve management and design decisions in the face of climate change. An Adaptive Management Plan (AMP) is required for some PWD projects being planned and designed in the coastal floodplain. This AIR sheet will help design engineers develop an AMP.	AIR sheet	https://phila.sharepoint.com/:f:/s/pwdowsccap/ElSQhCMuQHZJgSsHyY-YNPgBJiUilcM4oO68TVGtgqmEaA?e=etzBTY
Tidal Trepidation (sea level rise)	**Table with Annual SLR Amounts (Low and Primary SLR Planning Scenarios)**	These tables provide annual sea level rise amounts (interpolated from the SLR curves) for each of the sea level rise planning scenarios adopted from NASA for adaptation planning at PWD.	Appendix B-1	*See Appendix B-1*
Tidal Trepidation (sea level rise)	**Future Tide and Storm Tide Levels (Low and Primary SLR Planning Scenarios)**	These tables provide future tide and extreme water elevations for near-term, mid-century, and end-of-century, using PWD Low and PWD Primary Planning SLR scenarios.	Appendix B-2	*See Appendix B-2*
Tidal Trepidation (sea level rise)	**Tidal Datums AIR sheet**	This AIR Sheet provides definitions, background and context to help PWD staff work with tidal datums, including graphs that depict tidal datums for each of the PWD plants located along the tidal Delaware River. Note that this AIR sheet references NOAA (2017) SLR projections and CCAP has since transitioned to using NASA (2022) SLR projections. However, both sources use the year 2000 as their baseline year, so the information presented is transferrable to the NASA projections.	AIR sheet	https://phila.sharepoint.com/:f:/s/pwdowsccap/Ernju0IxNt1Ot-qRcP78wKEBHWHCObe7KfDiHzSJE2Hcbw?e=LrR7Il
Tidal Trepidation (sea level rise)	**Vertical Control Datums AIR sheet**	This AIR sheet provides an overview of vertical control datums and additional information and tools to help users at PWD convert between vertical control datums.	AIR Sheet	https://phila.sharepoint.com/:f:/s/pwdowsccap/ErEmTiE-r9NGj_Ui0YubZ-4BxGUDXhtK_Pae6cBzgVSMjw?e=CQXlc6
Tidal Trepidation (SLR & storm surge)	**Flood Mitigation Strategies AIR sheet**	This AIR sheet provides information about flood mitigation options and adaptation strategies for increasing flood resilience, such as relocation and elevating or floodproofing new or existing assets to the Design Flood Elevation.	AIR sheet	https://phila.sharepoint.com/:f:/s/pwdowsccap/EmGmjdC_FyZKtW_D1j9nuBYBq-ZKO3CUnALxufMXQRA_xA?e=duEXAL

Storm Ahead (precipitation)	**Cloudburst Management Examples AIR Sheet**	This AIR Sheet provides cloudburst management examples from Copenhagen, New York, and Phoenix – cities that have implemented a variety of strategies to alleviate flooding impacts and other risks that result from cloudburst events.	AIR sheet	https://phila.sharepoint.com/:f:/s/pwdowsccap/Ehqq4klNHCpBoQkzM7zpupsBTO_RzRK-oBlx-73ZdcJukA?e=RGDk1W
Storm Ahead (precipitation)	**IDF, DDF Tables and Curves, Rainfall Constants**	These tables and plots include observed and future precipitation Intensity-Duration-Frequency tables and precipitation Depth-Duration- Frequency tables and curves, that can be used to incorporate projected precipitation changes into project planning and design at PWD.	Appendix C	*See Appendices C-1 through C-4*
Storm Ahead (precipitation)	**Future Design Storm (Alternating Block Method) AIR sheet**	This AIR Sheet demonstrates the change in the 2-hr, 100-yr design storm from observed (1900-2022) to future (2080) periods using the Alternating Block Method.	AIR sheet	https://phila.sharepoint.com/:f:/s/pwdowsccap/Ek9d5CSELqBPsZ-Sj9uhTYMBm1uaOhuXl2bdwQiWp2SocQ?e=YQv1f4

Tidal Datums AIR Sheet

Climate Change Adaptation Program - Additional Information and Resources

AIR SHEET – TIDAL DATUMS

What are tidal datums?

Recorded along coastlines, estuaries, and tidal rivers, tidal datums refer to an average height of the water level at a particular phase of the tidal cycle. Tidal datums are useful for many applications such as boat navigation and fishing and they are critical to coastal development and floodplain management. Understanding tidal datums and their reference to a geodetic control (See AIR Sheet – Vertical Control Datums) is important as they can impact PWD's drainage system, plant outfalls and intakes and the extent of flooding in the coastal zone along the tidal Delaware and Schuylkill Rivers. At PWD tidal datums can be important inputs in engineering studies, project plans and designs and flood risk assessments.

In the U.S., official tidal datums are determined by NOAA's National Ocean Service using a network of tide stations. Because tidal datums shift over time due to environmental changes (e.g. sea level rise or vertical land movement), NOAA publishes tidal datums referenced to a specific period called the National Tidal Datum Epoch (NTDE). Because of differing hydrographic characteristics across regions, tidal datums should only be used as a reference to measure local water levels. PWD uses tidal datum values from several tide stations in the region. NOAA's Philadelphia tide station 8545240 has the longest period of record[1], providing information on tides in Philadelphia since 1900.

Please refer to the Figure 1 for commonly used tidal datums and the accompanying table for tidal datum descriptions.

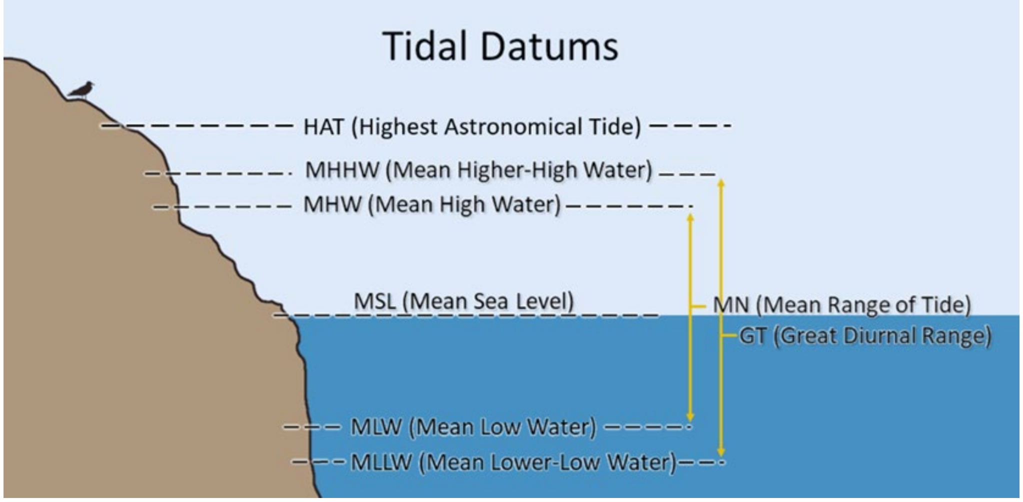


Figure 1. Cross section of tidal datums with horizontal reference. Mean Range of Tide (MN) is the difference in height between MHW and MLW. Great Diurnal Range (GT) is the difference in height between MHHW and MLLW.

Tidal datum	Acronym	Definition
Highest astronomical Tide	HAT	The elevation of the highest predicted astronomical tide expected to occur at a specific tide station over the NTDE.
Mean higher-high water	MHHW	The average of the higher high water height of each tidal day observed over the NTDE.
Mean high water	MHW	The average of all the high water heights observed over the NTDE.
Mean sea level	MSL	The arithmetic mean of hourly heights observed over the NTDE.
Mean low water	MLW	The average of all the low water heights observed over the NTDE.
Mean lower-low water	MLLW	The average of the lower low water height of each tidal day observed over the NTDE.

---

[1] *When the record is combined with that from decommissioned tide station #8545530 which was formerly located at Pier 11, roughly one mile upstream.*

August 2021

AIR SHEET – TIDAL DATUMS

What is the National Tidal Datum Epoch (NTDE)?

Established by NOAA/NOS, the National Tidal Datum Epoch is the official period of 19 years over which water level observations are averaged to determine tidal datums. The 19-year time segment is to account for the natural variation in the tide cycle due to long-term seasonal, meteorological, hydrologic, and oceanographic fluctuations. One of the main influences that drives changes in the tides globally is a small adjustment of the moon's orbit over an ~18.61-year cycle, called the regression of lunar nodes. The NTDE is reviewed for revision at least every 20 to 25 years to account for local changes in tidal datums. The present NTDE is 1983 through 2001 and is undergoing revision to be replaced by a new iteration. The update will be based on observed water levels from the years 2002-2020 and is proposed to release in 2025.

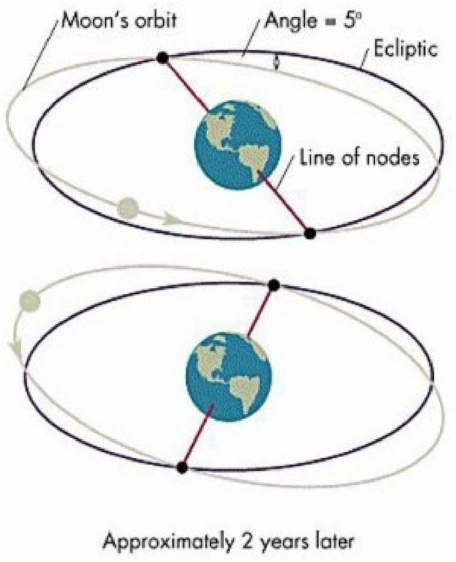


Figure 2. The lunar nodal cycle, produced by the varying declination of the Moon over a period of 18.61 years, drives changes in tidal amplitude globally.

Sea level rise projections: NTDE and CCAP approach

NOAA's tidal datums are referenced to the current NTDE: 1983-2001, centered on the year 1992. NOAA's sea level rise projections, however, have a baseline year of 2000, and must be referenced to a different epoch: 1991-2009, centered on the year 2000. When applying sea level rise scenarios, it is necessary to add them on top of the correct water elevations referenced to the same baseline year. Since NOAA's SLR projections have a baseline year of 2000, it is necessary to adjust Philadelphia tidal datums to the same baseline. To align with the baseline year of 2000, a conversion factor is required to account for the difference between the two tidal datums from different epochs. First, observed water levels from the local tide gauge are averaged over the period 1991-2009 (centered on year 2000) and then compared to the current NTDE tidal datums. The difference in mean sea level is then applied to all tidal datums to establish a complete set that corresponds to the same baseline year of 2000.

Following the method above, CCAP determined a conversion factor of +0.07' to account for any changes in sea levels that occurred between the current NTDE and year 2000.

Table 1. Table with tidal datums referenced to the NTDE and the baseline year for sea level rise projections using a conversion factor.

Philadelphia Station 8545240 Tidal Datums (NAVD88, feet)			
Tidal Datum	**NTDE** (1983-2001)	**Conversion Factor**	**SLR Baseline Year: 2000** (1991-2009)
HAT	4.83	0.07	4.90
MHHW	3.59	0.07	3.66
MHW	3.19	0.07	3.26
MSL	0.39	0.07	0.46
MLW	-2.91	0.07	-2.84
MLLW	-3.1	0.07	-3.03

Tidal datums in Philadelphia

There are three active tide gauges in the Philadelphia area: Philadelphia (NOAA Station 8545240), Bridesburg (NOAA Station 8546252), and Burlington-Bristol (NOAA Station 8539094). Figure 3 shows the locations of these tide gauges in the Philadelphia region. The Tacony-Palmyra tide gauge (NOAA Station 8538886) was decommissioned in 2013. While observed water levels are most accurate at tide gauge locations, staff can use NOAA's VDatum webtool model to estimate tide levels for any location along the Delaware River (user input latitude and longitude information). A general user guide on the VDatum webtool for tidal datums is attached to this document for reference (page 4).

Along with the VDatum user guide, a summary of the tidal datums (LMSL, MLLW, and MHHW) at PWD's tidally influenced water pollution control plants (WPCP) can be found on page 5. Tidal datums are referenced to NAVD 88 and Average City Datum. Using VDatum, the tidal datums are estimated at WPCP outfalls and then adjusted to the baseline year 2000.

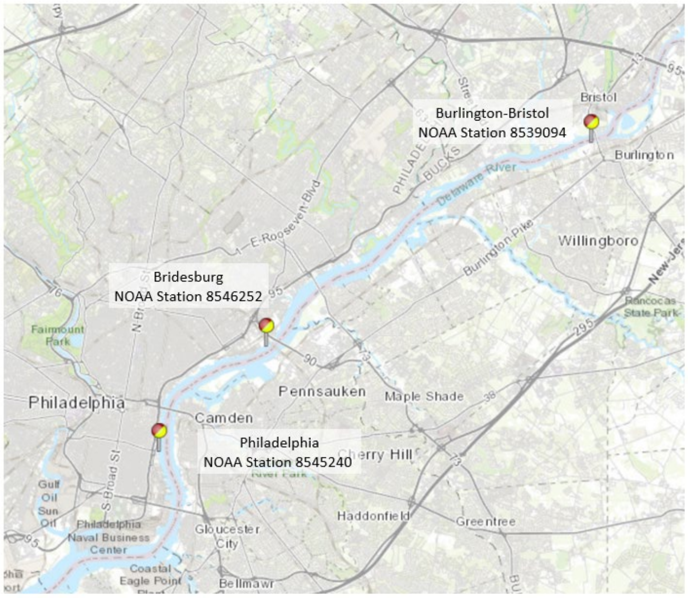


Figure 3 Locations of three tide gauges in the Philadelphia area. Information provided by NOAA.

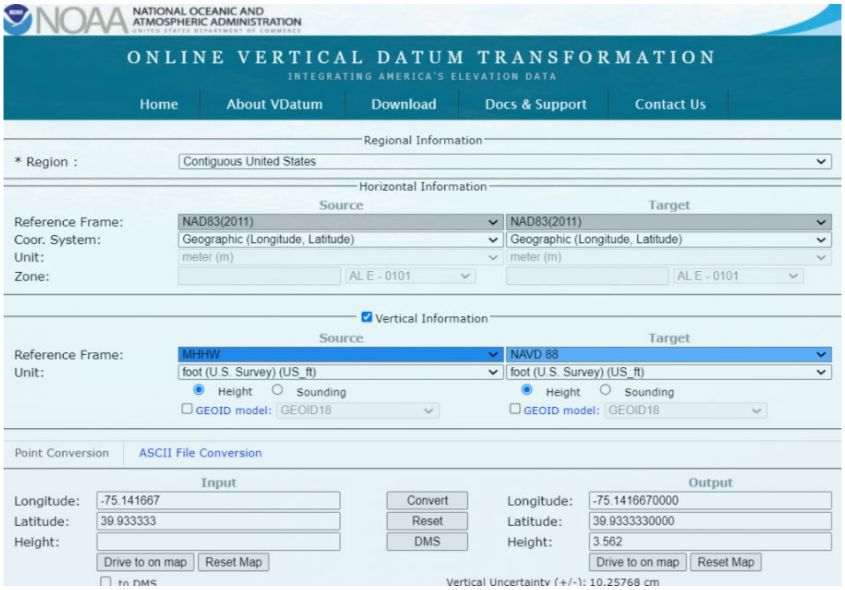
Historic trends of observed water levels in the Philadelphia region indicate a significant increase in tidal range in the past century. Tidal amplification is the increase in tidal range as a response to changes in basin and coastline morphometry due to both spatial and temporal factors. The spatial component of variation in tides is largely due to the constriction of the channel and thus a decrease in frictional effects in the basin interior –the upstream reaches of an estuary are generally narrower in width and water levels are higher compared to downstream conditions. Whereas the spatial factors contributing to tidal amplification are inherent to the estuary system, the temporal component of a changing tidal range can be attributed to anthropogenic influences over time. Shoreline construction, land filling, and dredging that occurred during the 1920s through the 1970s have largely impacted tidal flows and water levels in the Delaware Estuary. In particular, the Philadelphia gauge has recorded a significant change in the tidal range over the past century as land upheaval and shoreline alterations accompanied widespread urbanization efforts during that time. The increase in the tidal range can also be exacerbated by sea level rise with the superposition of tides and storm surge onto a higher baseline of water levels. Sensitive to downstream conditions, tides in the Delaware estuary with fixed boundaries may increase with sea level rise due to increased convergence but may be reduced if overland flooding occurs.

Useful Links

[Tidal datums for Philadelphia Station 8545240 (NOAA)]
[National Oceanography Centre Video on Regression of Lunar Nodes]
[NOAA VDatum Webtool]

User Guide on NOAA's VDatum Webtool for Tidal Datums

NOAA provides published tidal datums for locations with established tide gauges, but tidal datums can be estimated for any location in the Delaware Estuary using NOAA's free vertical datum transformation tool, VDatum. The tool uses latitude and longitude to define a location and provides tidal datums for the NTDE. This free software translates geospatial data between 36 different vertical reference systems, but only points lying within water areas will support a conversion involving tidal datums. Transformations between NAVD88 and tidal datums are performed by interpolation of a sea surface topography grid computed by either a hydrodynamic model or by spatial interpolation. NOAA's provides further documentation and background for VDatum on their webpage. Below is a general guide on using the online VDatum tool to estimate tidal datums for a given location.



Regional Information
* Region : Contiguous United States

Horizontal Information
Source / Target
Reference Frame: NAD83(2011) / NAD83(2011)
Coor. System: Geographic (Longitude, Latitude) / Geographic (Longitude, Latitude)
Unit: meter (m) / meter (m)
Zone: AL E - 0101 / AL E - 0101

☑ Vertical Information
Source / Target
Reference Frame: MHHW / NAVD 88
Unit: foot (U.S. Survey) (US_ft) / foot (U.S. Survey) (US_ft)
● Height ○ Sounding / ● Height ○ Sounding
☐ GEOID model: GEOID18 / ☐ GEOID model: GEOID18

Point Conversion | ASCII File Conversion

Input
Longitude: -75.141667
Latitude: 39.933333
Height:

Output
Longitude: -75.1416670000
Latitude: 39.9333330000
Height: 3.562
Vertical Uncertainty (+/-): 10.25768 cm

Above: VDatum webtool interface with coordinate inputs of Philadelphia tide gauge (NOAA Station 8545240

1. Launch NOAA's online VDatum tool: https://vdatum.noaa.gov/vdatumweb/

2. Enter Regional and Horizontal Information. The Default settings for Horizontal Information are NAD83(2011) for the Reference Frame with a 'Geographic (Longitude, Latitude)' coordinate system. User can define the system based on known Input information.

3. Under Vertical Information, define the Source and Target Reference Frame and Unit. The Default settings for Reference Frame and Unit are NAVD 88 and meter, respectively.

   For tidal datum results:
   Source > Reference Frame: Select the desired tidal datum output from the dropdown menu (MHHW, LMSL, etc.). In the example above, MHHW is selected.
   Target > Reference Frame: Select the desired vertical datum of which the tidal datum output will be referenced to. In the example above, NAVD 88 is selected.

   Adjust the Unit to the desired measurement system. In the example above, 'foot (US Survey) (US_ft)' is selected.

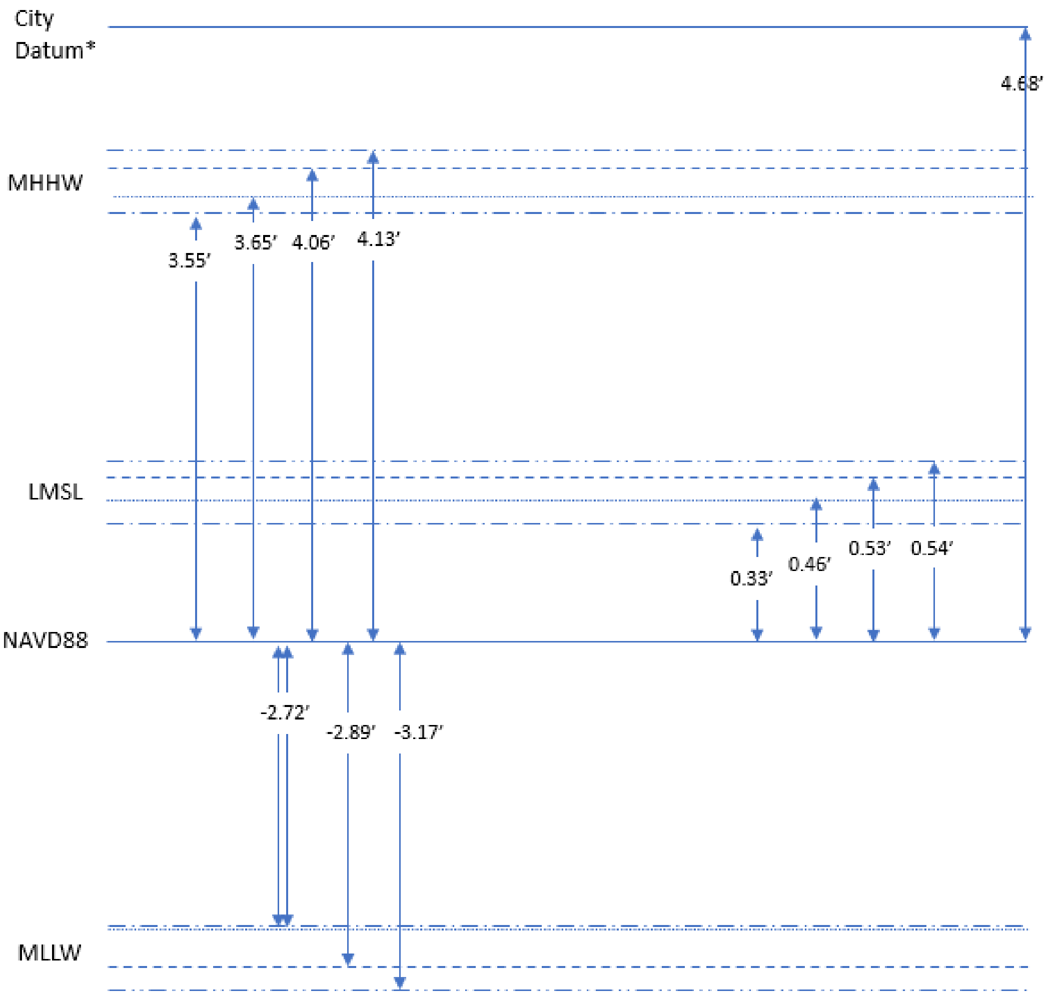
4. Input and Output: Enter the position (latitude and longitude) and select 'Convert'. The tidal datum will be shown in the Height cell under Output.

AIR SHEET – TIDAL DATUMS

Summary of Tidal Datums at PWD Water Pollution Control Plant Outfalls

Tidal elevations relative to NAVD88 and Average City Datum

Tidal elevations for PWD Water Pollution Control Plant (WPCP) outfalls have been adjusted to the baseline year 2000.



**4.68' was the conversion factor used in PWD's wastewater master plan*
Figure not drawn to scale

Key	
-·-·-·-	Southwest Water Pollution Control Plant
- - - -	Southeast Water Pollution Control Plant
········	Northeast Water Pollution Control Plant
-·—·—	Baxter Raw Water Basin
MHHW	Mean Higher-High Water
LMSL	Local Mean Sea Level
MLLW	Mean Lower-Low Water

		All Plants			
		Elevations Relative to NAVD88 (in feet) with Baseline Year 2000 (NTDE + 0.07')			
		Baxter Raw Water Basin	Southwest Water Pollution Control Plant	Southeast Water Pollution Control Plant	Northeast Water Pollution Control Plant
TIDE LEVELS	MHHW	4.13	3.55	3.65	4.06
	MHW	3.77	3.15	3.24	3.67
	MSL	0.53	0.33	0.46	0.54
	MTL	0.40	0.31	0.29	0.49
	MLW	-2.70	-2.53	-2.67	-2.69
	MLLW	-3.17	-2.72	-2.72	-2.89

Adaptive Management Plan AIR Sheet

Climate Change Adaptation Program - Additional Information and Resources

AIR SHEET - Adaptive Management Plan

Introduction

As impacts from climate change become more prevalent, PWD has an opportunity to learn from and respond to new and changing conditions by adapting plans and projects over time. **Adaptive management** is an iterative and dynamic process used to evaluate and apply information learned over time to improve management, planning, and design decisions. It promotes a flexible approach in shaping plans, projects, and programs, ultimately ensuring their long-term resilience through future adaptations.

The principles of adaptive management can be applied to any project or program and for a variety of climate impacts, including increasing precipitation, higher air temperatures and rising sea levels. In the context of the Climate-Resilient Planning & Design Guidance V1.1, specific requirements to employ adaptive management exist for PWD infrastructure at risk of coastal inundation from sea level rise and storm surge. Despite uncertainty in the specific rate and magnitude of SLR towards the end of the century, climate models and localized projections indicate that sea levels will continue to rise through 2100 and beyond and coastal flood risks will increase. Developing an **Adaptive Management Plan (AMP)** that identifies future adaptation measures and incorporates updates from scientific advances can help address uncertainties as we begin to adapt to the effects of climate change. **The AMP documents the adaptive management strategy that will be employed for a project or particular asset, ensuring that sufficient flexibility is built into the design to protect against high sea levels and storm surge through the end of the century, should they be realized.** Adaptive management is essential for PWD to navigate the complex and dynamic challenges presented by climate change and to ensure a high level of service. Enabling flexibility in planning and design leaves room for future adaptation and is essential to PWD's long-term resilience.

PWD requirements for an Adaptive Management Plan

Before determining *if* an Adaptive Management Plan (AMP) is needed for your project, preceding steps include confirming *if* the DFE applies to your project and *which* DFE applies. An **Adaptive Management Plan (AMP)** is part of the PWD Design Flood Elevation (DFE) requirement for new and renovated critical assets with end-of-century useful lives and located in areas susceptible to coastal inundation. If an AMP is required, it must be developed and submitted to CCAP and/or the project Core Review Committee (CRC). Additional guidance to determine the appropriate DFE for a PWD project is provided within the *Design Flood Elevation (DFE) AIR Sheet*.

Table 1: PWD Design Flood Elevation (DFE) Table showing DFEs for non-critical and critical assets with useful lives ranging from near-term to end-of-century.

PWD Design Flood Elevations			
Asset Criticality	Near-term *End of useful life does not extend beyond 2050*	Mid-century *End of useful life: 2050-2075*	End-of-century *End of useful life: 2075 +*
Non-Critical	Current floodplain regulations apply	12 ft. NAVD88* *OR* Lower DFE *with an approved Justification*	
Critical*	Current floodplain regulations apply	14 ft. NAVD88** *OR* Lower DFE *with an approved Justification*	14 ft. NAVD88* *+ Adaptive Management Plan (AMP)* *OR* Lower DFE *with an approved Justification + AMP*

**All PWD assets are by default assumed to be critical unless justification for non-critical status is documented by the Project Manager and approved by the Core Review Committee (if applicable) and/or CCAP.*

***If the protective elevation established by local regulations is higher than the required PWD DFE for the asset under consideration, the elevation established by local regulations MUST be used.*

Determining and Developing an AMP

The AMP is one of the main protective requirements for critical assets with a useful life beyond 2075 that are in either the current or future coastal floodplain. While the DFE is based on sea level rise projections for mid-century, because the asset's useful lifespan extends beyond this time period, additional measures must be in place to protect the asset from potentially higher levels of inundation.

The remainder of this AIR Sheet provides guidance on suggested criteria to be included in a project's AMP. The next section goes into depth with each of the criteria and provides examples where appropriate. The examples provided are not exhaustive and it is up to you, as the planner or designer, to choose an adaptation strategy or approach that fits with your project and meets the new DFE design standard.

Adaptive Management Plan Suggested Criteria

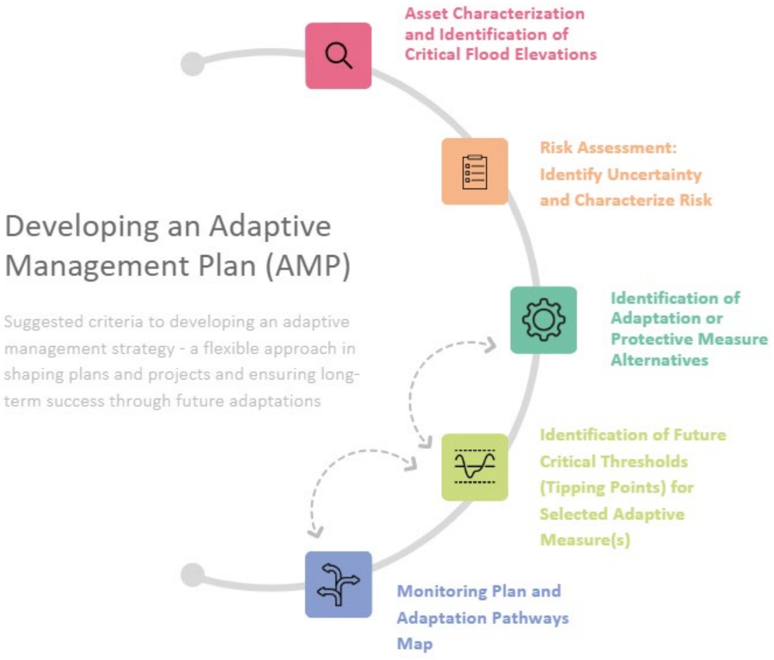


Figure 1. PWD's Climate Change Adaptation Program overview of suggested components in developing an Adaptive Management Plan (AMP)

There is no single methodology that has become a standard for integrating climate risk information into adaptive engineering planning and design practices for infrastructure-based projects. Thus, there is a great deal of flexibility in how to approach the development of an AMP. The following set of elements are recommended to form the basis of the AMP associated with PWD's coastal DFE:

1. Asset Characterization and Identification of Critical Flood Elevations

Background documentation of the critical assets or facility/system to be included in the AMP is an integral initial step and provides a clear understanding of existing conditions. The plan should include an inventory of critical assets with the following components: description of the asset and its function, asset repair or replacement costs, presence of existing protective measures, interdependencies, asset useful service and remaining life, potential flood pathways, and critical asset flood elevation. The following subsection will expand upon and go into more detail with a few of the key components:

- **Asset repair or replacement costs due to inundation:** Costs associated with repairing or replacing the asset to a functioning condition should be accounted for, including costs to repair the physical system and any intermediate repairs, resources, or facilities needed to maintain levels of service during asset repair. An estimated timeframe to repair or replace damaged equipment should be included as this will directly inform asset failure costs. This is used to determine appropriate adaptation actions considering failure of the physical asset and cascading system-wide impacts, as will be discussed below. There are approaches like engineering options analysis that can be used to consider how flexible design can help reduce asset repair or replacement costs as conditions change (Neufville & Smet, 2019).

- **Interdependencies and System impacts:** Costs associated with the wider impacts of asset failure to PWD's overall system, while often harder to estimate, should also be accounted for. Consider cascading impacts on other assets and processes, potential interruptions in level of service to customers, and PWD's ability to meet regulatory requirements. Cascading impacts affecting PWD's ability to serve customers and meet regulations may have more consequential cost implications than loss of the physical asset itself.

- **Critical Asset Flood Elevations:** An inventory of all critical flood elevations should be included in the AMP. This involves identifying elevation(s) at which the asset or system fails due to loss of functionality or presents health and safety hazards. Critical flood elevations could be the outlet elevation of a storm sewer, the bottom of the lowest doorway in a building, or the lowest electrical control box attached to a pump.

- **Flooding pathways:** It is important to assess not only the elevation at which your asset is vulnerable to inundation, but also the different pathways in which floodwaters may come in contact with the asset. Although it may appear that an asset is protected to a certain elevation, there could be other pathways for floodwaters to enter. For example, consider a building which is floodproofed but connected to another building via an underground gallery, walkway, pipes, or ductwork which are not sealed. Although the building structure is protected, water may still enter through pathways like unsealed pipes and ductwork and flood the building from the inside.

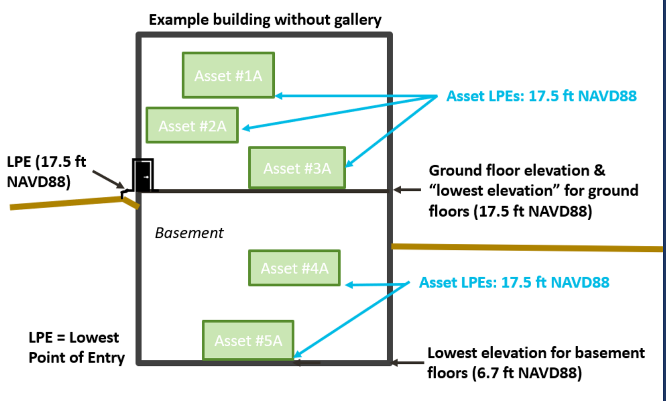
Note that planning and design teams may also consider completing AMPs for an overall facility or system in which most of the individual assets need to be protected to the end-of-century. For instance, it may be economical to build a flood protection wall around an entire site to protect all assets, rather than implementing individual asset flood protection measures.

Asset Characterization in Practice: Southwest Pollution Control Plant

In 2023, CCAP completed a flood risk assessment at the Southwest Pollution Control Plant (SWPCP) to quantify coastal flood risk over time and establish how susceptible the facility is to flood damages under current and future flooding conditions with sea level rise.

As part of the initial asset characterization phase, lowest elevations and lowest points of entry were determined for each electrical and mechanical asset included in the flood risk assessment. In line with the 'Critical Asset Flood Elevation' component, the 'lowest elevation' is defined as the elevation of the asset where water could reach and damage the asset. Likewise, a **flood pathways assessment** of the facility was used to identify lowest points of entry. The lowest point of entry (LPE) is defined as the elevation at which water can enter a building or come in contact with outdoor equipment or processes. An understanding of the facility's flood pathways and LPEs is essential to determining the consequences of flooding because floodwaters must reach the LPE before assets in the area can be damaged

The figure below provides an example of how LPEs were assigned to a building without underground gallery connections to another building. Asset #1A to Asset #5A are assets in a building without a gallery, so all LPEs are equal to the building's lowest ground flood elevation (17.5 ft NAVD88), regardless if it is in the basement or ground floor.



2. Accounting for Uncertainty and Characterizing Risk

For an asset that is vulnerable to inundation at several elevations, the quantifiable risk of different flood levels must be examined to develop appropriate adaptive actions. **Developing an appropriate AMP requires identifying the critical flood elevations where risk of inundation (i.e., in probable cost to replace an asset) exceeds a pre-determined acceptable value (i.e., the value of flood protection).** This is generally the point where risk-based costs (i.e., cost to replace an asset) exceed the cost of protecting the asset. CCAP recommends that planning assessments consider multiple sea level rise scenarios (e.g., for use in model runs), including **PWD's Low SLR Scenario** and the **PWD Primary Planning SLR Scenario**[1]. CCAP also provides probabilities associated with future storm intensity and storm surge events[2]. However, if only one scenario can be included in the planning and risk assessments, the PWD Primary Planning SLR Scenario in combination with the 100-year storm event should be used.

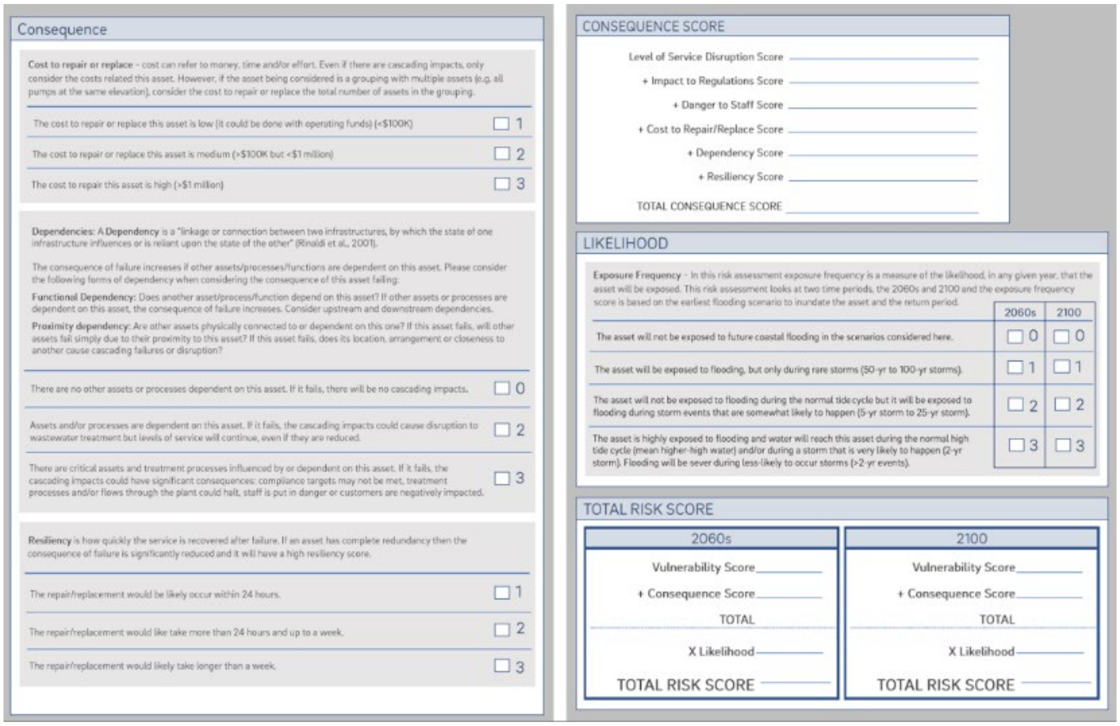
---

[1] See the PWD Climate-Resilient Planning and Design Guidance V1.1, Section 4.4(a), for detailed information on CCAP's recommended Sea Level Rise scenarios.

[2] PWD Climate-Resilient Planning and Design Guidance V1.1, Table 4-4

CCAP evaluated climate scenarios to provide ranges of inundation for different future time periods and developed tools for PWD staff to estimate future coastal flood risk. The following list includes a few resources that will be helpful in evaluating flood risks for your project:

- The *Changing Flood Frequency Tool* can help planners and engineers better understand cumulative risk over the useful lifespan of the asset. The tool determines flood probabilities of your asset or system based on its critical flood elevation and remaining service life.
- CCAP also developed an ***Exposure Analysis*** memo which includes results from a desktop analysis of PWD's water and wastewater facilities using CCAP's *Inundation Mapping Tool*. The memo provides a summary of results for each facility, identifying which assets are projected to flood under the PWD Primary Planning SLR Scenario and various storm surge events.
- The PWD Asset Risk Assessment Data Sheet, which CCAP developed for PWD facility risk assessments, is a useful worksheet that can guide the user to evaluate risk through physical vulnerabilities, consequences, and likelihood of an event. Upon request, CCAP can provide the Asset Risk Assessment Data Sheet and is available to assist with developing the AMP.



Consequence

Cost to repair or replace – cost can refer to money, time and/or effort. Even if there are cascading impacts, only consider the costs related this asset. However, if the asset being considered is a grouping with multiple assets (e.g. all pumps at the same elevation), consider the cost to repair or replace the total number of assets in the grouping.

The cost to repair or replace this asset is low (it could be done with operating funds) (<$100K) ☐ 1
The cost to repair or replace this asset is medium (>$100K but <$1 million) ☐ 2
The cost to repair this asset is high (>$1 million) ☐ 3

Dependencies: A Dependency is a "linkage or connection between two infrastructures, by which the state of one infrastructure influences or is reliant upon the state of the other" (Rinaldi et al., 2001).

The consequence of failure increases if other assets/processes/functions are dependent on this asset. Please consider the following forms of dependency when considering the consequence of this asset failing:

Functional Dependency: Does another asset/process/function depend on this asset? If other assets or processes are dependent on this asset, the consequence of failure increases. Consider upstream and downstream dependencies.

Proximity dependency: Are other assets physically connected to or dependent on this one? If this asset fails, will other assets fail simply due to their proximity to this asset? If this asset fails, does its location, arrangement or closeness to another cause cascading failures or disruption?

There are no other assets or processes dependent on this asset. If it fails, there will be no cascading impacts. ☐ 0
Assets and/or processes are dependent on this asset. If it fails, the cascading impacts could cause disruption to wastewater treatment but levels of service will continue, even if they are reduced. ☐ 2
There are critical assets and treatment processes influenced by or dependent on this asset. If it fails, the cascading impacts could have significant consequences: compliance targets may not be met, treatment processes and/or flows through the plant could halt, staff is put in danger or customers are negatively impacted. ☐ 3

Resiliency is how quickly the service is recovered after failure. If an asset has complete redundancy then the consequence of failure is significantly reduced and it will have a high resiliency score.

The repair/replacement would be likely occur within 24 hours. ☐ 1
The repair/replacement would like take more than 24 hours and up to a week. ☐ 2
The repair/replacement would likely take longer than a week. ☐ 3

CONSEQUENCE SCORE

Level of Service Disruption Score ____
+ Impact to Regulations Score ____
+ Danger to Staff Score ____
+ Cost to Repair/Replace Score ____
+ Dependency Score ____
+ Resiliency Score ____
TOTAL CONSEQUENCE SCORE ____

LIKELIHOOD

Exposure Frequency – In this risk assessment exposure frequency is a measure of the likelihood, in any given year, that the asset will be exposed. This risk assessment looks at two time periods, the 2060s and 2100 and the exposure frequency score is based on the earliest flooding scenario to inundate the asset and the return period.

	2060s	2100
The asset will not be exposed to future coastal flooding in the scenarios considered here.	☐ 0	☐ 0
The asset will be exposed to flooding, but only during rare storms (50-yr to 100-yr storms).	☐ 1	☐ 1
The asset will not be exposed to flooding during the normal tide cycle but it will be exposed to flooding during storm events that are somewhat likely to happen (5-yr storm to 25-yr storm).	☐ 2	☐ 2
The asset is highly exposed to flooding and water will reach this asset during the normal high tide cycle (mean higher-high water) and/or during a storm that is very likely to happen (2-yr storm). Flooding will be sever during less-likely to occur storms (>2-yr events).	☐ 3	☐ 3

TOTAL RISK SCORE

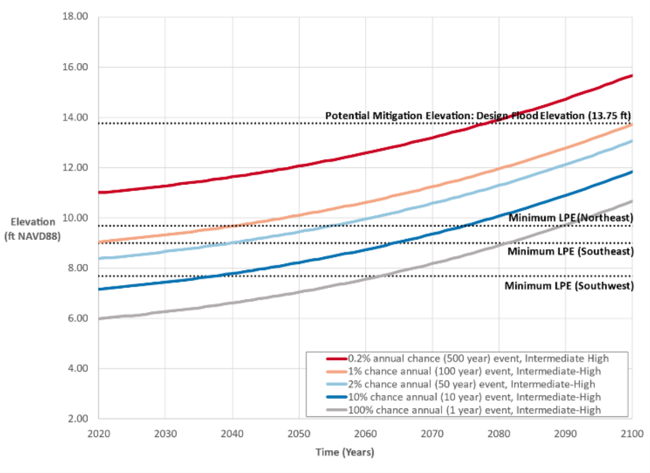
2060s
Vulnerability Score ____
+ Consequence Score ____
TOTAL
X Likelihood ____
TOTAL RISK SCORE ____

2100
Vulnerability Score ____
+ Consequence Score ____
TOTAL
X Likelihood ____
TOTAL RISK SCORE ____

Figure 2. Select pages from the PWD Asset Risk Assessment Data Sheet developed by CCAP using a risk assessment scoring system approach informed by American Water Works Association J-100 framework. Contact CCAP for access to worksheets.

Characterizing Flood Risk in Practice: Flood Risk Assessment at PWD's Water Pollution Control Plants

An integral component of CCAP's coastal flood risk assessments at all three PWD Water Pollution Control Plants (Southwest, Southeast, and Northeast WPCP) is an understanding of the changing flood risk at the facilities due to sea level rise. Due to the uncertainty associated with future sea level rise projections, various climate scenarios were applied (per planning best practice), including PWD's Primary Planning Sea Level Rise Scenario. **Using the Changing Flood Frequency Tool, recurrence interval estimates (flood probabilities) were then calculated for the critical flood elevations at each facility (the minimum Lowest Point of Entry).** As depicted below, graphical results from the tool are represented using a flood frequency graph. **The graph below shows how the flood elevation for each respective storm event increases over time under the Intermediate-High scenario, also known as PWD's Primary Planning Sea Level Rise Scenario**. The Lowest Point of Entry (LPE) elevation is used as a point of reference to evaluate the flood risk at each facility. For example, this characterization of flood risk shows that the Northeast WPCP is more likely to experience flooding from the 1%-annual-chance, or 100-year, storm event in 2040 and beyond.



3. Identification of Adaptation or Protective Measure Alternatives

In this step, the planner or designer will identify one or more adaptation measures to reduce risk from inundation and provide estimated cost analyses results calculated from the risk assessment. See the *Flood Mitigation AIR Sheet* for examples on various types of flood protection actions. The U.S. Environmental Protection Agency developed an Adaptation Strategies Guide for Water Utilities as an informational resource for drinking water, wastewater and stormwater utilities to identify potential strategies for adapting to climate change impacts, including sea level rise and storm surge (EPA, 2015).

Adaptation actions, in the context of coastal flooding, are solutions which can be implemented to reduce risk and handle the uncertainty of future sea-level rise projections. Our guidance on the development of an AMP focuses on applying flexible adaptation measures and actions which can be implemented in the future to reduce the impact of inundation. These actions can be infrastructural changes to the design of an asset (e.g., a foundation built with additional capacity to be raised in the future), operational, and/or policy-based (e.g. land use policies that guide future development away from areas that are potentially vulnerable to sea level rise). Approaches like **engineering options analysis** (sometimes referred to as real options analysis) can inform how to incorporate flexible design by considering potential costs of measures and actions across a range of future conditions (Neufville & Smet, 2019). It is important to understand that there is no one-size-fits-all solution for adaptation planning and a variety of protective strategies can be selected that suit your project's specific needs and available resources.

a. City of Wilmington, New Hanover County, and Cape Fear Public Utility Authority Example

In partnership with EPA's Office of Sustainable Communities, the City of Wilmington, North Carolina, New Hanover County, and Cape Fear Public Utility Authority (CFPUA) piloted a Community Resilience Project that focused on addressing the challenges that sea level rise and coastal flooding are creating for their water and wastewater infrastructure. After completing the vulnerability assessment, the group identified a suite of 54 adaptation strategies focused on infrastructure and land use planning (including regulatory tools and incentives) that can be employed to increase resilience from sea level rise and extreme storm events. Section 3 'Adaptation Strategies' of the report outlines the identified adaptation actions and approaches used to select the strategies. An example of an adaptation strategy includes the assessment and revision of infrastructure design standards (e.g. Design Flood Elevation, flood-proofing, decommissioning of pump stations) every 5 to 10 years as assets are replaced (City of Wilmington, 2013).

b. Southern Monmouth Regional Sewer Authority Example

A wastewater service provider for many coastal communities in New Jersey, the Southern Monmouth Regional Sewer Authority (SMRSA), is at risk to impacts from coastal storms and future sea level rise. Previous coastal storms have damaged and partially flooded existing pump stations at the facility. To address flooding from coastal storm surges which are expected to increase in frequency and intensity due to climate change, SMRSA adopted an adaptive approach and installed mobile pumping station enclosures to safely store equipment and protect wastewater infrastructure. The mobile pump stations are designed to house the primary electrical equipment and controls in a mobile enclosure that would elevate the equipment above the level of flood damage. When an approaching coastal storm has the potential to damage the pump station, the enclosure can be removed from the site and transported to an area of higher elevation. The use of these mobile stations is an alternative protective strategy that minimizes damage to pumping station's electrical equipment, significantly reducing system downtime. These stations proved successful, as they provided protection during Hurricane Irene in 2011 and Superstorm Sandy in 2012, allowing the utility to continue providing wastewater services during critical events (SMRSA, 2012).

Figure 3. South Monmouth Regional Sewer Authority's second mobile pump station in the Borough of Belmar. Recognized by the Federal Emergency Management Agency (FEMA) and the EPA as 'Best Management Practice' for mitigation of damages related to extreme wet weather events (Dalal, 2017).

4. Identification of Future Critical Thresholds (Tipping Points) for Selected Adaptive Measure(s)

The tipping point is the elevation threshold at which the cost of replacing or repairing an asset is the better option to maintain the asset, or at which additional action is needed to protect the asset. If water inundates to this level, the asset is compromised and requires repair and/or replacement. This can be identified as a 'tipping point' for failure and should be part of the AMP strategy (Haasnoot, 2011). Once the tipping point or threshold is passed, the existing adaptation strategies are considered no longer effective, therefore it becomes necessary to determine when to apply or combine additional adaptive strategies before the tipping point is reached. Calculated adaptation tipping points are either 1) scenario dependent (i.e. a top-down approach where climate scenarios drive the assessment of, e.g., future sea levels) or 2) conditions-based (i.e. a bottom-up approach that is dependent on system configuration, sensitivity, and constraints such as drainage system capacity and/or costs). Examples of how tipping points are determined include applying future sea level and storm surge elevations, using critical flood elevations of assets, identifying the frequency of service disruptions or climate impacts resulting in repair costs, and calculating the magnitude of annual repair costs (Zhang, 2019). **Engineering options analysis** can be adopted to determine thresholds based on the cost implications for asset modification over a range of future conditions (Neufville & Smet, 2019). The AMP should identify these tipping points through the end of useful service life of the asset and develop a plan to monitor how and when the tipping point may be reached in the future.

PWD Staff should also consider how to monitor the tipping point, with regular check-ins (in conjunction with updated climate science when IPCC and NCA reports are released: 5-years at a minimum) to determine historic sea level rise trajectory and evaluate the latest future climate model projections. In addition to monitoring when the tipping point may be reached, the plan should also outline how different actions can be implemented over time as new information emerges. These two processes, developing the monitoring plan and adaptation pathways map, represent the core of a successful AMP and are described in the next section below.

5. Monitoring Plan and Adaptation Pathways Map

PWD cannot afford to wait to adapt, as it is more difficult and expensive to make substantial infrastructure or operational changes in a short period of time rather than gradually. Developing an **adaptation pathways map** can help strategically address climate change impacts over a long period of time while reducing the risk of being unprepared or preparing at unnecessary cost. Adaptation pathways maps represent multiple strategies (as identified in *Step 3: Identification of Adaptation or Protective Measure Alternatives*) that are evaluated and implemented in different stages over time as new information emerges and as conditions change (Zhang, 2019). The resulting timeline identifies the adaptation actions that would occur with each tipping point or critical threshold (as determined previously in *Step 4: Identification of Future Critical Thresholds/Tipping Points for Selected Adaptive Measures*). **A well-crafted adaptation pathways map presents not only the possible strategies to implement, but also when and where they could fail (i.e., tipping points and critical thresholds).** For example, when monitored flood elevations near the tipping point or threshold, the AMP should detail when adaptive strategies must be implemented while accounting for estimated planning, design and construction timelines. Examples c) and d) below showcase adaptation pathways maps and established tipping points/thresholds applied by agencies for long-term planning of their facilities. Adopting an adaptive pathways approach also encourages proactive monitoring of climate change impacts to ensure adaptation actions are employed at the appropriate time. It is important to note that the adaptation pathways map and monitoring plan work together in an iterative process as new information becomes available.

A **monitoring plan** to track updates to measurable climate change impacts and to identify when critical thresholds are met is a key component of an AMP. The monitoring plan should entail a routine assessment of the asset's changing risk of inundation and cumulative flood probabilities based on the best and most recent data available. For example, this can entail periodic review of NASA and/or NOAA observed and projected data for sea level rise and storm surge probabilities. This can also include regular monitoring of riverine water elevation levels during normal high tide and precipitation events. Recurrence intervals can be determined for riverine streamflow during precipitation events and compared with existing and climate-adjusted FEMA data[3]. For tracking precipitation events, periodic reassessment of IDF curves and monitoring the frequency of extreme precipitation events should be implemented. The PWD Climate-Resilient Planning and Design Guidance is regularly updated to provide staff and consultants with local climate change projections and serves as a reliable source to aid in developing a monitoring plan for the AMP.

The New York City Panel on Climate Change (NPCC) stresses the need to monitor not only climate impacts, such as sea level rise, but also changes in adaptation strategies (Rosenzweig & Solecki, 2014, p. 402). Therefore, the monitoring plan should also incorporate periodic reassessments of the planned adaptation pathways/strategies chosen in *Step 3: Identification of Adaptation or Protective Measure Alternatives*. Research shows the importance of re-evaluating the chosen adaptation approaches over time as technologies advance, additional data and information become available, and/or certain adaptation strategies show greater success and therefore become preferable over other strategies (Jacob et al., 2010, p. 129). The Thames Estuary 2100 (TE 2100) project in the UK, which entails an adaptation pathways approach to flood risk management in the Thames Estuary, requires a “scheduled review and re-appraisal of the TE 2100 Plan every 10 years with a mid-term monitoring review to be undertaken every 5 years” (Bloemen et al, 2018, p. 1102). The CCAP recommends a scheduled monitoring review take place every 5 years for critical PWD assets or a timeframe that aligns with broader strategic planning efforts relevant to your project team.

Results from monitoring observed climate change impacts and modeled projections over time can largely influence which adaptation actions are incorporated into the adaptation pathways map. For instance, if, in 2050, observed trends indicate that sea levels are rising faster than previously projected, a more robust adaptation strategy may be required. If sea levels are rising slower than previously projected, perhaps the asset can be protected with minimal additional resources. It is up to the planner or designer to develop appropriate actions which can be implemented once more information is available on observed sea level rise over time.

c. Philadelphia Water Department Example

Using PWD’s flood risk assessment at the WPCPs as an example, results from the risk analysis show that flood mitigation would provide significant benefit to all WPCPs. An AMP for flood mitigation at the facilities could consider protection at lower elevations in the near-term while preparing for higher mitigation elevations later in the century. This includes consistent monitoring of sea level rise and coastal flooding likelihood over time. In this example, two adaptive approaches could be considered:

- The first alternative entails building a sitewide floodwall at a lower flood mitigation elevation but with a foundation that is large enough to accommodate a future increase in height up to PWD’s coastal Design Flood Elevation of 14 feet NAVD88. The initial phase is anticipated to be more resource intensive; subsequent phases of increasing the protection height would likely be comparatively less cost prohibitive.

---

[3] As a follow up to the extreme local flooding incurred by Hurricane Ida, CCAP evaluated flooding conditions by the Belmont Raw Water Pumping Station on the Schuylkill River and developed a method that estimates future riverine flood elevations and return intervals. For projects impacted by riverine flooding, CCAP can provide site-specific flood elevations and streamflows for future conditions.

- The second alternative involves delaying the construction of a sitewide floodwall until a future time, focusing instead on the elevation of individual assets, the dry-floodproofing of individual buildings/assets to the lower mitigation elevation, and/or sealing underground connections between buildings.

d. City of Olympia, Washington Example

To address future sea level rise and storm surge effects, the City of Olympia, Washington developed a phased implementation approach for flood protection which includes permanent structures, consolidated outfalls, tide gates on outfalls, and new pump stations. Their long-term planning approach through the end-of-century establishes the following tipping points and thresholds based on existing conditions of the shoreline and observed water elevations and sea level rise: 0.25, 0.5, and 2.0 feet of sea level rise. For example, implementation of the first permanent barriers would be finalized by the time of 0.25 feet of sea level rise is observed (City of Olympia, 2011). These initial phases are planned and implemented to support future strategies that build upon near-term actions. Subsequent adaptation strategy decisions will be made alongside close monitoring of identified trigger points and sea level rise (City of Olympia, 2019).

e. South Florida Water Management District (SFWMD)

In 2021, the South Florida Water Management District (SFWMD) developed a Sea Level Rise and Flood Resilience Plan that utilizes a dynamic adaptive pathways approach where projects are evaluated based on a tipping point and threshold. Current and future projections of different sea level rise scenarios are used as thresholds based on cost (e.g. expected damages) vs. benefit (e.g. avoided costs) for each mitigation strategy (i.e. operational, regulatory, and/or structural). Figure 4 below shows an implementation timeline developed for the selected solutions, taking into account the design and construction time period.

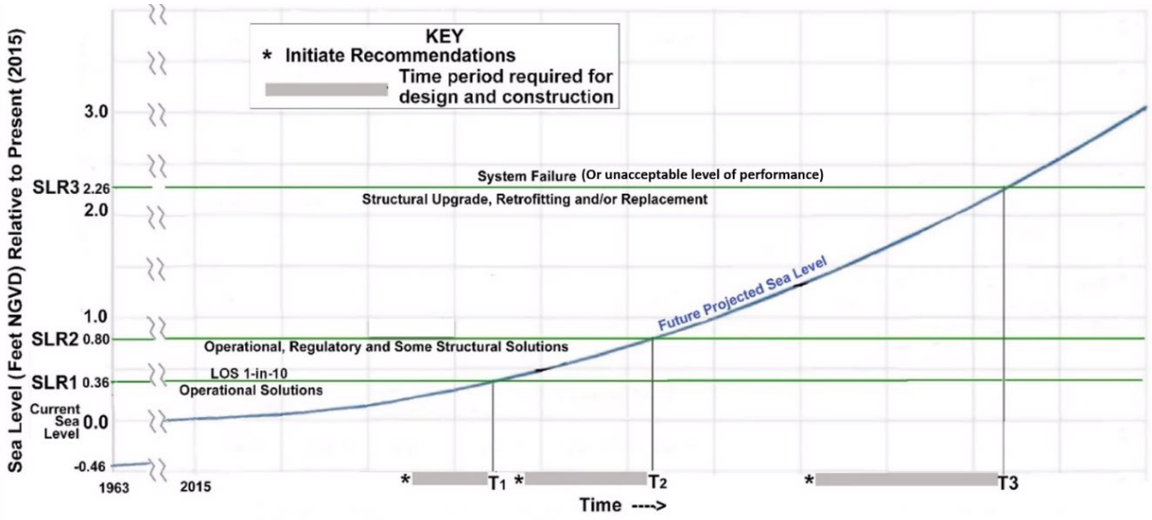


Figure 3. South Florida Water Management District's example implementation timeline for selected mitigation strategies (i.e. operation, regulatory, structural). Trigger points and thresholds are identified based on sea level rise (SLR) amounts (i.e. 0.36, 0.80, and 2.26 feet) for the selected SLR scenario (show here as the blue line). The timing for implementation takes into account the estimated design and construction time period of the solution.

f. LA County Metro's 2019 Climate Action and Adaptation Plan

Figure 2 below is from LA County Metro's 2019 Climate Action and Adaptation Plan and shows an example of an adaptation pathways map which can be followed to ensure rail station accessibility during heat waves through enhanced elevator management. The selected adaptation measures are represented as A through D, and nearing a threshold (i.e. number of extreme heat days per year, cost of heat-related elevator repairs) will trigger transition to another pathway (e.g. from Point 1 to 2).

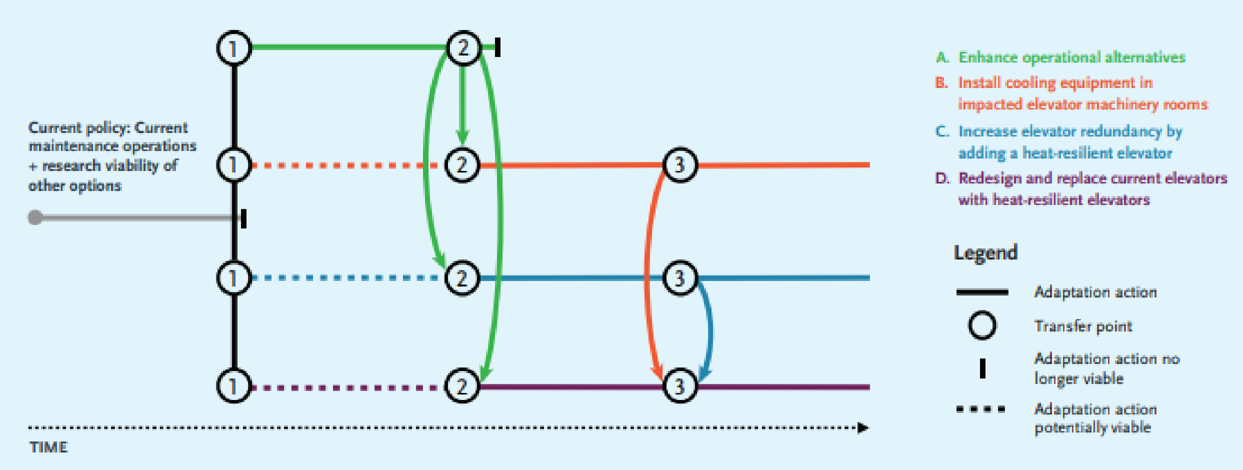


Figure 5. An example of an Adaptation Pathways map for building station elevator resilience to extreme heat. The Adaptation Actions that were identified are listed from A through D in the top right corner. Source: Los Angeles County Metro, 2019 Climate Action and Adaptation Plan (CAAP), p. 38.

References and further reading

Bloemen, P., Reeder, T., Zevenbergen, C., Rijke, J., & Kingsborough, A. (2017). Lessons learned from applying adaptation pathways in flood risk management and challenges for the further development of this approach. *Mitigation and Adaptation Strategies for Global Change*, 23, 1083-1108. doi: 10.1007/s11027-017-9773-9

City of Olympia, LOTT Clean Water Alliance, Port of Olympia, Washington. (2019). Olympia Sea Level Rise Response Plan. Retrieved from https://www.olympiawa.gov/services/water_resources/storm___surface_water/sea_level_rise.php

City of Olympia Public Works Department, Planning & Engineering, Washington. (2011). City of Olympia Engineered Response to Sea Level Rise Technical Report. Retrieved from https://cms7files.revize.com/olympia/Document_center/Community/Climate%20Change%20Response/SLR/Other/SLR-Report-2011.pdf

City of Wilmington, North Carolina & U.S. Environmental Protection (EPA). (2013). Community Resilience Pilot Project, Wilmington, North Carolina. Retrieved from https://wilmingtonnc.prelive.opencities.com/files/assets/city/v/1/development-amp-business/documents/sea-level-rise.pdf

Dalal, Rina N. (2017). A Small Utility's Path to Climate Change Readiness. *Water Online*. Retrieved from www.wateronline.com/doc/a-small-utility-s-path-to-climate-change-readiness-0001.

de Neufville, Richard & Scholtes, Stefan. (2011). Flexibility in Engineering Design. doi: 10.7551/mitpress/8292.001.0001.

Haasnoot, Marjolijn, Middelkoop, H., Van Beek, E., Van Deursen, W.P.A. (2011). A Method to Develop Sustainable Water Management Strategies for an Uncertain Future. Sustainable Development, 19(6): 369-381.

Haasnoot, Marjolijn, Kwakkel, J.H., Walker, W.E., & ter Maat, J. (2013). Dynamic Adaptive Policy Pathways: A Method for Crafting Robust Decisions for a Deeply Uncertain World. *Global Environmental Change,* 23(2), 485–98. Retrieved from https://doi.org/10.1016/j.gloenvcha.2012.12.006.

Jacob, K., Blake, R., Horton, R., Bader, D., & O'Grady, M. (2010, May). Chapter 7: Indicators and monitoring. *Annals of the New York Academy of Sciences*, 1196, 127-142. Retrieved from https://pubs.giss.nasa.gov/docs/2010/2010_Jacob_ja09100s.pdf

National Oceanic and Atmospheric Administration (NOAA) Office for Coastal Management. (2023). Adapting Stormwater Management for Coastal Floods. Retrieved from https://coast.noaa.gov/stormwater-floods/

Neufville, R.D., & Smet, K. (2019). Engineering Options Analysis (EOA). Decision Making under Deep Uncertainty.

Rosenzweig, C. & Solecki, W. (2014). Hurricane Sandy and adaptation pathways in New York: Lessons from a first-responder city. *Global Environmental Change,* 28, 395-408. doi: 10.1016/j.gloenvcha.2014.05.003

South Monmouth Regional Sewerage Authority (SMRSA). (2012). Sea Girt Pump Station Mobile Enclosure: Improving the Environmental Infrastructure of a Small Coastal community, Sea Girt Avenue Pump Station Reconstruction. Retrieved from https://www.smrsa.org/innovative-designs/

United States Environmental Protection Agency (EPA). (2015). Adaptation Strategies Guide for Water Utilities. Retrieved from https://www.epa.gov/sites/default/files/2015-04/documents/updated_adaptation_strategies_guide_for_water_utilities.pdf

EPA. Creating Resilient Water Utilities (CRWU). (2023). Initiative. https://www.epa.gov/crwuYohe, G. & Leichenko, R. (2010). Chapter 2: Adopting a risk-based approach*. Annals of the New York Academy of Sciences*, 1196, 29–40. Retrieved from https://nyaspubs.onlinelibrary.wiley.com/doi/10.1111/j.1749-6632.2009.05310.x

Zhang, Wenxing. (2019). Adaptive Planning of Stormwater Management Measures to Mitigate Pluvial Flooding under Climatic and Socio-Economic Uncertainties. Delft University of Technology and the National University of Singapore. Retrieved from https://repository.tudelft.nl/islandora/object/uuid:cd6aa934-db29-4193-b242-0f89b70b824f?collection=education

Vertical Control Datums AIR Sheet

AIR SHEET – VERTICAL DATUMS

OVERVIEW

A datum is a standard reference position or level that measurements are taken from. There are horizontal datums and vertical datums. As the first national vertical control datum, the **National Geodetic Vertical Datum of 1929 (NGVD29)** has been used by surveyors and engineers for most of the 20th century. The most recent update is the **North American Vertical Datum of 1988 (NAVD88).** In 2022, NAVD88 will be replaced by a new and more accurate vertical control datum.

The City of Philadelphia adopted their own local **City Datum**, known as **Philadelphia Vertical Datum (PVD)**. Currently, City Datum is maintained by the Streets Department Survey Bureau and is the official datum for all municipal infrastructure. PWD uses City Datum for linear assets but has its own datum--**Plant Datum—**for its drinking water treatment plants and water pollution control plants. Plant Datum was created to avoid the use of negative elevations in design (e.g. considering tidal datums).

CONVERSIONS

CCAP provides all coastal flood information using NAVD88 as it is the nationally vetted vertical control datum. It is also important that NAVD88 is used for floodplain management because it is a standard that is consistent from place to place—i.e. what is 4 ft. NAVD88 in Philadelphia will be the same as 4ft. NAVD88 in Camden. Having this vertical continuity is key to understanding where flood waters will go as they rise and reach farther inland.

*Conversions for vertical datums can vary spatially

Due to different vertical standards for each survey district in Philadelphia, **the conversion factor between the City Datum to NAVD88 or NGVD29 will vary by location within the city**. When a high level of accuracy is necessary, elevations in City Datum should be confirmed by the PWD Survey Unit. The Survey Unit regularly makes vertical elevation corrections in linear asset construction projects for consistency.

Conversion Factor Ranges and Suggested Values for Planning and Design

City Datum and NAVD88	***Conversion factors range between 4.15 and 4.85 feet.*** 4.68’ is the suggested conversion factor used in PWD’s wastewater master plan. *[City Datum = NAVD88-4.68’]*
City Datum and NGVD29	***Conversion factors range between 5.6 and 5.8 feet.*** 5.76’ is the suggested conversion factor to use for projects at PWD and matches city code. *[City Datum = NGVD29-5.76’]*
City Datum and Plant Datum	***Conversion is always 100 feet*** *[Plant Datum = City Datum + 100’]*
NGVD29 and NAVD88	***Conversion varies spatially***. Conversions calculated using NOAA VERTCON[1] at geographic coordinates of NOAA Tide Station #8545240. *[NAVD88 = NGVD29-1.08’]*

However, as noted above, PWD and other city agencies do not always work with NAVD88 and therefore, conversions are needed. It should also be noted that some FEMA flood insurance maps (including Philadelphia’s) use the outdated national vertical control datum NGVD29, requiring yet another conversion. When using City Datum or converting to or from City Datum, elevations should be examined closely because vertical benchmarks vary within the City (i.e. there is no one standard conversion factor between City Datum and other datums). Using the correct conversion is important since using the wrong value could make a project more vulnerable to flooding.

While there is no single accurate conversion between the vertical datums in Philadelphia, the CCAP worked with PWD staff to confirm average conversion factors as a general guide. The table to the left provides conversion factor ranges and a suggested value for use in PWD Projects. The following page provides this information in a ‘Conversion Table Guide’ and a figure on the left is useful for understanding the conversions using Plant Datum as a reference point.

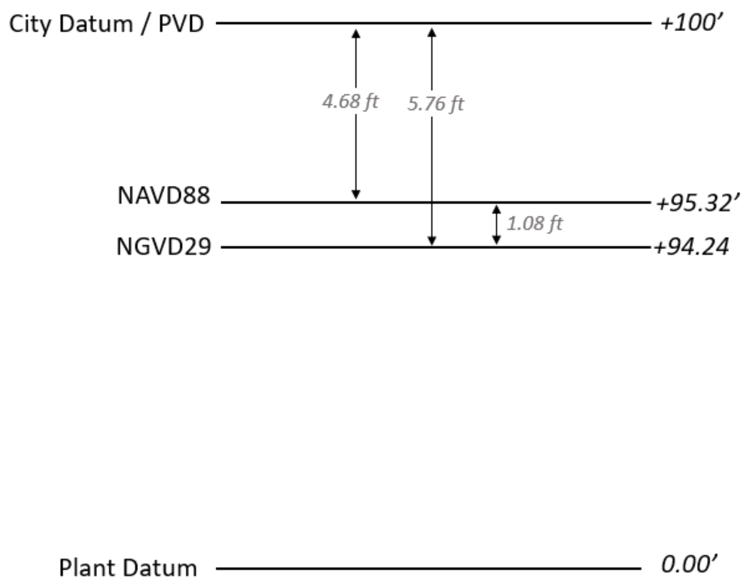
---

[1] NOAA VERTCON tool: http://www.ngs.noaa.gov/TOOLS/Vertcon/vertcon.html

Additional Information and Resources

AIR SHEET – VERTICAL DATUMS

Elevations Relative to Plant Datum



In Gray: General conversion values between City Datum, NAVD88, and NGVD29

Elevations relative to plant datum

Figure guide:

This Figure may not be intuitive and at first appear to be upside down.

Elevations in this figure are relative to **Plant Datum**, which is the reference point or the zero plane. To convert to any datum above it, a positive conversion factor must be added.

- Plant Datum
  - = NGVD29 + 94.24
  - = NAVD88 + 95.32
  - = City Datum +100

Vertical Datums Conversion Table

		INPUT DATUM			
	y x ➡	Plant Datum	NGVD29	NAVD88	City Datum
OUTPUT DATUM	Plant Datum	0.00	+94.24	+95.32	+100
	NGVD29	-94.24	0.00	+1.08	+5.76
	NAVD88	-95.32	-1.08	0.00	+4.68
	City Datum	-100	-5.76	-4.68	0.00

Conversion Table Guide:

This table and the instructions below can be used to convert between the four main vertical control datums used at PWD.

Row (x) represents the **input** datums that are to be converted. Column (y) represent the **output** datums that you want to covert to.

1. Find your input datum in row X
2. Find the output datum in column Y
3. Find the intersection between those two cells and ADD the conversion factor listed in that cell—be careful to use the correct algebraic sign—to determine what your final output datum value is.

Example Application

FEMA flood insurance rate map shows a base flood elevation for the area of concern at 10 ft. NGVD29. I need to convert this value to Plant Datum for a proposed project. Based on the table and instructions above, Plant Datum = my value in NGVD29 + 94.24. Therefore, 10 ft. NGVD29 is equivalent to 104.24 ft. Plant Datum.

Additional Resources:

- Excel Datum Conversion Tool
- Slide deck with additional datum information

Flood Mitigation Strategies AIR Sheet

AIR SHEET - Flood Mitigation Strategies

Common Flood Mitigation Adaptation Strategies

The most effective flood mitigation method is to relocate existing assets and locate new assets outside of the current and future floodplain. However, as mentioned in the *Climate-Resilient Planning and Design Guidance* document, this will often not be an option. Elevating the asset to or above the design flood elevation (DFE) is the next most effective flood mitigation method. When possible, all critical assets—whether existing or new—should be elevated. When relocation or elevation are not feasible or cost-effective, floodproofing is the appropriate, though least effective, alternative. Thus, the order of preference for adaptation actions is: 1) Relocate asset, 2) Elevate asset, and 3) Floodproofing asset.

a. Relocating assets

Locating or relocating the asset outside of the current or future floodplain is fairly straightforward, therefore, the focus of this AIR sheet is on the flood mitigation options of elevating and floodproofing.

b. Elevating assets

Elevating an asset to or above the DFE should always be explored as a possible flood mitigation option if relocation is not possible. Elevating an asset, in addition to providing protection from coastal inundation, can also protect the asset from additional forms of flooding, such as infrastructure-based flooding (e.g. a water main break) or flooding caused by groundwater changes (e.g. due to sea level rise).

New assets

All new projects should first consider elevating assets to or above the DFE, especially those with electrical or mechanical components or those that contain hazardous materials. Comparing the cost of elevating versus not elevating a new asset should be included in the alternatives analysis phase. If a new asset is anticipated to have a long useful life that extends beyond the year 2075, an AMP is needed to protect the asset from higher inundation risk expected in the future. This may include construction to a higher elevation to account for end-of-century sea level rise projections and uncertainty, or the flexibility to adapt design and construction later to guard against inundation.

Existing assets

Any critical asset, especially those with electrical or mechanical components, that is already in operation and within the current or future floodplain should be elevated if possible. However, retroactively modifying an asset to raise its elevation may be cost-prohibitive or impossible. The best time to consider elevating an existing asset is when it is a candidate for repair or replacement or when the flood risk is deemed unacceptable. Likely there are many PWD assets that fall into this category and a systematic way to prioritize which assets are at the most risk is necessary. Ideally this will be done with an asset-by-asset risk assessment for the entire system or facility, such as a Water Pollution Control Plant.[1]

---

[1] The Climate Change Adaptation Program (CCAP) is coordinating with other PWD programs and staff to conduct comprehensive, asset-by-asset risk assessments at PWD facilities that are vulnerable to inundation from sea level rise and storm surge. As part of this effort, CCAP has developed an *Asset Risk Assessment Worksheet* that staff can utilize as a guide to identify and prioritize assets which are at the most risk.

Assessing risks at different scales of impact must be considered in the planning process as well. For instance, each Water Pollution Control Plant will have a different level of risk to future climate changes due to its location. An initial, high-level assessment prioritizes which facilities to focus floodproofing efforts. Within each facility, various assets will be at more risk than others and can be individually prioritized for retrofitting. The first choice in protecting assets is to raise existing assets, but when this is not possible, other measures such as floodproofing should be considered, along with plans for implementation.

c. *Floodproofing*

If relocating or elevating the critical asset is impossible or cost prohibitive, floodproofing should be implemented. Here we use the term “floodproofing” as a catch-all term for multiple flexible strategies to protect an asset against flood inundation, such as sealing building openings, installing a flood gate, or sandbagging. When choosing floodproofing strategies to meet the DFE, it is important to understand dependencies and consider flood pathways. Some common flood pathways—flow and entry points where surface ground flow could enter buildings or reach assets—are provided in Figure 1. Some flood pathways, such as doorways, windows, vents and grates can be easy to identify, but understanding the often-complex system of underground tunnels, pipes, HVAC ducts and electrical conduits can be more difficult and may require looking at plan sets. It is also important to note that in many cases, floodproofing measures fail due to unknown flood pathways, material/mechanical failures, or operator/installation error. For example, a flood gate could be installed to protect doorways but if it is not activated in time, flooding may still occur.

Figure 1. Common flood pathway examples from the New York City Wastewater Resiliency Plan (2013).

Generally, when protecting critical assets, FEMA recommends employing dry floodproofing[2] methods, as opposed to wet floodproofing[3] methods. Dry floodproofing involves completely sealing the building or asset below the DFE, cutting off flood pathways to prevent the entry of coastal floodwaters. Dry floodproofing will generally include sealing doors, windows, entryways and exterior walls and installing protective gaskets or coverings at openings. Dry floodproofing methods may be permanent and costly, such as a floodgate, or temporary and less expensive, such as sandbagging.

In addition to dry floodproofing, various tools can help with flood mitigation when relocation or elevation are not options, such as installing sump pumps for any water that does find its way inside and protecting and tethering any equipment outside of buildings that could be buoyant and float away. Examples of floodproofing adaptation strategies chosen for New York City's Wastewater Resiliency Plan (NYC DEP, 2013) are provided in Figure 2.

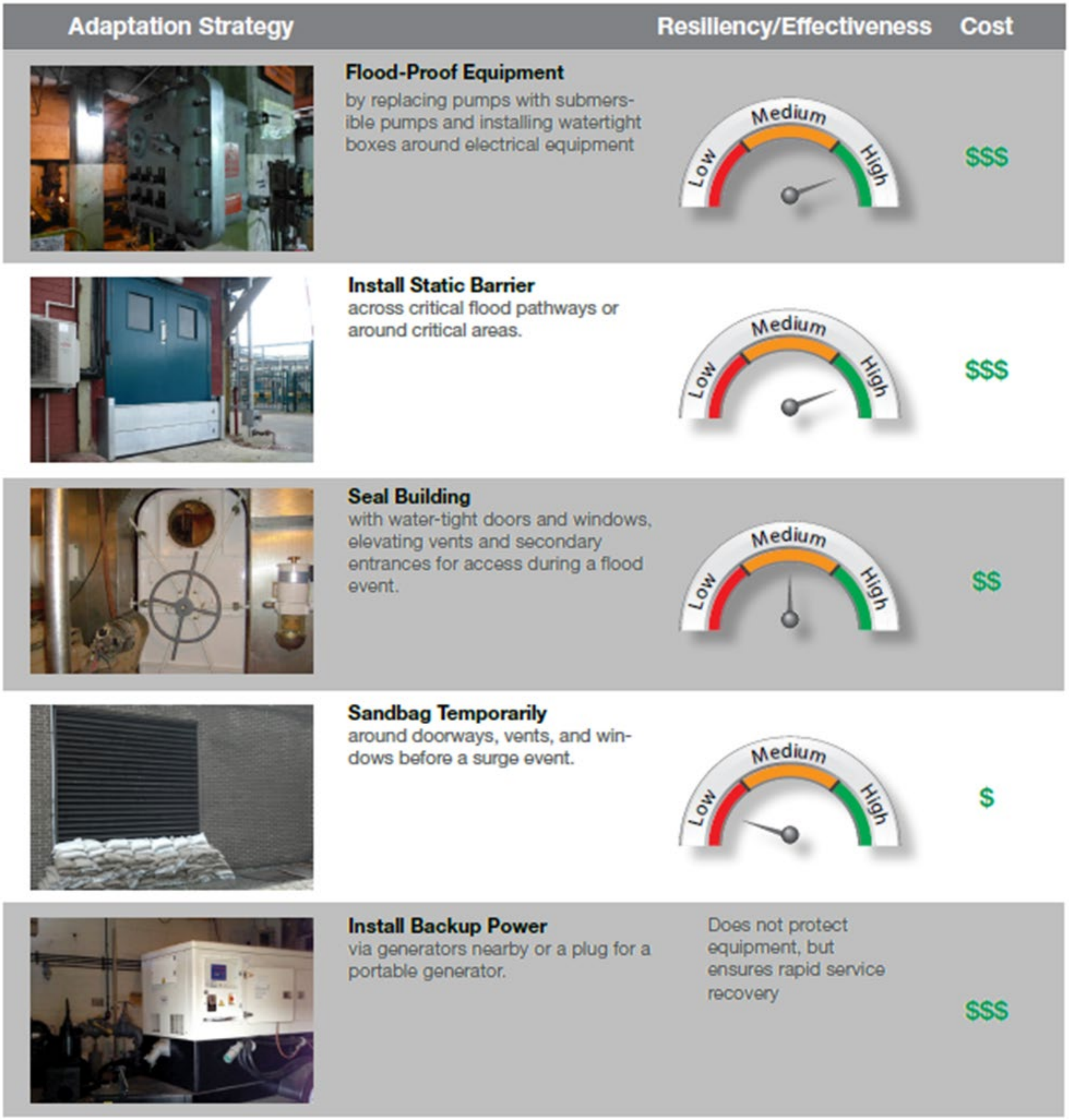
When developing plans that involve floodproofing, it is necessary to understand the resources required to implement a particular measure when flooding is forecasted. These resources should be considered in context with the capital cost of construction for a comprehensive assessment of floodproofing options. For instance, although sandbagging may be less expensive than permanently raising an asset, there are additional resources required to forecast inundation events and to deploy personnel to fill and stack sandbags. In addition, if a temporary structure is not deployed in time – or deployed incorrectly – it may leave an asset vulnerable to inundation. When developing plans for temporary floodproofing measures, the full cost of physical materials and operational resources should be included in the action plan.

---

[2] Dry floodproofing prevents the entry of floodwaters (FEMA, 2013).

[3] Wet floodproofing allows floodwaters to enter the enclosed areas that are designed to temporarily hold water (FEMA, 2013).

AIR SHEET - Flood Mitigation Strategies



Adaptation Strategy		Resiliency/Effectiveness	Cost
	Flood-Proof Equipment by replacing pumps with submersible pumps and installing watertight boxes around electrical equipment		$$$
	Install Static Barrier across critical flood pathways or around critical areas.		$$$
	Seal Building with water-tight doors and windows, elevating vents and secondary entrances for access during a flood event.		$$
	Sandbag Temporarily around doorways, vents, and windows before a surge event.		$
	Install Backup Power via generators nearby or a plug for a portable generator.	Does not protect equipment, but ensures rapid service recovery	$$$

Figure 2. Examples of floodproofing adaptation strategies adapted from the NYC Wastewater Resiliency Plan (2013).

Cloudburst Management Examples AIR Sheet

AIR SHEET- Cloudburst Management Strategies

Overview

CCAP precipitation products, including future time series and future Intensity Duration Frequency (IDF) curves, can be applied to assessments that seek to identify strategies to reduce risks to infrastructure, property, and health and safety that result from cloudburst events.

Philadelphia faces increasing risks from the impacts of global climate change. According to CCAP analysis, Philadelphia is projected to have a warmer and wetter future with an increase in the number and intensity of extreme storm events. Recent intense storms in Philadelphia, some with return periods of 500 and 1,000 years, demonstrate that the city's residents, public and private property, and infrastructure already face risks from extreme precipitation. Reducing these risks may require the use of innovative adaptation methods that go beyond traditional stormwater management solutions.

These heavy rainfall events (also known as "cloudbursts") usually occur within a short period of time and can inundate urban areas, threaten human health and safety and potentially cause severe damage, making the need for innovative cloudburst management solutions urgent for our region. Cities in the U.S. like New York and Phoenix, as well as cities abroad like Copenhagen, have developed and implemented cloudburst management projects and plans that use a variety of strategies to alleviate flooding impacts that result from cloudburst events.

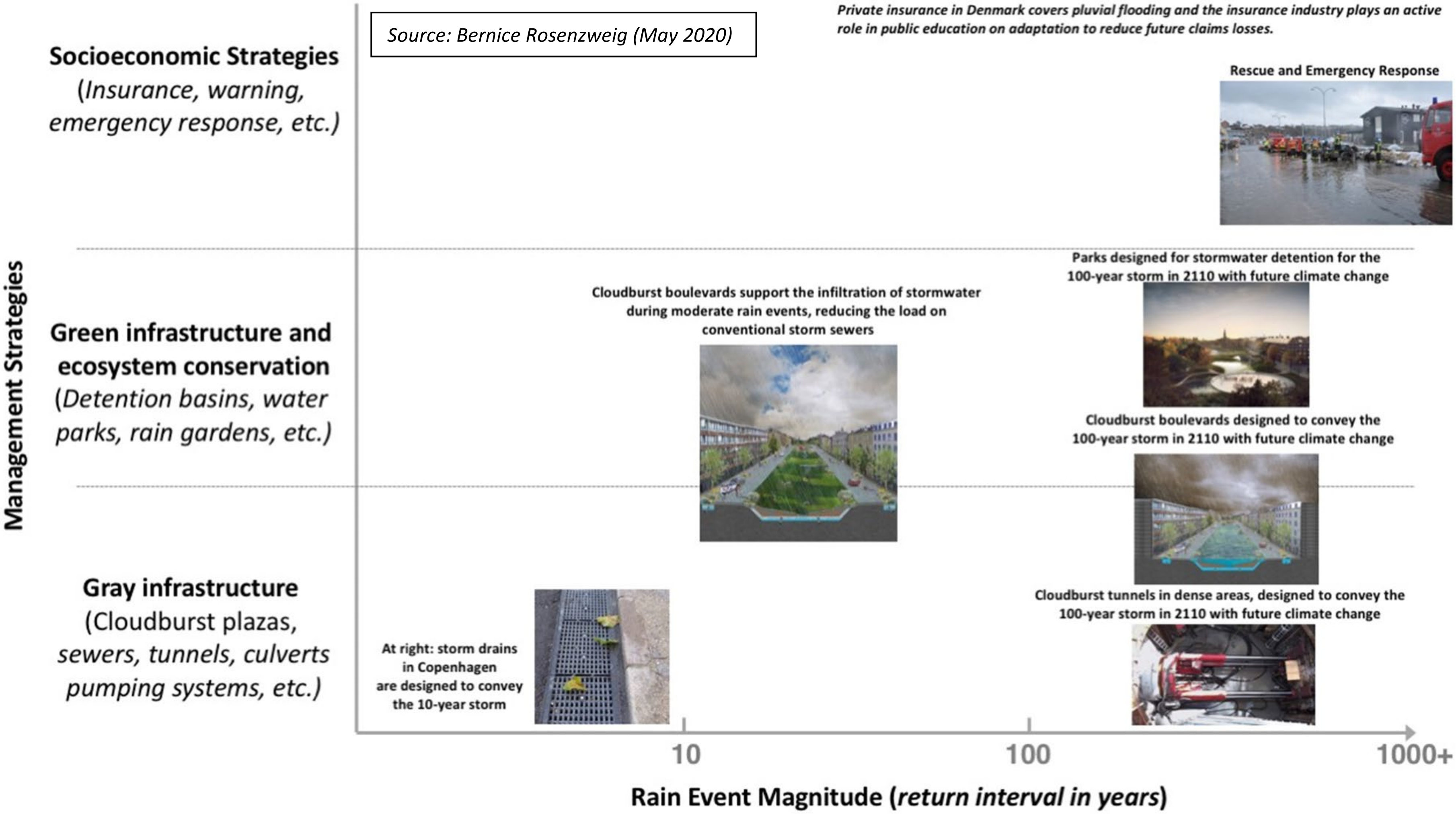
Conventional pipe systems and traditional drainage solutions that convey or store stormwater underground are not always viable or adequate solutions for extreme weather events. They tend to be costly to build, cause massive disruption during construction and are difficult to site as other utilities and city infrastructure occupy space underground. Cities around the world are developing best practices to manage cloudburst events using combinations of gray and green infrastructure called "Blue-Green" solutions. Cloudburst management plans often employ networks of large nature-based projects in addition to above-ground storage and conveyance solutions (e.g. cloudburst streets or retention areas in squares or parks) that manage stormwater at the source, significantly reducing the strain on already overburdened stormwater drainage systems.

Below are examples of cloudburst management plans from Copenhagen, New York and Phoenix. These case studies were summarized by the Urban Resilience to Extremes Sustainability Research Network (UREx SRN), a group of researchers who supports efforts to make cities more resilient by promoting flexible, adaptable, socially equitable, and ecologically based infrastructure in the face of extreme events and climate uncertainty. The images presented below were taken from a presentation given to the Water Utility Climate

Alliance (WUCA) Stormwater and Wastewater Committee by Bernice Rosenzweig (May 2020) as part of her work for UREx SRN on cloudburst management.

Cloudburst Planning in Copenhagen, Denmark

As part of Copenhagen's Climate Action Plan, the City developed a Cloudburst Management Plan that focuses on solutions that combine large-scale green and grey stormwater infrastructure that manage stormwater above ground while utilizing underground tunnels where needed. The City of Copenhagen used projected rainfall intensities for a 100-year event in 2100 to determine the level of service for their cloudburst management infrastructure design.



Private insurance in Denmark covers pluvial flooding and the insurance industry plays an active role in public education on adaptation to reduce future claims losses.

Parks designed for stormwater detention for the 100-year storm in 2110 with future climate change

Cloudburst boulevards support the infiltration of stormwater during moderate rain events, reducing the load on conventional storm sewers

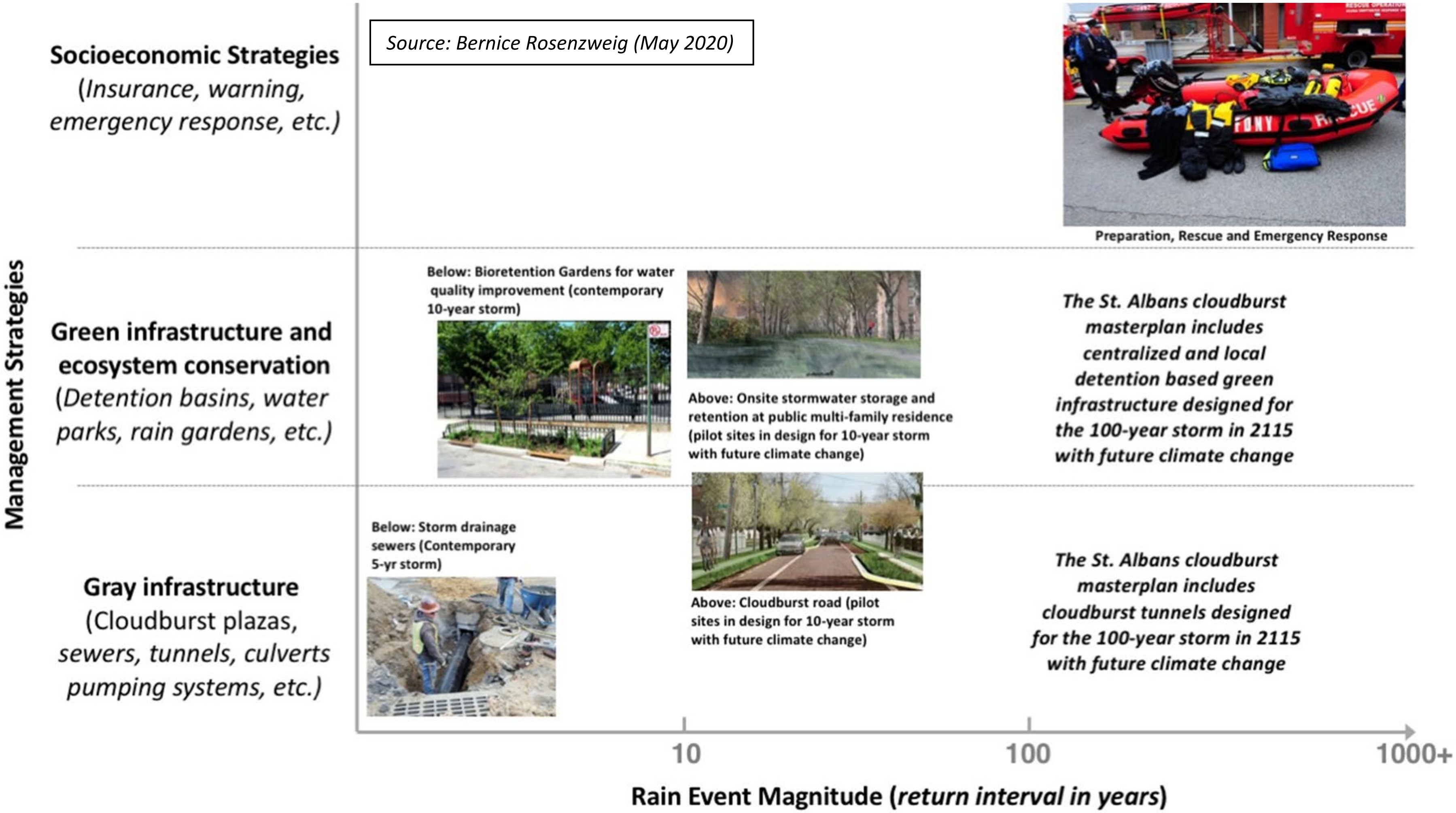
Cloudburst boulevards designed to convey the 100-year storm in 2110 with future climate change

Cloudburst tunnels in dense areas, designed to convey the 100-year storm in 2110 with future climate change

At right: storm drains in Copenhagen are designed to convey the 10-year storm

Cloudburst Planning in Southeast Queens, New York

The New York City DEP developed innovative cloudburst management solutions by conducting the Cloudburst Resiliency Planning Study, focusing on a pilot area in Southeast Queens (St. Albans) to provide insight on ways to mitigate inland flooding and accommodate future increases in rainfall intensity resulting from climate change. The pilot involved integration of underground drainage systems with surface drainage systems (onsite retention and cloudburst roads) to enhance stormwater management. The St. Albans pilot includes a design of Blue-Green Infrastructure to handle a 100-year storm in 2115 that replaces the need for a pumping station.



Source: Bernice Rosenzweig (May 2020)

Management Strategies

Socioeconomic Strategies
(*Insurance, warning, emergency response, etc.*)

Preparation, Rescue and Emergency Response

Green infrastructure and ecosystem conservation
(*Detention basins, water parks, rain gardens, etc.*)

Below: Bioretention Gardens for water quality improvement (contemporary 10-year storm)

Above: Onsite stormwater storage and retention at public multi-family residence (pilot sites in design for 10-year storm with future climate change)

The St. Albans cloudburst masterplan includes centralized and local detention based green infrastructure designed for the 100-year storm in 2115 with future climate change

Gray infrastructure
(Cloudburst plazas, *sewers, tunnels, culverts pumping systems, etc.*)

Below: Storm drainage sewers (Contemporary 5-yr storm)

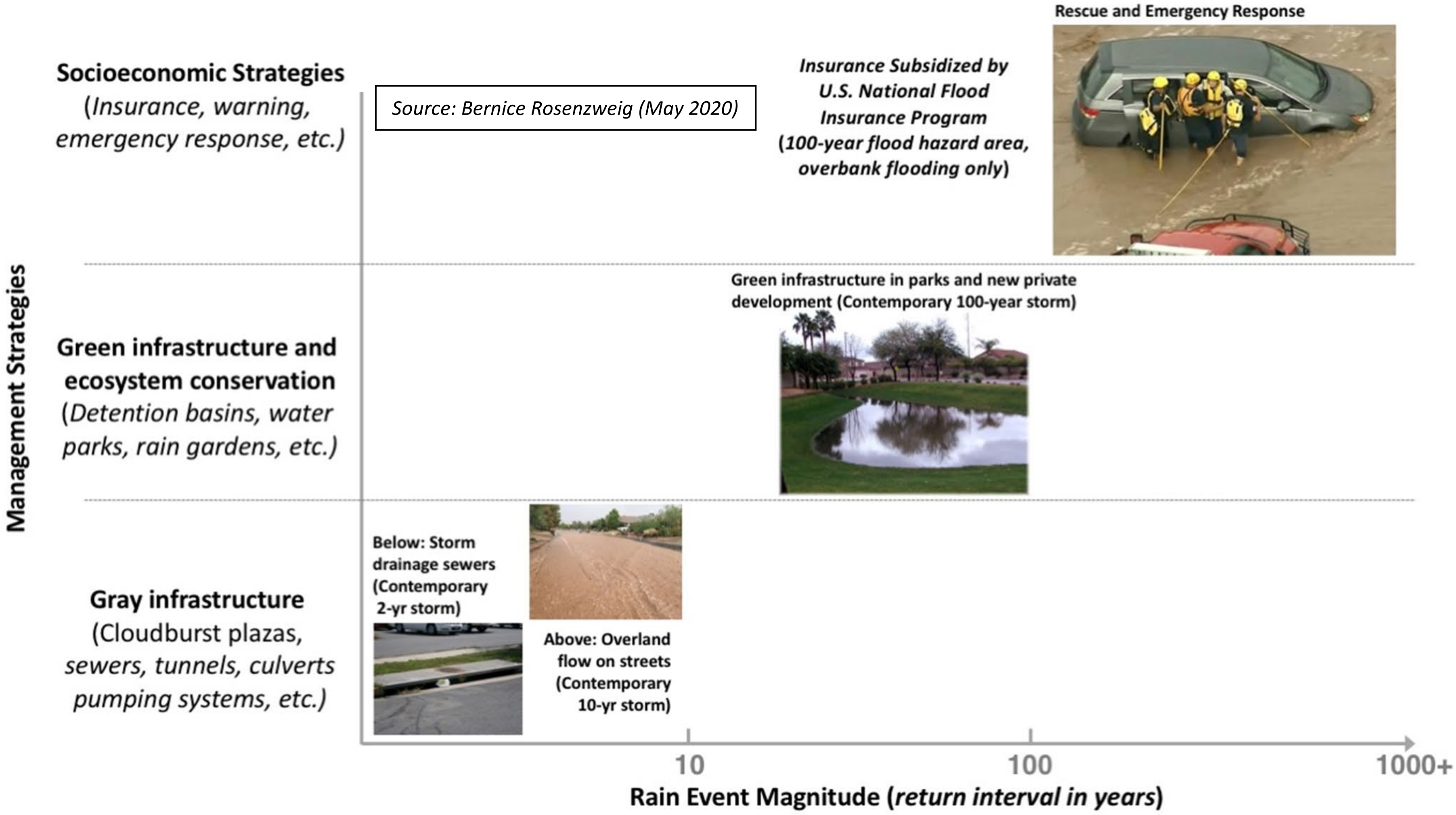
Above: Cloudburst road (pilot sites in design for 10-year storm with future climate change)

The St. Albans cloudburst masterplan includes cloudburst tunnels designed for the 100-year storm in 2115 with future climate change

Rain Event Magnitude (*return interval in years*)

Cloudburst Planning in Phoenix, Arizona

The City of Phoenix integrates the management of short-duration intense rainfall events into regional flood management planning. In response to a severe flash flooding event in 1972, the City of Phoenix adopted an ordinance that requires the onsite retention of stormwater from the 10-year storm for new subdivisions and also updated its street design guidelines to include the use of an ‘inverted crown’ in flood-prone areas to facilitate the conveyance of stormwater. In response to additional flooding events between 1978 and 1980, the City of Phoenix implemented updated design standards that require onsite stormwater retention of the 2-hour, 100-year storm.



Future Design Storms (Alternating Block Method) AIR Sheet

Overview

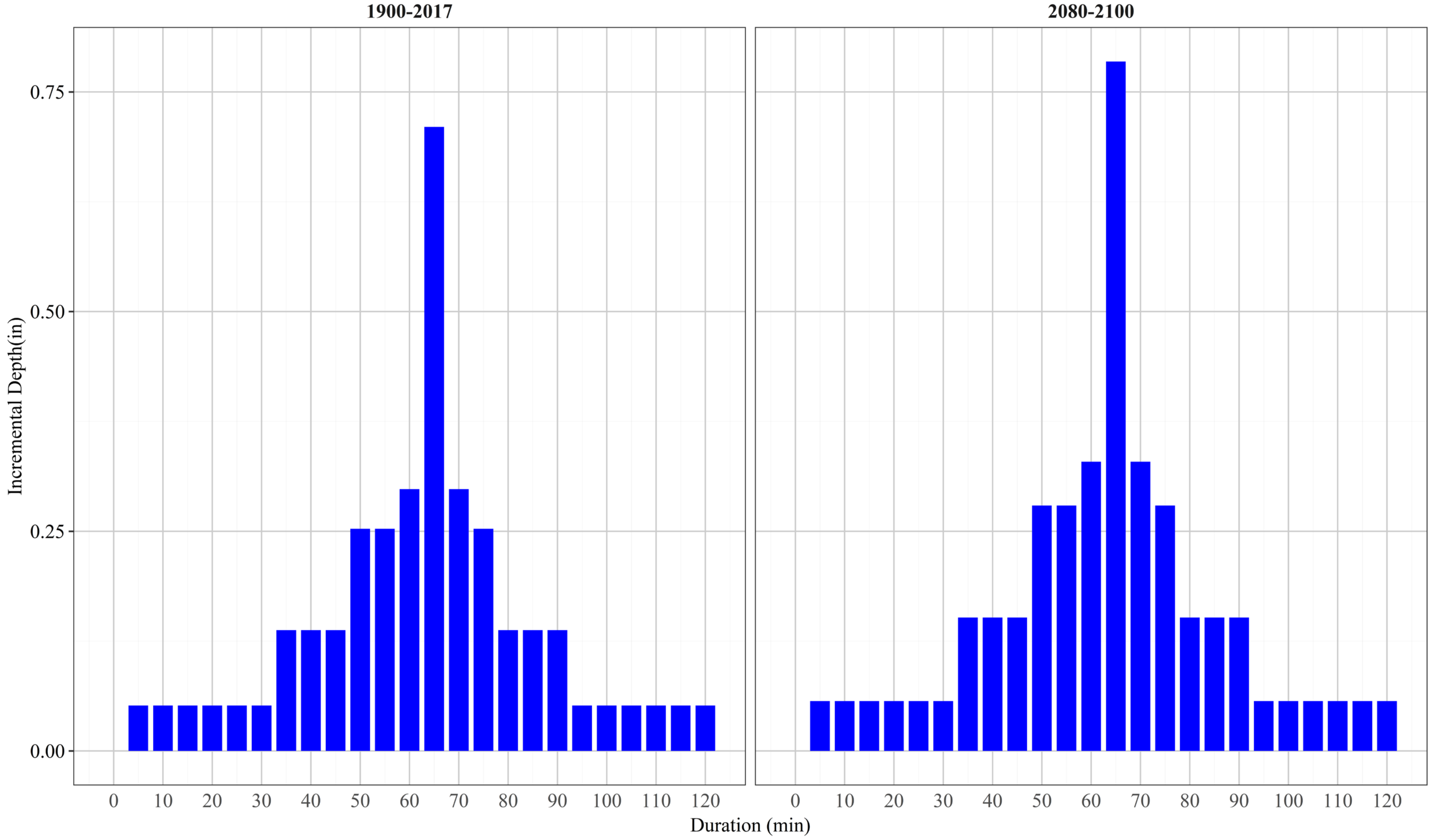
The Philadelphia Water Department (PWD) uses design storms, which are characterized by hyetographs (distributions of rainfall intensity or depth over time), for planning and designing sewers and flood risk management infrastructure. The size of the design storm that is used corresponds to the level of service being provided and reflects a perceived acceptable level of risk for infrastructure damage or failure. As climate change continues to increase the frequency and intensity of storms, it is imperative that PWD understand the changes to current design storms, so that existing levels of service can be maintained under future conditions of more extreme rainfall.

Below is an example that demonstrates the change in the 2-hr, 100-year design storm from observed (1900-2017) to future (2080-2100) periods, using the Alternating Block Method. The plots show that by the end of the century, the volume and intensity of a 2-hr, 100-yr storm will increase. The same method can be applied to other design storms to determine the projected changes for different time periods using the depth and intensities provided by CCAP in Appendix C of the *Climate Resilient Planning and Design Guidance* document.

A design storm is synthesized from segments of extreme rainfall taken from many actual storm events in the period of record. Due to the effects of climate change, **the historical record will not accurately reflect the frequency and intensities of future storms**. Consequently, wastewater and stormwater planners and engineers need to utilize **future precipitation projections** to analyze changes in existing design storms so that level of service goals can continue to be met.

CCAP's high resolution future precipitation time series and precipitation frequency estimates can be applied to analyze future changes to design storms.

Comparison of Observed and Projected Precipitation at PHL for 2-hr, 100-yr Design Storm



Appendix B

Appendix B-1 Sea Level Rise Annual Interpolation Table (Low and Primary Planning Sea Level Rise Scenarios)

Annual Interpolation of NASA SLR Scenarios		
Year	**PWD Low Scenario (ft.)**	**PWD Primary Planning Scenario (ft.)**
	NASA Int-Low	*NASA Int-High*
2000	0.00	0.00
2001	0.01	0.01
2002	0.03	0.03
2003	0.05	0.05
2004	0.07	0.07
2005	0.09	0.09
2006	0.11	0.11
2007	0.13	0.13
2008	0.16	0.15
2009	0.18	0.17
2010	0.20	0.19
2011	0.22	0.21
2012	0.25	0.24
2013	0.27	0.26
2014	0.29	0.28
2015	0.32	0.31
2016	0.34	0.33
2017	0.36	0.36
2018	0.39	0.38
2019	0.41	0.41
2020	0.44	0.44
2021	0.46	0.46
2022	0.49	0.49
2023	0.51	0.52
2024	0.54	0.55
2025	0.56	0.58
2026	0.59	0.61
2027	0.61	0.64
2028	0.64	0.67
2029	0.66	0.70

2030	0.69	0.73
2031	0.71	0.77
2032	0.74	0.80
2033	0.76	0.84
2034	0.79	0.87
2035	0.82	0.91
2036	0.84	0.94
2037	0.87	0.98
2038	0.89	1.02
2039	0.92	1.06
2040	0.95	1.10
2041	0.97	1.14
2042	1.00	1.18
2043	1.03	1.22
2044	1.05	1.26
2045	1.08	1.31
2046	1.11	1.35
2047	1.13	1.40
2048	1.16	1.44
2049	1.19	1.49
2050	1.21	1.53
2051	1.24	1.58
2052	1.26	1.63
2053	1.29	1.68
2054	1.32	1.73
2055	1.34	1.78
2056	1.37	1.84
2057	1.40	1.89
2058	1.42	1.94
2059	1.45	2.00
2060	1.47	2.05
2061	1.50	2.11
2062	1.53	2.17
2063	1.55	2.23
2064	1.58	2.29
2065	1.60	2.35
2066	1.63	2.41
2067	1.66	2.47
2068	1.68	2.54

2069	1.71	2.60
2070	1.73	2.67
2071	1.76	2.73
2072	1.78	2.80
2073	1.81	2.87
2074	1.83	2.94
2075	1.86	3.01
2076	1.88	3.08
2077	1.91	3.15
2078	1.93	3.23
2079	1.96	3.30
2080	1.98	3.38
2081	2.00	3.45
2082	2.03	3.53
2083	2.05	3.61
2084	2.07	3.69
2085	2.10	3.77
2086	2.12	3.86
2087	2.14	3.94
2088	2.17	4.02
2089	2.19	4.11
2090	2.21	4.20
2091	2.23	4.29
2092	2.25	4.37
2093	2.27	4.47
2094	2.30	4.56
2095	2.32	4.65
2096	2.34	4.75
2097	2.36	4.84
2098	2.38	4.94
2099	2.40	5.04
2100	2.42	5.14
2101	2.44	5.24
2102	2.46	5.34
2103	2.48	5.44
2104	2.50	5.55
2105	2.51	5.65
2106	2.53	5.76
2107	2.55	5.87

2108	2.57	5.98
2109	2.59	6.09
2110	2.60	6.20
2111	2.62	6.31
2112	2.64	6.43
2113	2.65	6.55
2114	2.67	6.66
2115	2.68	6.78
2116	2.70	6.90
2117	2.71	7.03
2118	2.73	7.15
2119	2.74	7.27
2120	2.75	7.40
2121	2.77	7.53
2122	2.78	7.66
2123	2.79	7.79
2124	2.81	7.92
2125	2.82	8.06
2126	2.83	8.19
2127	2.84	8.33
2128	2.85	8.47
2129	2.86	8.61
2130	2.87	8.75
2131	2.88	8.89
2132	2.89	9.03
2133	2.90	9.18
2134	2.91	9.33
2135	2.91	9.48
2136	2.92	9.63
2137	2.93	9.78
2138	2.93	9.93
2139	2.94	10.09
2140	2.94	10.25
2141	2.95	10.40
2142	2.95	10.56
2143	2.96	10.73
2144	2.96	10.89
2145	2.96	11.06
2146	2.97	11.22

2147	2.97	11.39
2148	2.97	11.56
2149	2.97	11.73
2150	2.97	11.91

Appendix B-2 Future Tide & Storm Tide Levels

Low SLR Scenario

Future Tide and Storm Tide Levels for Philadelphia **(NASA Intermediate-Low SLR Scenario)**
All values in ft. NAVD88

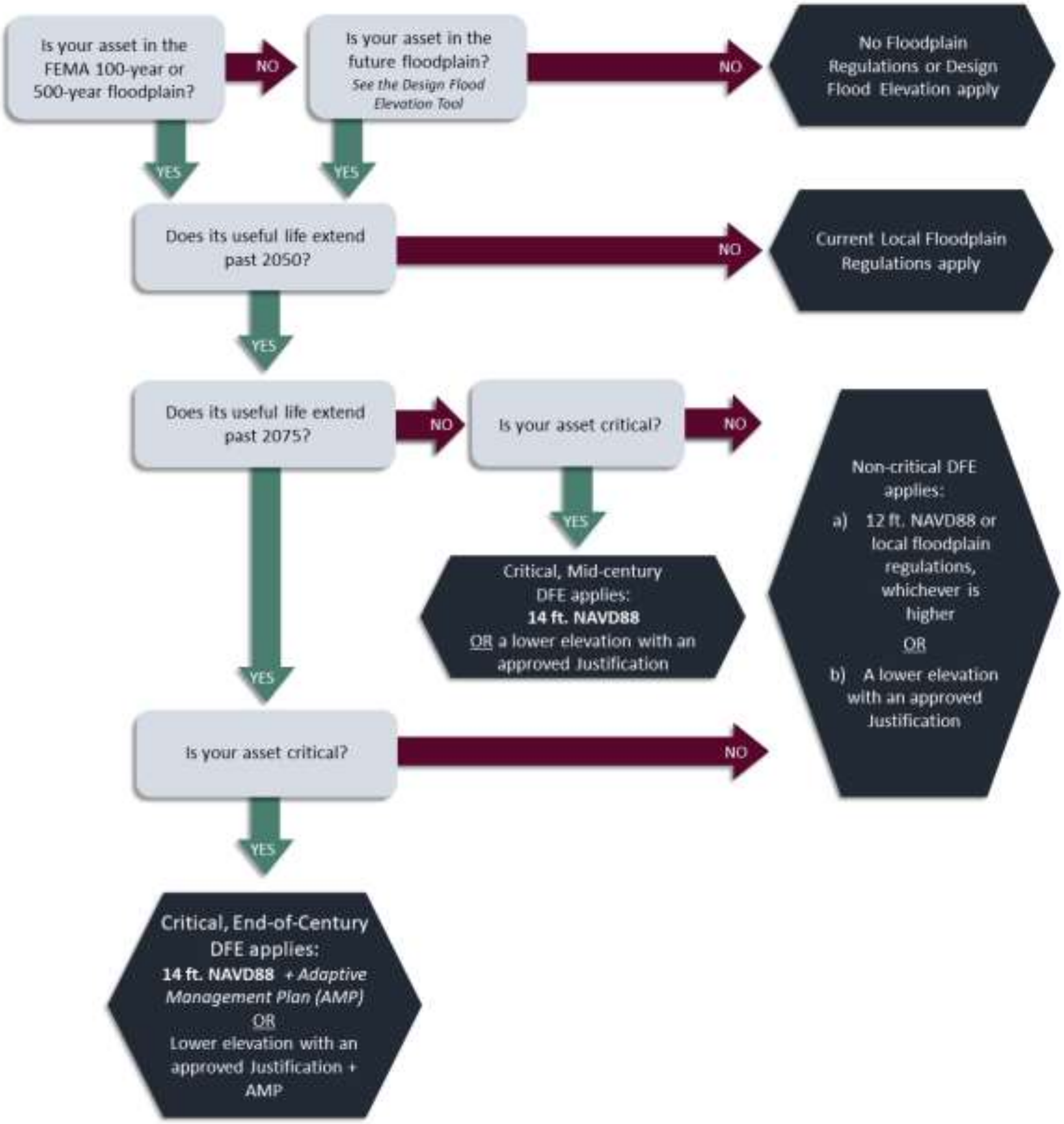
	Baseline (year 2000)	**Near-term (2030s)**	**Mid-century (2060s)**	**End-of-century (2100)**	
		+ 0.69 ft. SLR	***+ 1.48 ft. SLR***	***+2.43 ft. SLR***	
MLLW (mean lower-low water)	-3.03	-2.34	-1.55	-0.6	***Permanent inundation*** *- occurs within the regular predicted tide cycle*
MLW (mean low water)	-2.84	-2.15	-1.36	-0.41	
MSL (mean sea level)	0.46	1.15	1.94	2.89	
MHW (mean high water)	3.26	3.95	4.74	5.69	
MHHW (mean higher-high water)	3.66	4.35	5.14	6.09	
HAT (highest astronomical Tide)	4.9	5.59	6.38	7.33	
Storm tide levels below place storm surge on top of Mean Higher High Water					
50% annual chance storm (+2.25 ft.)	5.91	6.60	7.39	8.34	***Temporary inundation –*** *occurs during extreme storm events (50%-1% annual chance)*
20% annual chance storm (+2.71 ft.)	6.37	7.06	7.85	8.80	
10% annual chance storm (+3.11 ft.)	6.77	7.46	8.25	9.20	
4% annual chance storm (+3.75 ft.)	7.41	8.10	8.89	9.84	
2% annual chance storm (+4.32 ft.)	7.98	8.67	9.46	10.41	
1% annual chance storm (+4.97 ft)	8.63	9.32	10.11	11.06	

PWD Primary Planning SLR Scenario

Future Tide and Storm Tide Levels for Philadelphia **(NASA Intermediate-High SLR Scenario)**
All values in ft. NAVD88

	Baseline (year 2000)	**Near-term (2030s)**	**Mid-century (2060s)**	**End-of-century (2100)**	
		+0.75 ft. SLR	***+2.05 ft. SLR***	***+5.12 ft. SLR***	
MLLW (mean lower-low water)	-3.03	-2.28	-0.98	2.09	***Permanent inundation*** *- occurs within the regular predicted tide cycle*
MLW (mean low water)	-2.84	-2.09	-0.79	2.28	
MSL (mean sea level)	0.46	1.21	2.51	5.58	
MHW (mean high water)	3.26	4.01	5.31	8.38	
MHHW (mean higher-high water)	3.66	4.41	5.71	8.78	
HAT (highest astronomical Tide)	4.9	5.65	6.95	10.02	
Storm tide levels below place storm surge on top of Mean Higher High Water					
50% annual chance storm (+2.25 ft.)	5.91	6.66	7.96	11.03	***Temporary inundation –*** *occurs during extreme storm events (50%-1% annual chance)*
20% annual chance storm (+2.71 ft.)	6.37	7.12	8.42	11.49	
10% annual chance storm (+3.11 ft.)	6.77	7.52	8.82	11.89	
4% annual chance storm (+3.75 ft.)	7.41	8.16	9.46	12.53	
2% annual chance storm (+4.32 ft.)	7.98	8.73	10.03	13.10	
1% annual chance storm (+4.97 ft)	8.63	9.38	10.68	13.75	

Appendix B-3 Design Flood Elevation Flowchart



**** By default, all PWD projects are assumed to be critical and the non-critical DFE can only be used with approval from a Core Review Committee.***

Appendix C

Appendix C-1 Observed and Future Intensity-Duration-Frequency Tables

1900-2022 Precipitation Intensity Estimates (in/hr)						
	2-yr	**5-yr**	**10-yr**	**25-yr**	**50-yr**	**100-yr**
5-min	5.27	5.92	6.54	7.50	8.37	9.46
10-min	4.21	4.74	5.23	5.98	6.66	7.52
15-min	3.53	4.00	4.41	5.05	5.63	6.33
30-min	2.44	2.84	3.19	3.74	4.24	4.85
1-hr	1.53	1.82	2.08	2.49	2.87	3.34
2-hr	0.93	1.12	1.29	1.53	1.76	2.01
3-hr	0.68	0.84	0.98	1.20	1.41	1.66
6-hr	0.41	0.49	0.57	0.69	0.81	0.96
12-hr	0.24	0.29	0.34	0.41	0.48	0.56
24-hr	0.14	0.17	0.20	0.24	0.27	0.31

2020 Precipitation Intensity Estimates (in/hr)						
	2-yr	**5-yr**	**10-yr**	**25-yr**	**50-yr**	**100-yr**
5-min	6.17	6.96	7.72	8.90	9.98	11.33
10-min	4.93	5.57	6.18	7.09	7.94	9.00
15-min	4.13	4.70	5.21	5.99	6.71	7.58
30-min	2.85	3.34	3.77	4.44	5.05	5.81
1-hr	1.79	2.14	2.46	2.95	3.42	4.00
2-hr	1.07	1.31	1.51	1.80	2.08	2.39
3-hr	0.78	0.97	1.14	1.41	1.66	1.96
6-hr	0.46	0.57	0.66	0.81	0.95	1.12
12-hr	0.27	0.33	0.39	0.48	0.56	0.66
24-hr	0.16	0.19	0.22	0.27	0.31	0.37

2030 Precipitation Intensity Estimates (in/hr)						
	2-yr	**5-yr**	**10-yr**	**25-yr**	**50-yr**	**100-yr**
5-min	6.36	7.19	7.99	9.21	10.33	11.74
10-min	5.09	5.76	6.38	7.34	8.23	9.33
15-min	4.26	4.85	5.38	6.20	6.94	7.86
30-min	2.95	3.45	3.90	4.59	5.23	6.02
1-hr	1.85	2.21	2.54	3.06	3.54	4.15
2-hr	1.11	1.35	1.56	1.86	2.15	2.48
3-hr	0.80	1.00	1.18	1.45	1.72	2.03
6-hr	0.48	0.58	0.68	0.83	0.98	1.16
12-hr	0.28	0.34	0.40	0.49	0.58	0.68
24-hr	0.16	0.20	0.23	0.28	0.32	0.38

2040 Precipitation Intensity Estimates (in/hr)						
	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
5-min	6.58	7.44	8.27	9.55	10.72	12.19
10-min	5.26	5.96	6.61	7.61	8.54	9.69
15-min	4.41	5.02	5.58	6.43	7.20	8.16
30-min	3.05	3.57	4.04	4.76	5.43	6.25
1-hr	1.91	2.29	2.63	3.17	3.68	4.30
2-hr	1.14	1.39	1.61	1.93	2.23	2.57
3-hr	0.83	1.03	1.22	1.50	1.78	2.10
6-hr	0.49	0.60	0.70	0.86	1.01	1.20
12-hr	0.28	0.35	0.41	0.51	0.59	0.70
24-hr	0.16	0.20	0.23	0.29	0.33	0.39

2050 Precipitation Intensity Estimates (in/hr)						
	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
5-min	7.06	7.99	8.90	10.29	11.57	13.18
10-min	5.64	6.40	7.12	8.20	9.22	10.47
15-min	4.73	5.40	6.00	6.93	7.78	8.83
30-min	3.27	3.83	4.35	5.13	5.86	6.76
1-hr	2.05	2.46	2.83	3.42	3.97	4.66
2-hr	1.22	1.49	1.73	2.08	2.40	2.78
3-hr	0.88	1.10	1.30	1.61	1.91	2.27
6-hr	0.52	0.64	0.75	0.92	1.09	1.29
12-hr	0.30	0.37	0.44	0.54	0.64	0.75
24-hr	0.17	0.21	0.25	0.30	0.36	0.42

2060 Precipitation Intensity Estimates (in/hr)						
	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
5-min	7.37	8.35	9.31	10.78	12.14	13.84
10-min	5.89	6.69	7.45	8.59	9.66	10.99
15-min	4.94	5.64	6.28	7.26	8.16	9.26
30-min	3.41	4.01	4.55	5.38	6.14	7.09
1-hr	2.14	2.57	2.96	3.58	4.16	4.89
2-hr	1.27	1.56	1.81	2.17	2.52	2.91
3-hr	0.97	1.22	1.44	1.79	2.13	2.53
6-hr	0.54	0.66	0.78	0.96	1.14	1.35
12-hr	0.31	0.39	0.46	0.56	0.66	0.79
24-hr	0.18	0.22	0.26	0.32	0.37	0.43

2070 Precipitation Intensity Estimates (in/hr)

	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
5-min	7.84	8.89	9.93	11.51	12.97	14.81
10-min	6.27	7.12	7.94	9.17	10.33	11.77
15-min	5.25	6.01	6.70	7.75	8.72	9.92
30-min	3.63	4.27	4.85	5.74	6.57	7.59
1-hr	2.28	2.74	3.16	3.82	4.45	5.23
2-hr	1.35	1.66	1.92	2.31	2.68	3.11
3-hr	0.97	1.22	1.44	1.79	2.13	2.53
6-hr	0.57	0.70	0.82	1.02	1.21	1.44
12-hr	0.33	0.41	0.48	0.60	0.70	0.84
24-hr	0.19	0.23	0.27	0.33	0.39	0.46

2080 Precipitation Intensity Estimates (in/hr)

	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
5-min	8.01	9.10	10.16	11.78	13.29	15.18
10-min	6.41	7.29	8.13	9.39	10.58	12.06
15-min	5.37	6.14	6.85	7.93	8.93	10.16
30-min	3.71	4.37	4.97	5.88	6.73	7.78
1-hr	2.33	2.80	3.23	3.91	4.56	5.36
2-hr	1.38	1.69	1.96	2.37	2.75	3.18
3-hr	0.99	1.25	1.47	1.83	2.18	2.59
6-hr	0.58	0.72	0.84	1.04	1.24	1.47
12-hr	0.33	0.42	0.49	0.61	0.72	0.86
24-hr	0.19	0.24	0.28	0.34	0.40	0.47

2090 Precipitation Intensity Estimates (in/hr)

	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
5-min	8.56	9.74	10.89	12.64	14.27	16.32
10-min	6.85	7.80	8.71	10.07	11.37	12.97
15-min	5.74	6.57	7.34	8.51	9.59	10.93
30-min	3.96	4.67	5.32	6.30	7.22	8.37
1-hr	2.49	2.99	3.46	4.20	4.89	5.76
2-hr	1.47	1.81	2.10	2.54	2.95	3.42
3-hr	1.05	1.33	1.57	1.96	2.33	2.78
6-hr	0.62	0.76	0.89	1.11	1.32	1.58
12-hr	0.35	0.44	0.52	0.65	0.77	0.91
24-hr	0.20	0.25	0.30	0.36	0.43	0.50

Appendix C-2 Observed and Future Depth-Duration-Frequency Tables

1900-2020 Precipitation Depth Estimates (in)

	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
5-min	0.44	0.49	0.54	0.62	0.70	0.79
10-min	0.70	0.79	0.87	1.00	1.11	1.25
15-min	0.88	1.00	1.10	1.26	1.41	1.58
30-min	1.22	1.42	1.60	1.87	2.12	2.42
1-hr	1.53	1.82	2.08	2.49	2.87	3.34
2-hr	1.85	2.24	2.57	3.06	3.51	4.02
3-hr	2.03	2.52	2.94	3.61	4.23	4.97
6-hr	2.43	2.95	3.41	4.16	4.87	5.73
12-hr	2.85	3.51	4.06	4.95	5.76	6.74
24-hr	3.32	4.06	4.68	5.64	6.5	7.53

1900-2022 Precipitation Depth Estimates (in)

	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
5-min	0.44	0.49	0.54	0.62	0.70	0.79
10-min	0.70	0.79	0.87	1.00	1.11	1.25
15-min	0.88	1.00	1.10	1.26	1.41	1.58
30-min	1.22	1.42	1.60	1.87	2.12	2.42
1-hr	1.53	1.82	2.08	2.49	2.87	3.34
2-hr	1.85	2.24	2.57	3.06	3.51	4.02
3-hr	2.03	2.52	2.94	3.61	4.23	4.97
6-hr	2.43	2.95	3.41	4.16	4.87	5.73
12-hr	2.85	3.51	4.06	4.95	5.76	6.74
24-hr	3.32	4.06	4.68	5.64	6.5	7.53

2020 Precipitation Depth Estimates (in)

	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
5-min	0.51	0.58	0.64	0.74	0.83	0.94

10-min	0.82	0.93	1.03	1.18	1.32	1.50
15-min	1.03	1.17	1.30	1.50	1.68	1.90
30-min	1.43	1.67	1.89	2.22	2.52	2.90
1-hr	1.79	2.14	2.46	2.95	3.42	4.00
2-hr	2.15	2.61	3.01	3.61	4.16	4.79
3-hr	2.34	2.92	3.42	4.23	4.98	5.89
6-hr	2.78	3.39	3.94	4.84	5.70	6.75
12-hr	3.23	4.00	4.66	5.72	6.70	7.89
24-hr	3.73	4.59	5.33	6.48	7.52	8.77

2030 Precipitation Depth Estimates (in)

	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
5-min	0.53	0.60	0.67	0.77	0.86	0.98
10-min	0.85	0.96	1.06	1.22	1.37	1.55
15-min	1.07	1.21	1.35	1.55	1.74	1.96
30-min	1.47	1.72	1.95	2.30	2.61	3.01
1-hr	1.85	2.21	2.54	3.06	3.54	4.15
2-hr	2.21	2.70	3.11	3.73	4.30	4.96
3-hr	2.41	3.01	3.53	4.36	5.15	6.09
6-hr	2.85	3.49	4.06	4.99	5.88	6.97
12-hr	3.31	4.11	4.79	5.89	6.91	8.15
24-hr	3.82	4.71	5.48	6.66	7.74	9.04

2040 Precipitation Depth Estimates (in)

	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
5-min	0.55	0.62	0.69	0.80	0.89	1.02
10-min	0.88	0.99	1.10	1.27	1.42	1.61
15-min	1.10	1.26	1.39	1.61	1.80	2.04
30-min	1.52	1.78	2.02	2.38	2.71	3.13
1-hr	1.91	2.29	2.63	3.17	3.68	4.30
2-hr	2.28	2.79	3.22	3.86	4.46	5.14

3-hr	2.48	3.10	3.65	4.51	5.33	6.31
6-hr	2.93	3.59	4.19	5.15	6.08	7.22
12-hr	3.40	4.23	4.94	6.08	7.14	8.43
24-hr	3.92	4.84	5.64	6.86	7.99	9.34

2050 Precipitation Depth Estimates (in)

	2-yr	**5-yr**	**10-yr**	**25-yr**	**50-yr**	**100-yr**
5-min	0.59	0.67	0.74	0.86	0.96	1.10
10-min	0.94	1.07	1.19	1.37	1.54	1.75
15-min	1.18	1.35	1.50	1.73	1.94	2.21
30-min	1.63	1.92	2.17	2.57	2.93	3.38
1-hr	2.05	2.46	2.83	3.42	3.97	4.66
2-hr	2.44	2.98	3.46	4.15	4.80	5.55
3-hr	2.64	3.31	3.90	4.84	5.73	6.80
6-hr	3.12	3.83	4.47	5.52	6.53	7.76
12-hr	3.60	4.49	5.26	6.49	7.64	9.04

2060 Precipitation Depth Estimates (in)

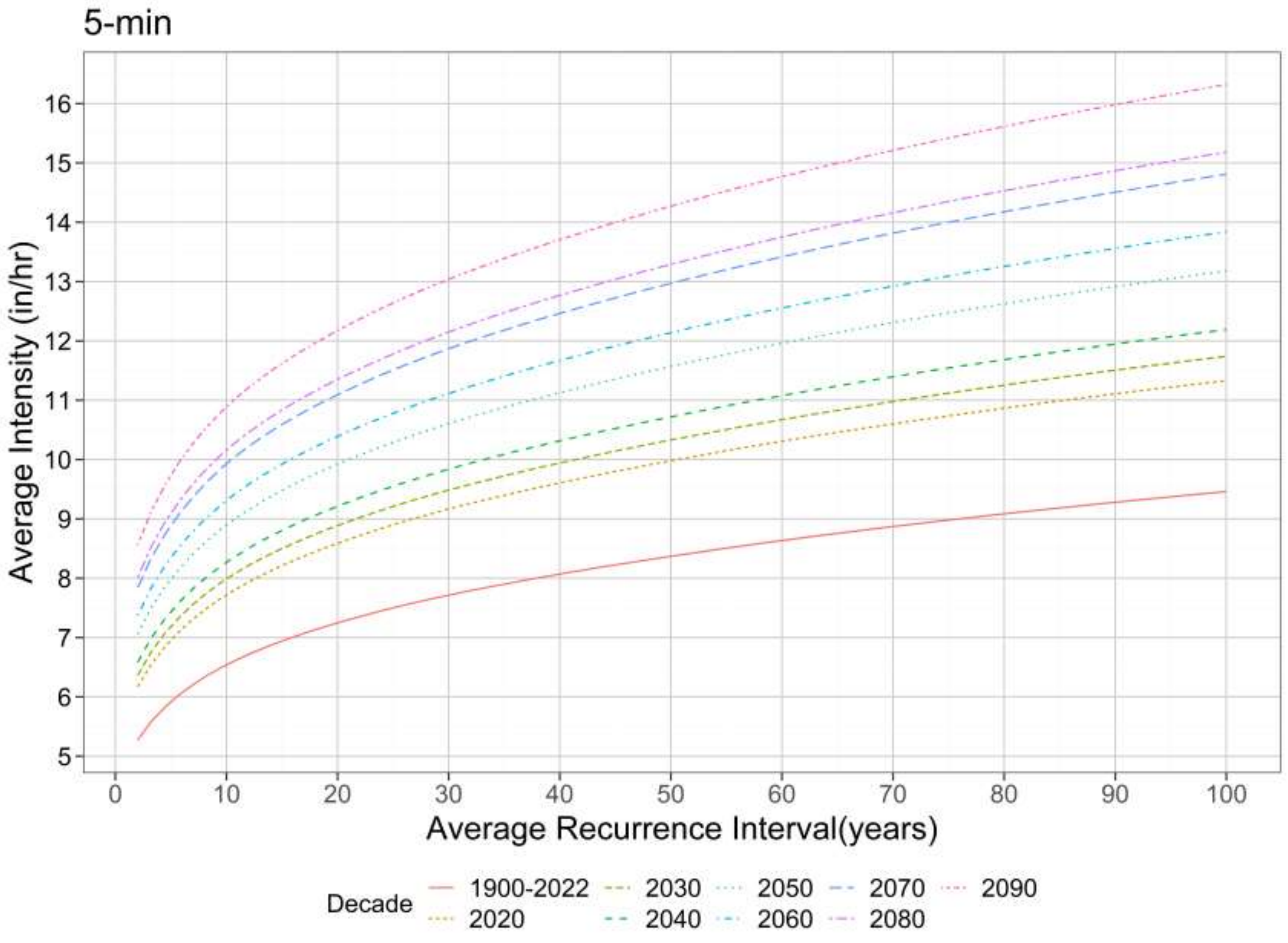
	2-yr	**5-yr**	**10-yr**	**25-yr**	**50-yr**	**100-yr**
5-min	0.61	0.70	0.78	0.90	1.01	1.15
10-min	0.98	1.11	1.24	1.43	1.61	1.83
15-min	1.23	1.41	1.57	1.81	2.04	2.32
30-min	1.71	2.00	2.28	2.69	3.07	3.55
1-hr	2.14	2.57	2.96	3.58	4.16	4.89
2-hr	2.55	3.12	3.61	4.34	5.03	5.82
3-hr	2.91	3.66	4.33	5.38	6.38	7.59
6-hr	3.24	3.98	4.66	5.75	6.82	8.12
12-hr	3.74	4.67	5.47	6.76	7.97	9.44
24-hr	4.28	5.31	6.21	7.60	8.88	10.43

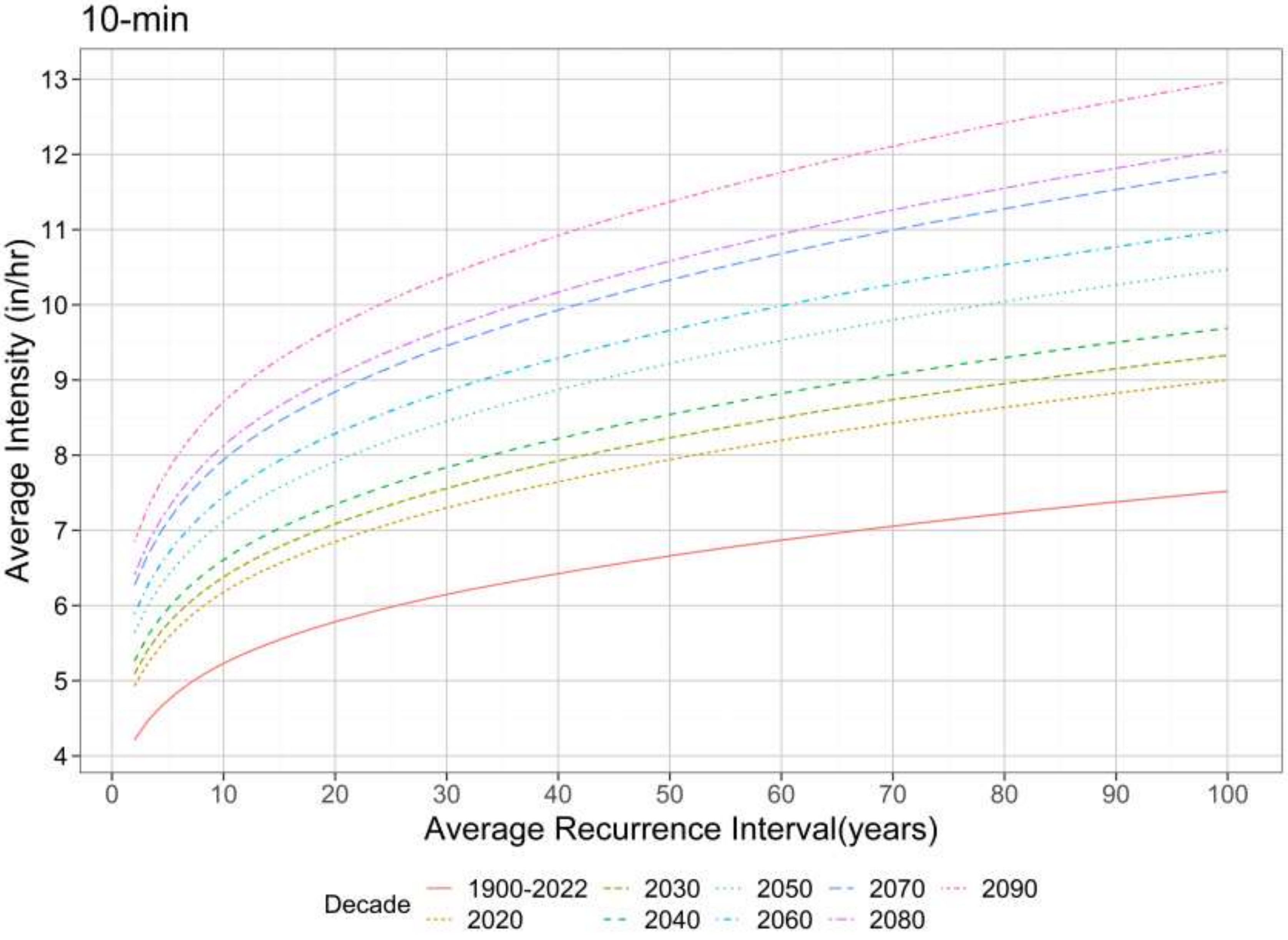
2070 Precipitation Depth Estimates (in)						
	2-yr	**5-yr**	**10-yr**	**25-yr**	**50-yr**	**100-yr**
5-min	0.65	0.74	0.83	0.96	1.08	1.23
10-min	1.04	1.19	1.32	1.53	1.72	1.96
15-min	1.31	1.50	1.67	1.94	2.18	2.48
30-min	1.81	2.13	2.43	2.87	3.28	3.80
1-hr	2.28	2.74	3.16	3.82	4.45	5.23
2-hr	2.70	3.31	3.84	4.63	5.37	6.22
3-hr	2.91	3.66	4.33	5.38	6.38	7.59
6-hr	3.42	4.21	4.94	6.11	7.25	8.65
12-hr	3.93	4.92	5.78	7.16	8.46	10.04
24-hr	4.49	5.59	6.56	8.03	9.41	11.08

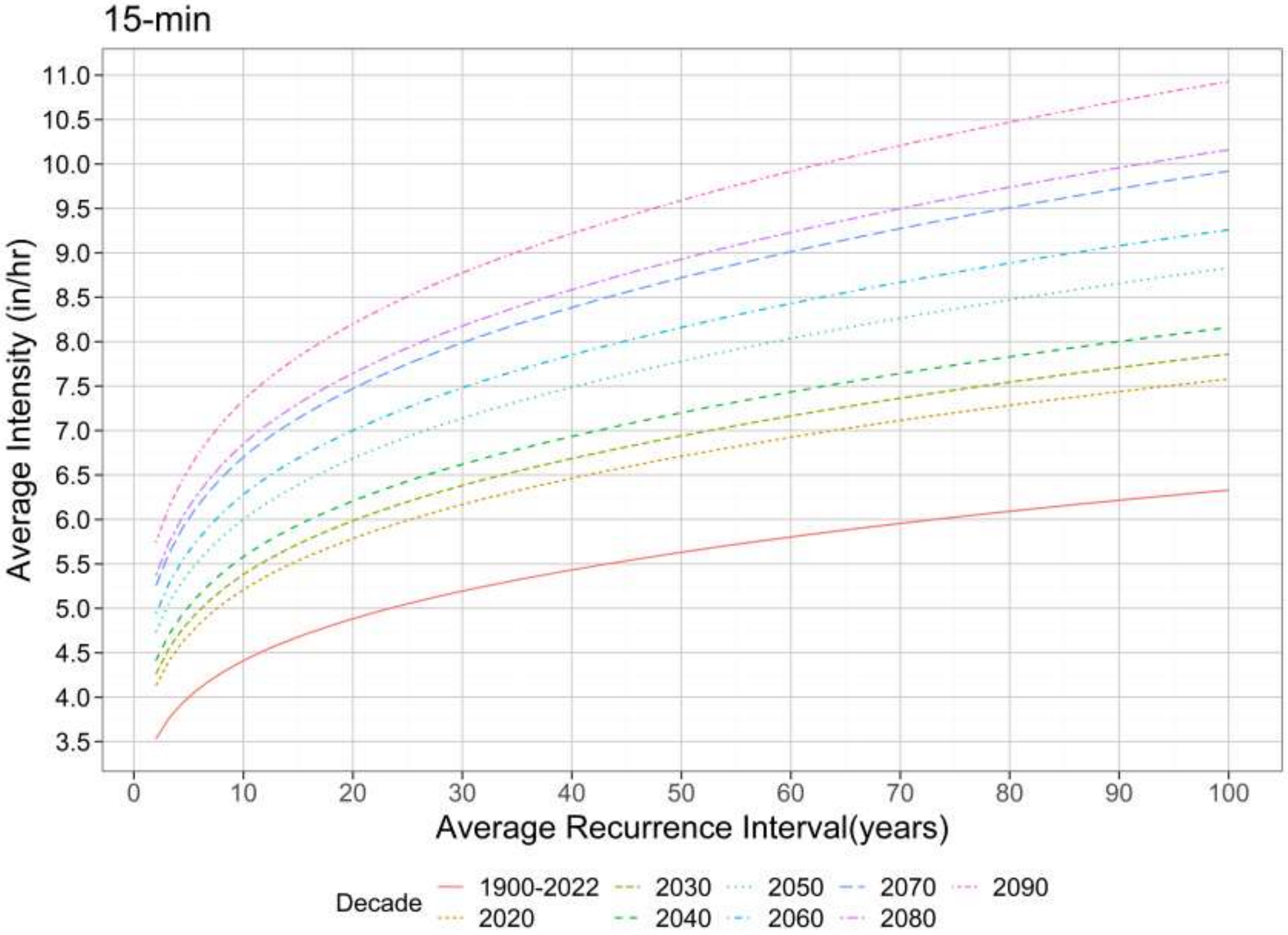
2080 Precipitation Depth Estimates (in)						
	2-yr	**5-yr**	**10-yr**	**25-yr**	**50-yr**	**100-yr**
5-min	0.67	0.76	0.85	0.98	1.11	1.26
10-min	1.07	1.21	1.35	1.56	1.76	2.01
15-min	1.34	1.54	1.71	1.98	2.23	2.54
30-min	1.85	2.18	2.48	2.94	3.36	3.89
1-hr	2.33	2.80	3.23	3.91	4.56	5.36
2-hr	2.76	3.38	3.93	4.74	5.50	6.37
3-hr	2.97	3.74	4.42	5.50	6.53	7.77
6-hr	3.49	4.30	5.04	6.24	7.41	8.85
12-hr	4.01	5.02	5.90	7.31	8.64	10.27
24-hr	4.57	5.70	6.68	8.20	9.61	11.32

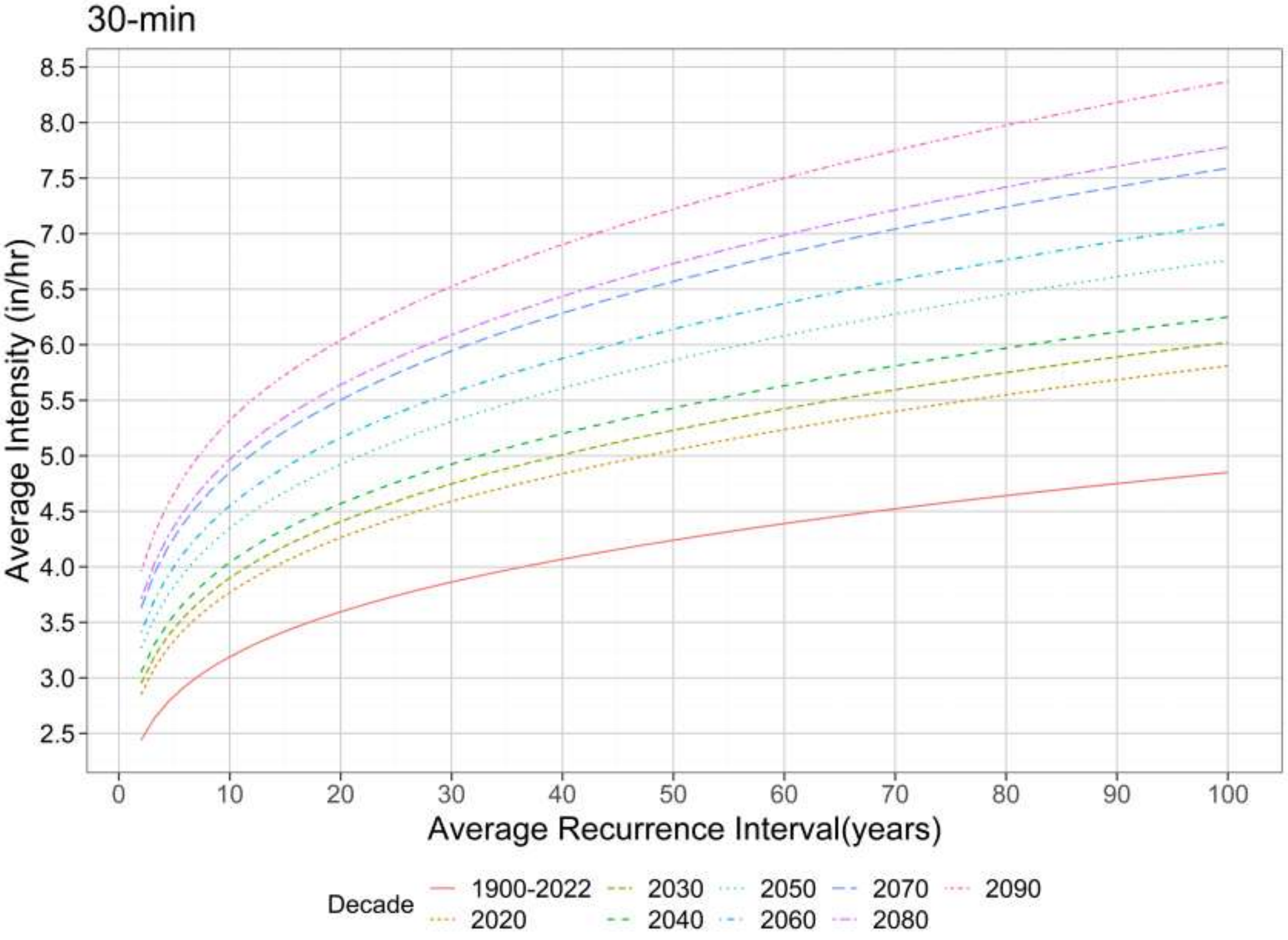
2090 Precipitation Depth Estimates (in)						
	2-yr	**5-yr**	**10-yr**	**25-yr**	**50-yr**	**100-yr**
5-min	0.71	0.81	0.91	1.05	1.19	1.36
10-min	1.14	1.30	1.45	1.68	1.89	2.16
15-min	1.43	1.64	1.84	2.13	2.40	2.73
30-min	1.98	2.34	2.66	3.15	3.61	4.18
1-hr	2.49	2.99	3.46	4.20	4.89	5.76
2-hr	2.94	3.61	4.20	5.07	5.89	6.84
3-hr	3.16	3.98	4.72	5.88	6.99	8.34
6-hr	3.70	4.57	5.37	6.66	7.92	9.47
12-hr	4.24	5.32	6.27	7.78	9.22	10.98
24-hr	4.83	6.02	7.09	8.71	10.23	12.08

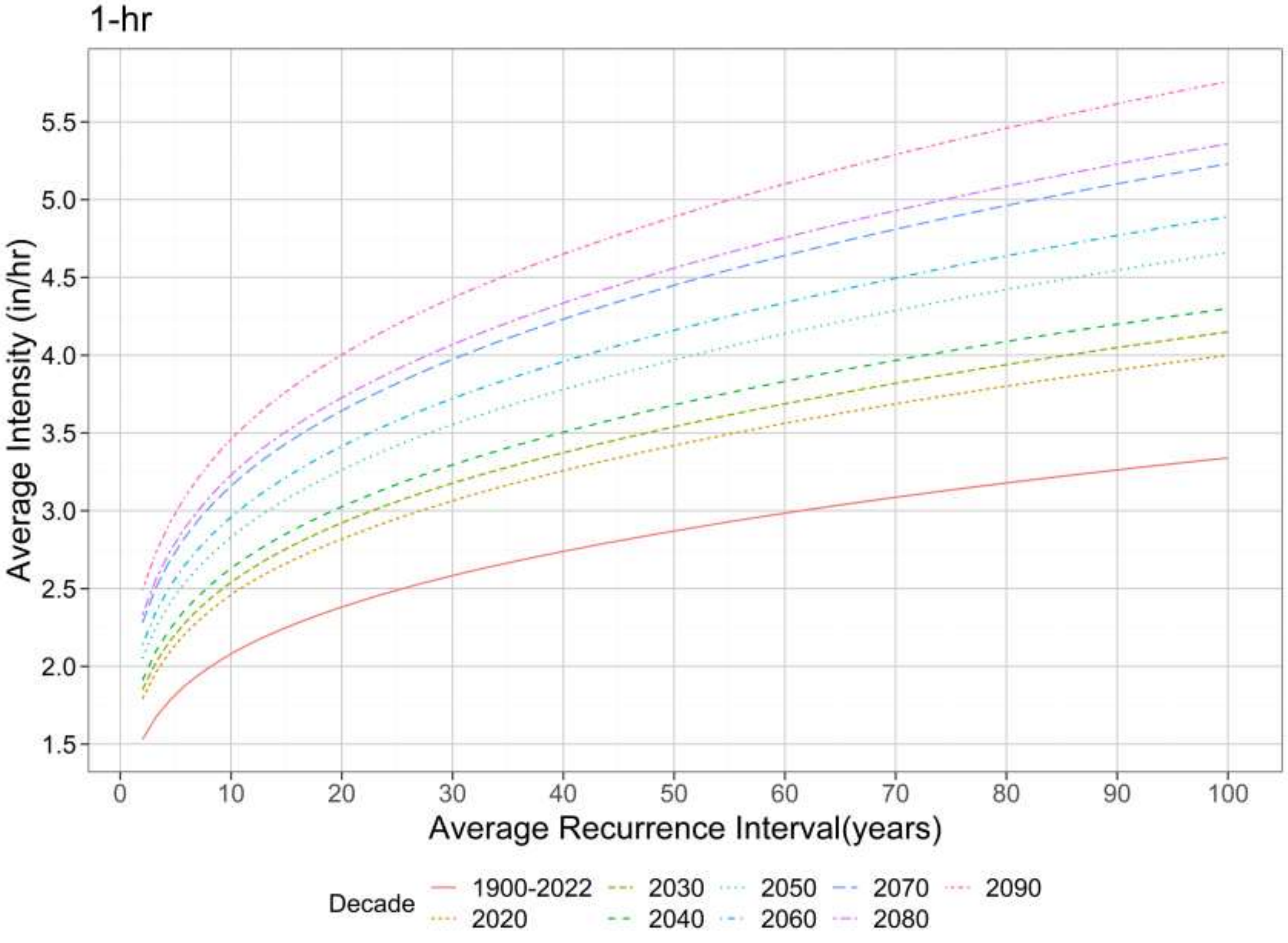
Appendix C-3 Observed and Future Intensity-Duration-Frequency Plots

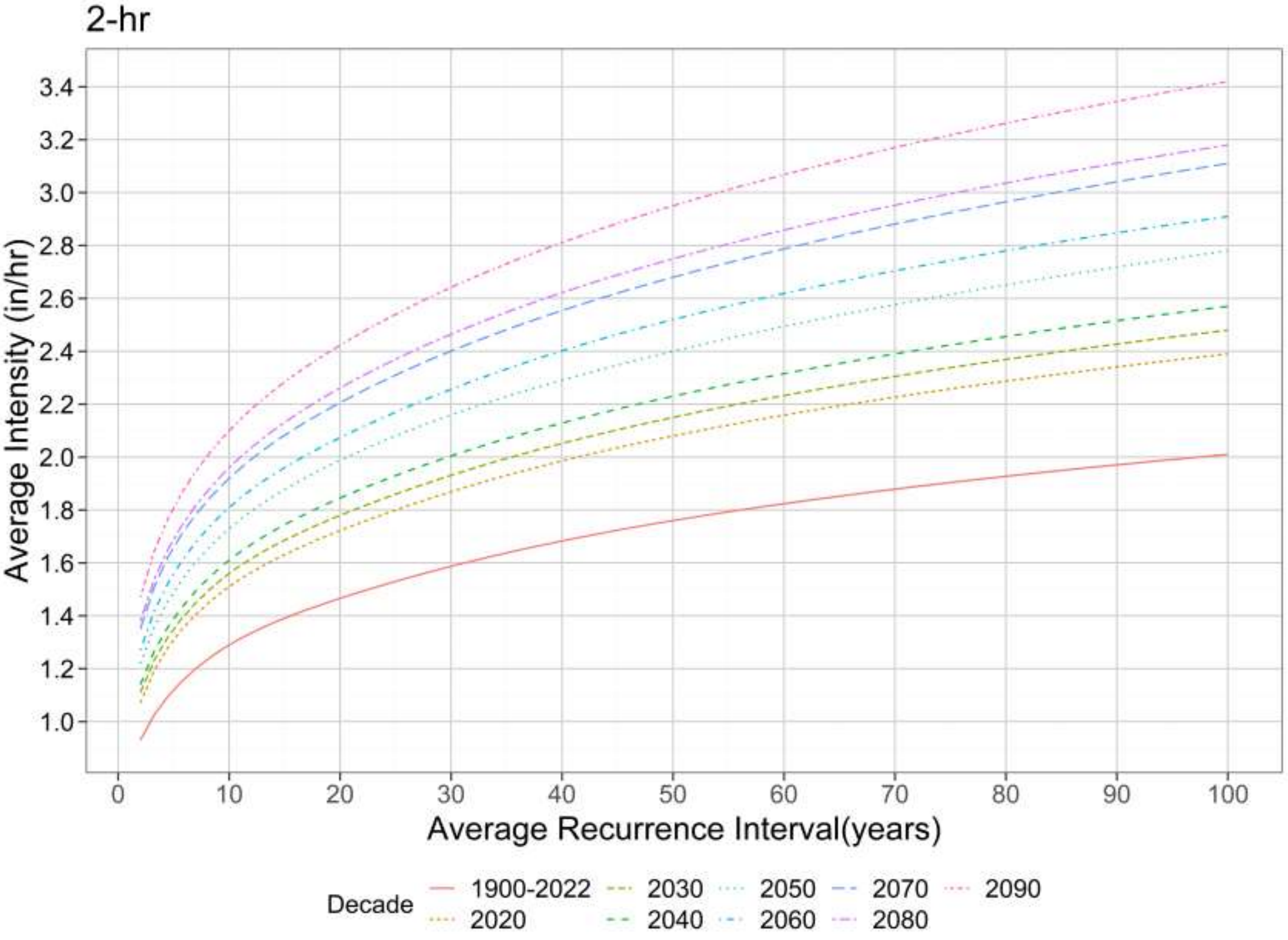

5-min
Average Intensity (in/hr)
16
15
14
13
12
11
10
9
8
7
6
5
0
10
20
30
40
50
60
70
80
90
100
Average Recurrence Interval(years)
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090

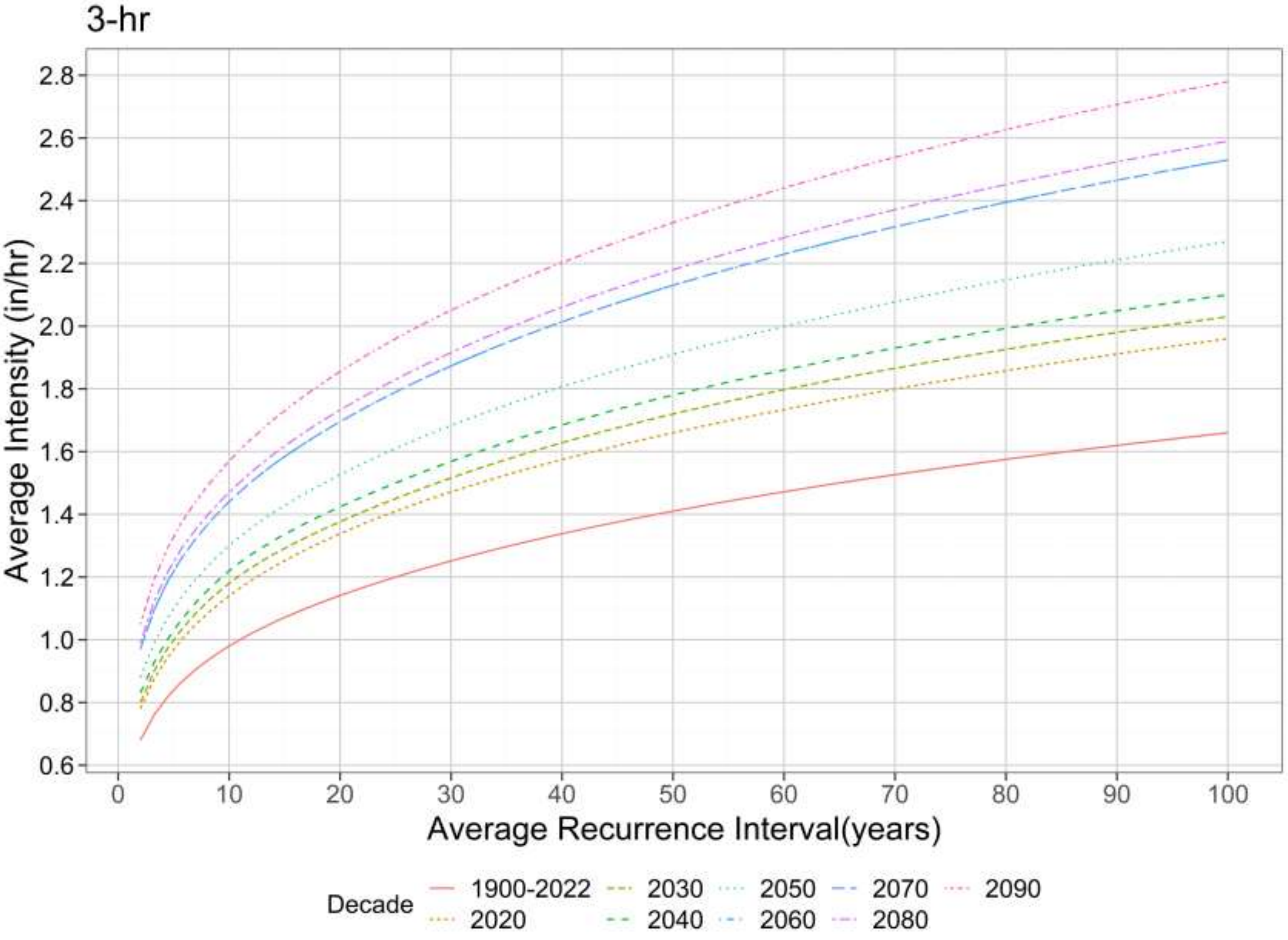

10-min
Average Intensity (in/hr)
13
12
11
10
9
8
7
6
5
4
0
10
20
30
40
50
60
70
80
90
100
Average Recurrence Interval(years)
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090

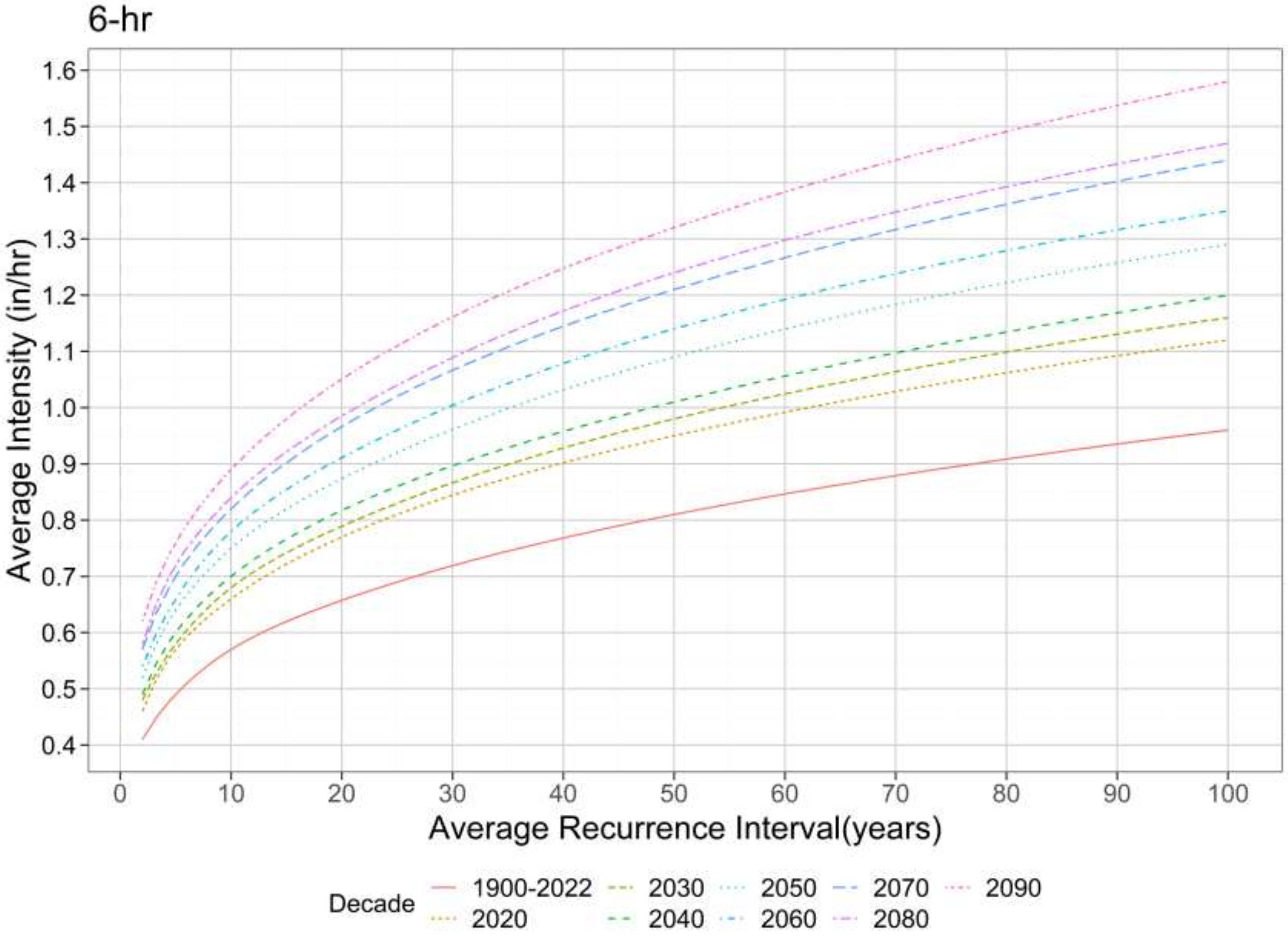

15-min
Average Intensity (in/hr)
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
0
10
20
30
40
50
60
70
80
90
100
Average Recurrence Interval(years)
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090

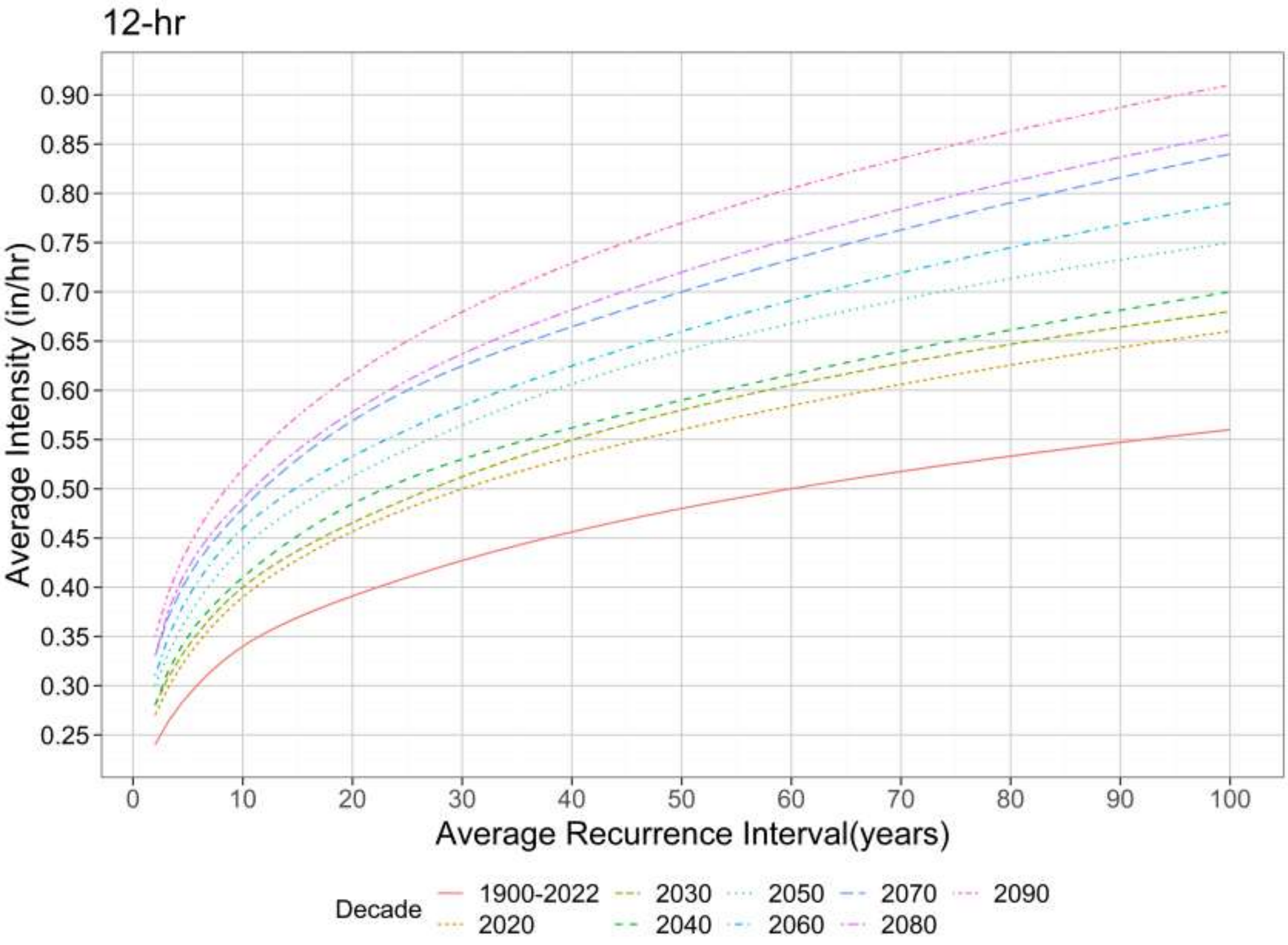

30-min
Average Intensity (in/hr)
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
0
10
20
30
40
50
60
70
80
90
100
Average Recurrence Interval(years)
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090

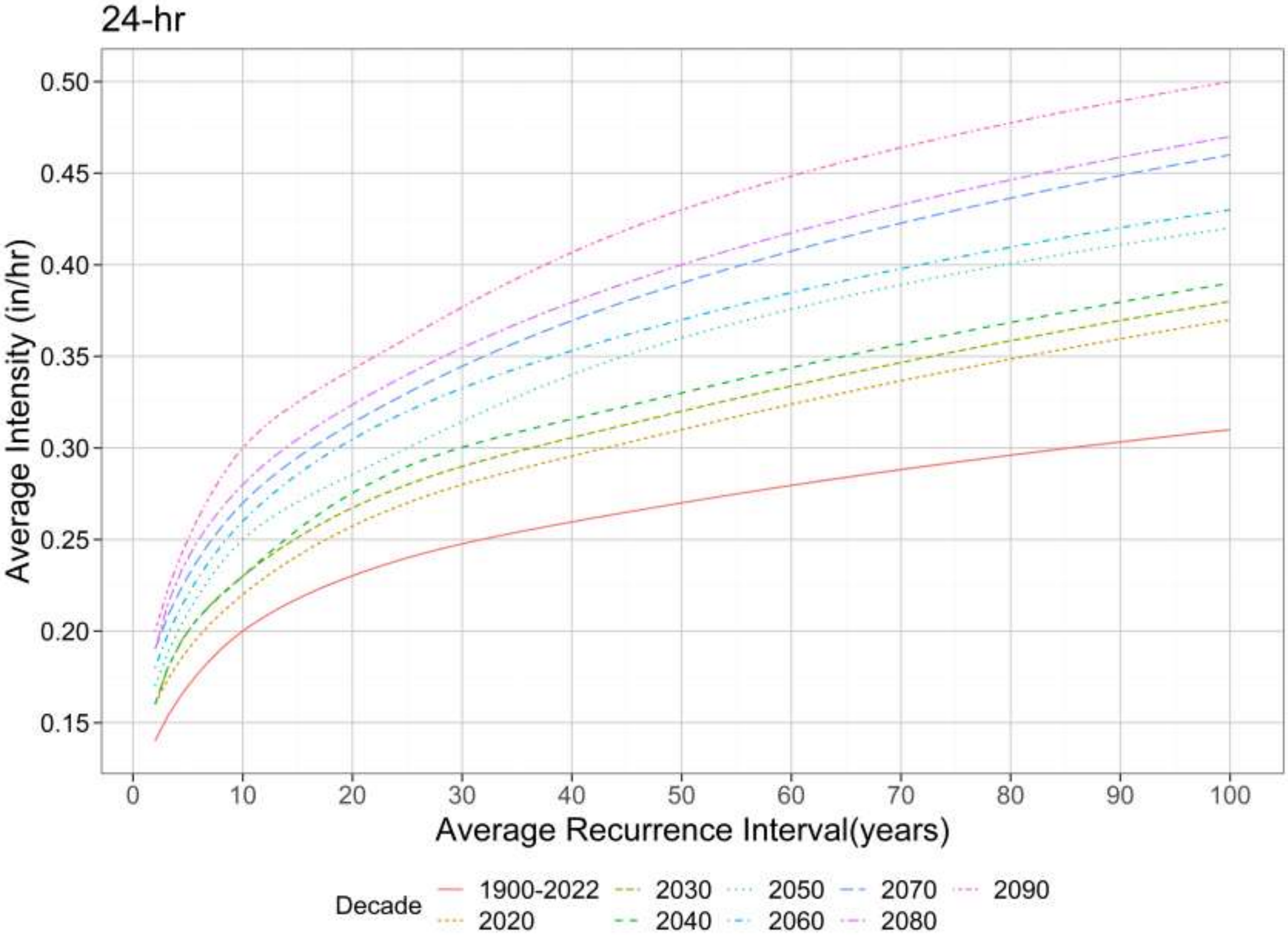

1-hr
Average Intensity (in/hr)
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
0
10
20
30
40
50
60
70
80
90
100
Average Recurrence Interval(years)
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090

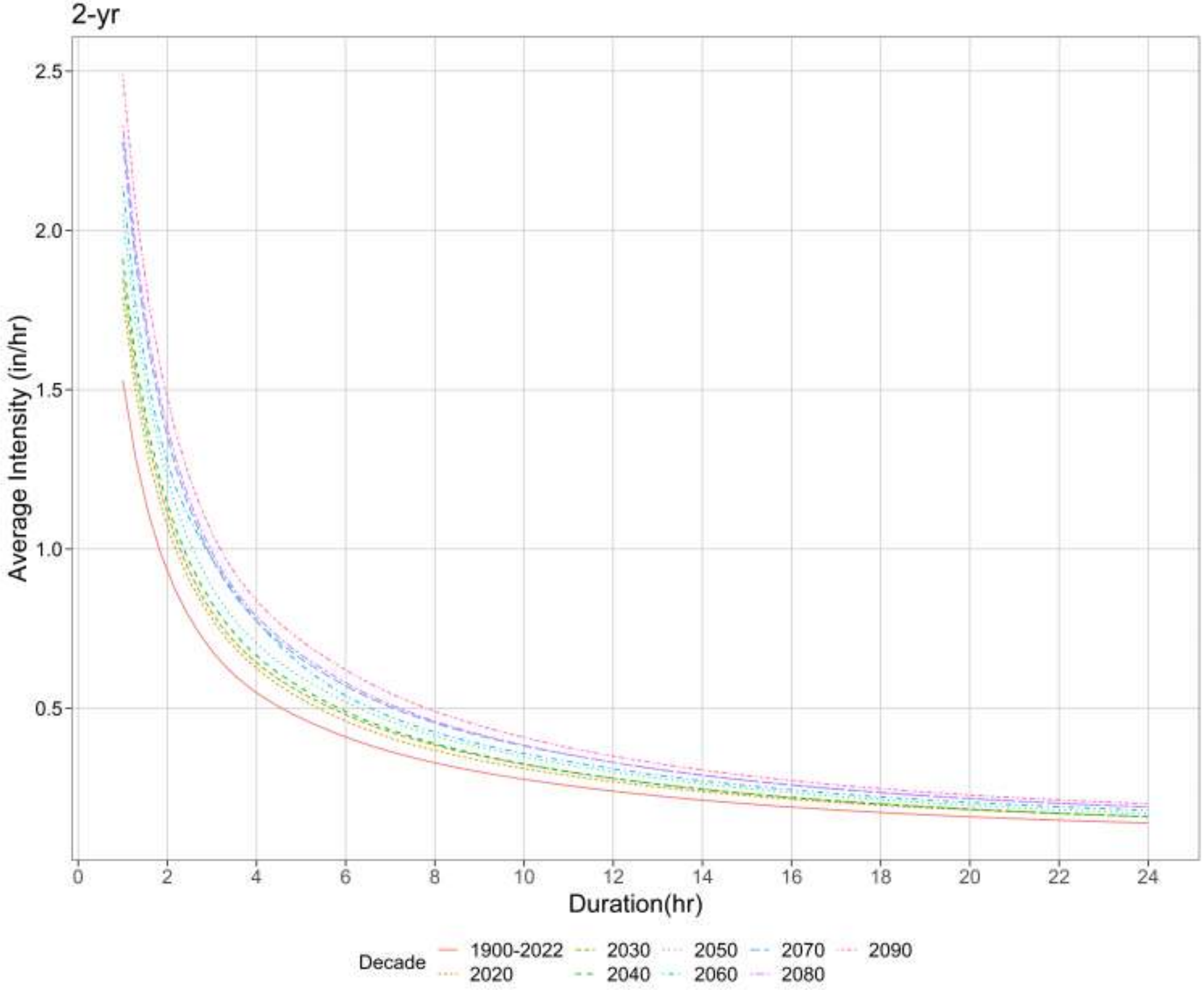

2-hr
Average Intensity (in/hr)
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0
10
20
30
40
50
60
70
80
90
100
Average Recurrence Interval(years)
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090

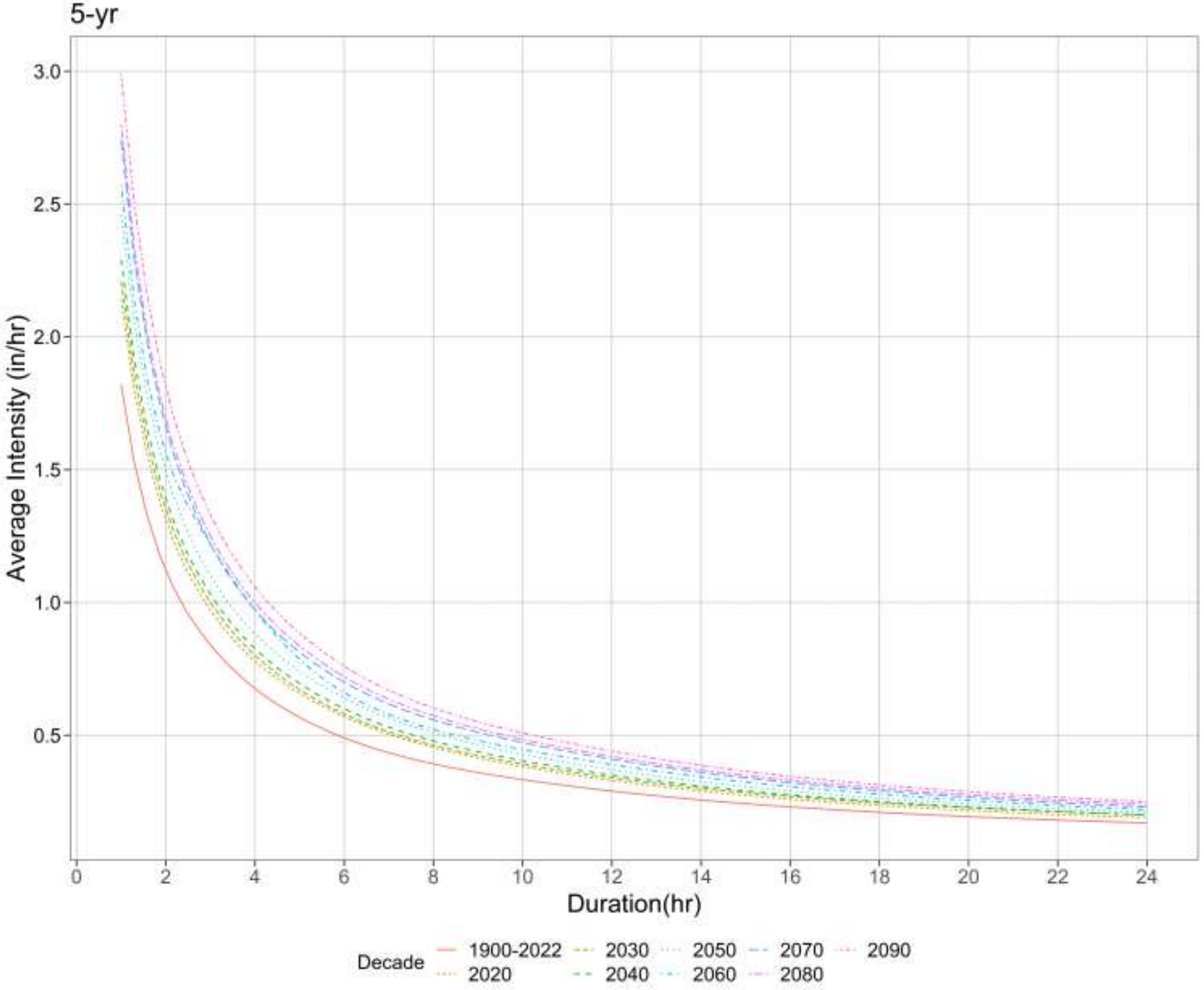

3-hr
Average Intensity (in/hr)
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0
10
20
30
40
50
60
70
80
90
100
Average Recurrence Interval(years)
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090

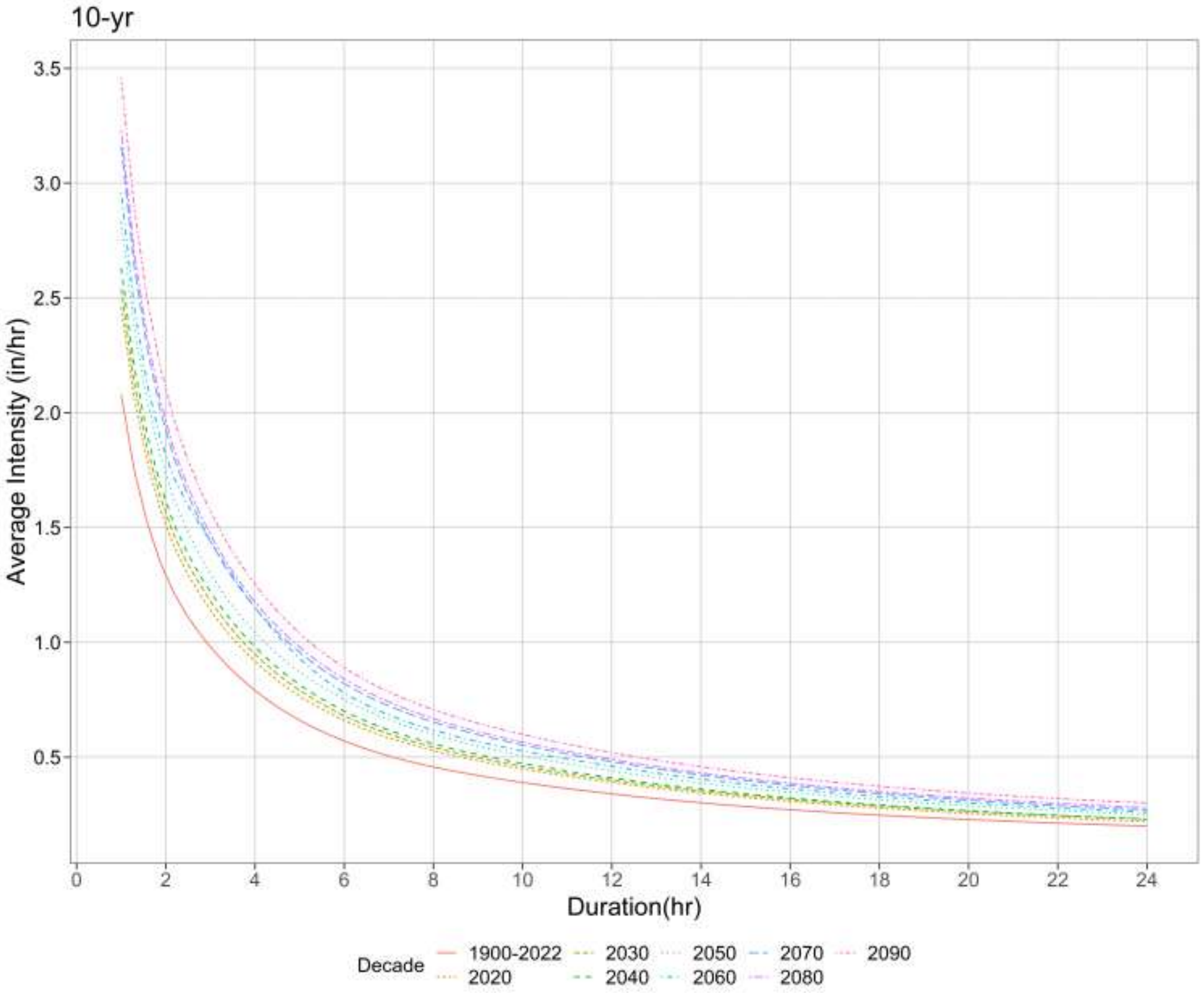

6-hr
Average Intensity (in/hr)
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0
10
20
30
40
50
60
70
80
90
100
Average Recurrence Interval(years)
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090

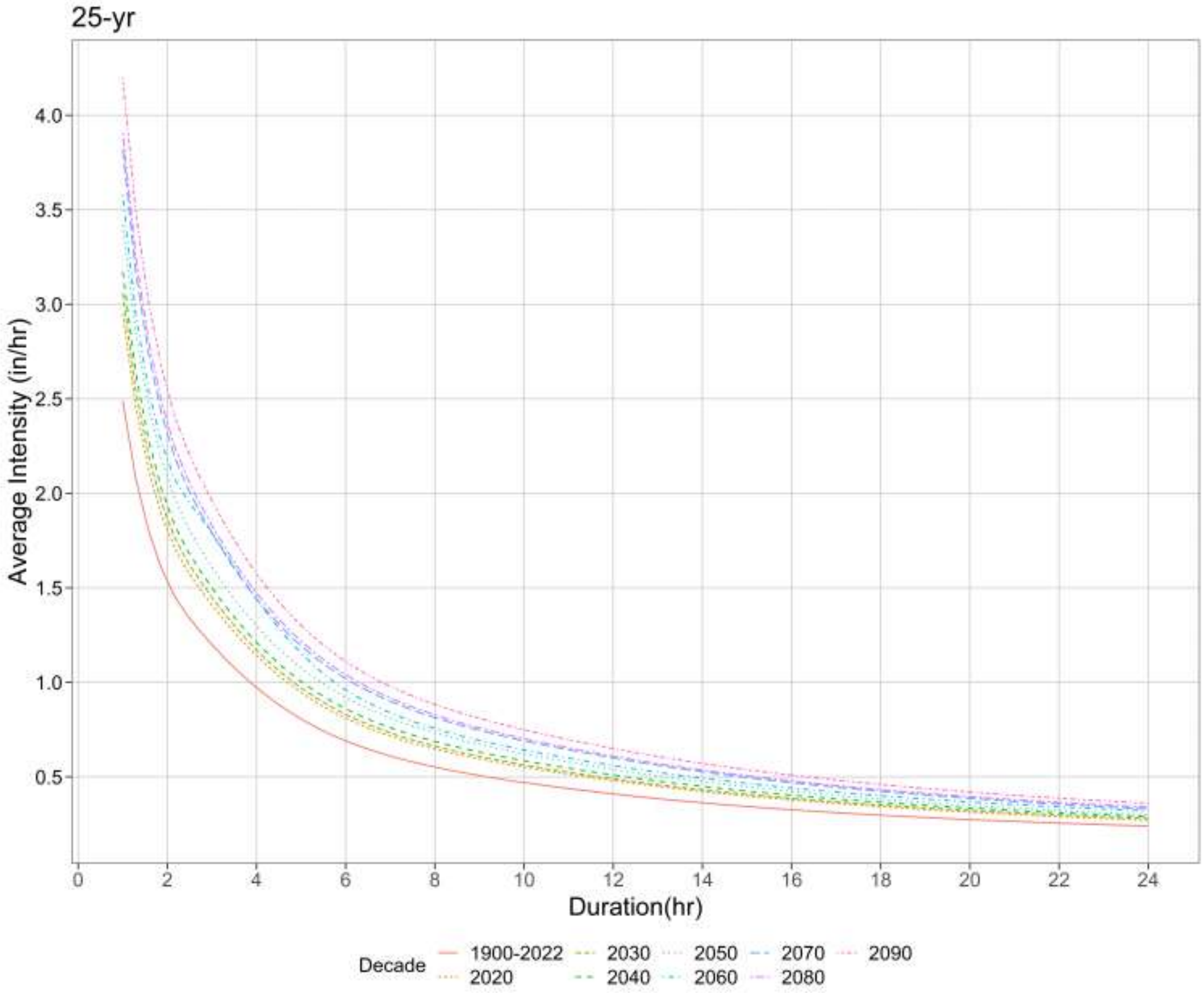

12-hr
Average Intensity (in/hr)
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0
10
20
30
40
50
60
70
80
90
100
Average Recurrence Interval(years)
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090

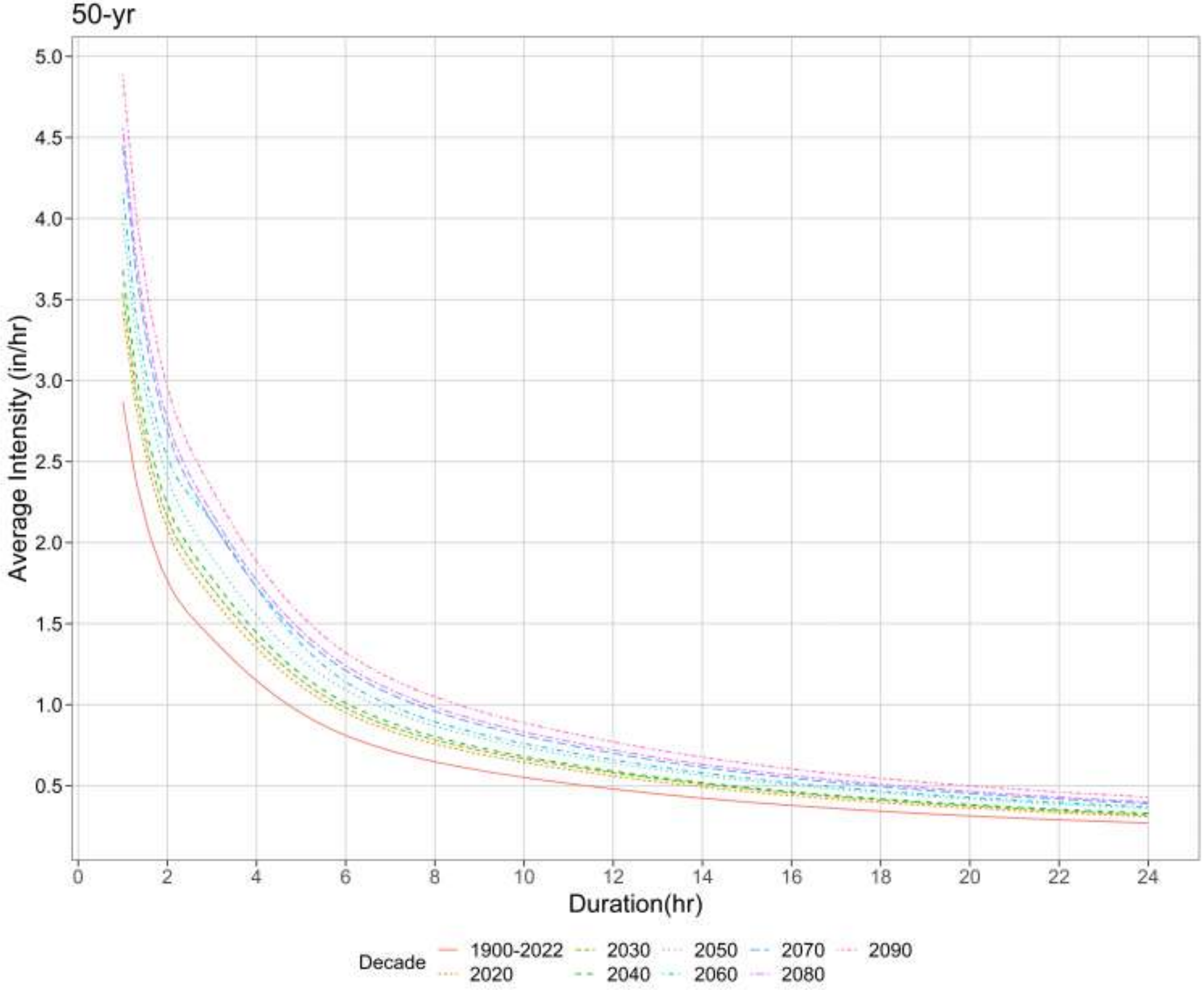

24-hr
Average Intensity (in/hr)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0
10
20
30
40
50
60
70
80
90
100
Average Recurrence Interval(years)
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090

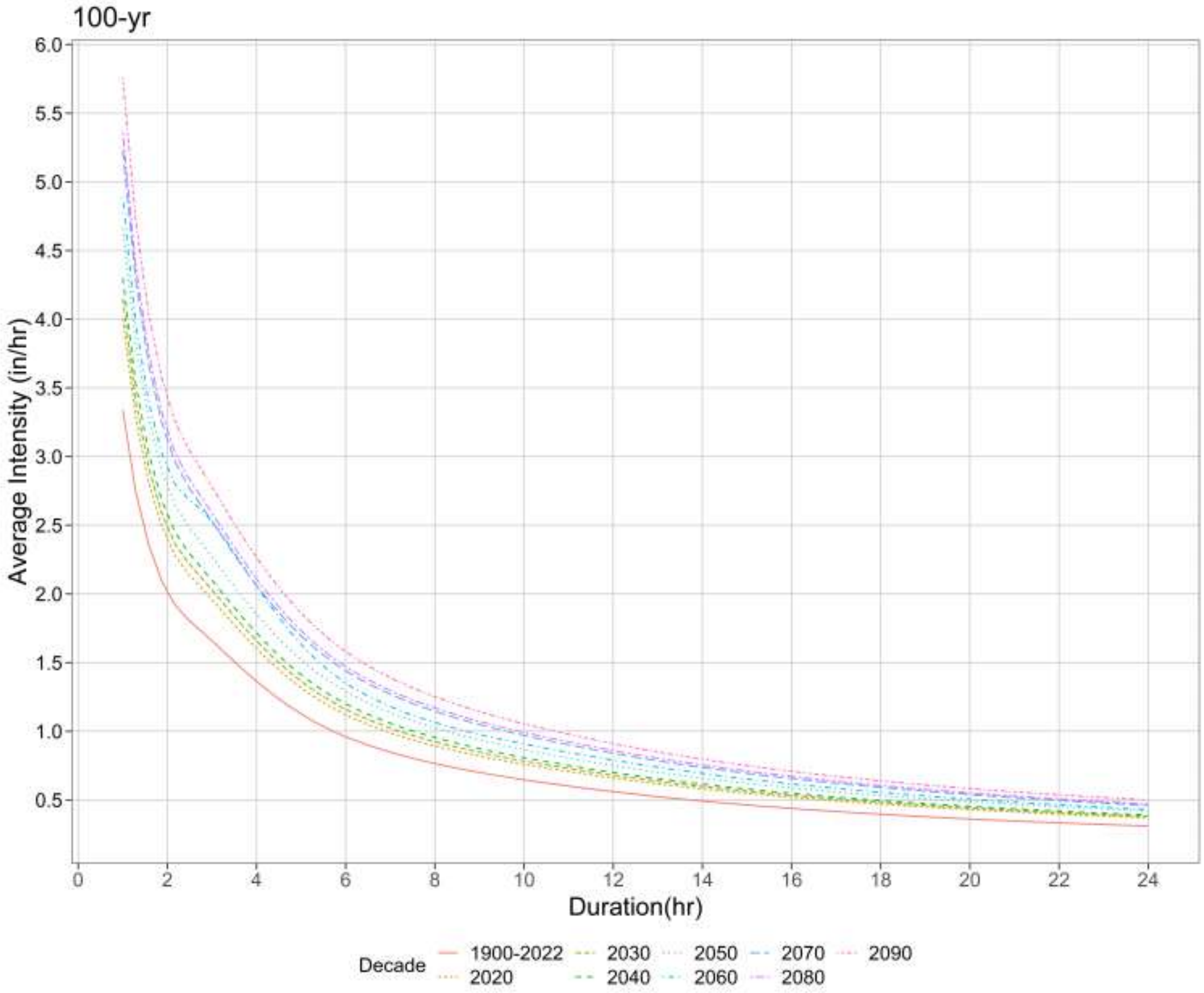

2-yr
Average Intensity (in/hr)
2.5
2.0
1.5
1.0
0.5
Duration(hr)
0
2
4
6
8
10
12
14
16
18
20
22
24
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090


5-yr
Average Intensity (in/hr)
3.0
2.5
2.0
1.5
1.0
0.5
Duration(hr)
0
2
4
6
8
10
12
14
16
18
20
22
24
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090

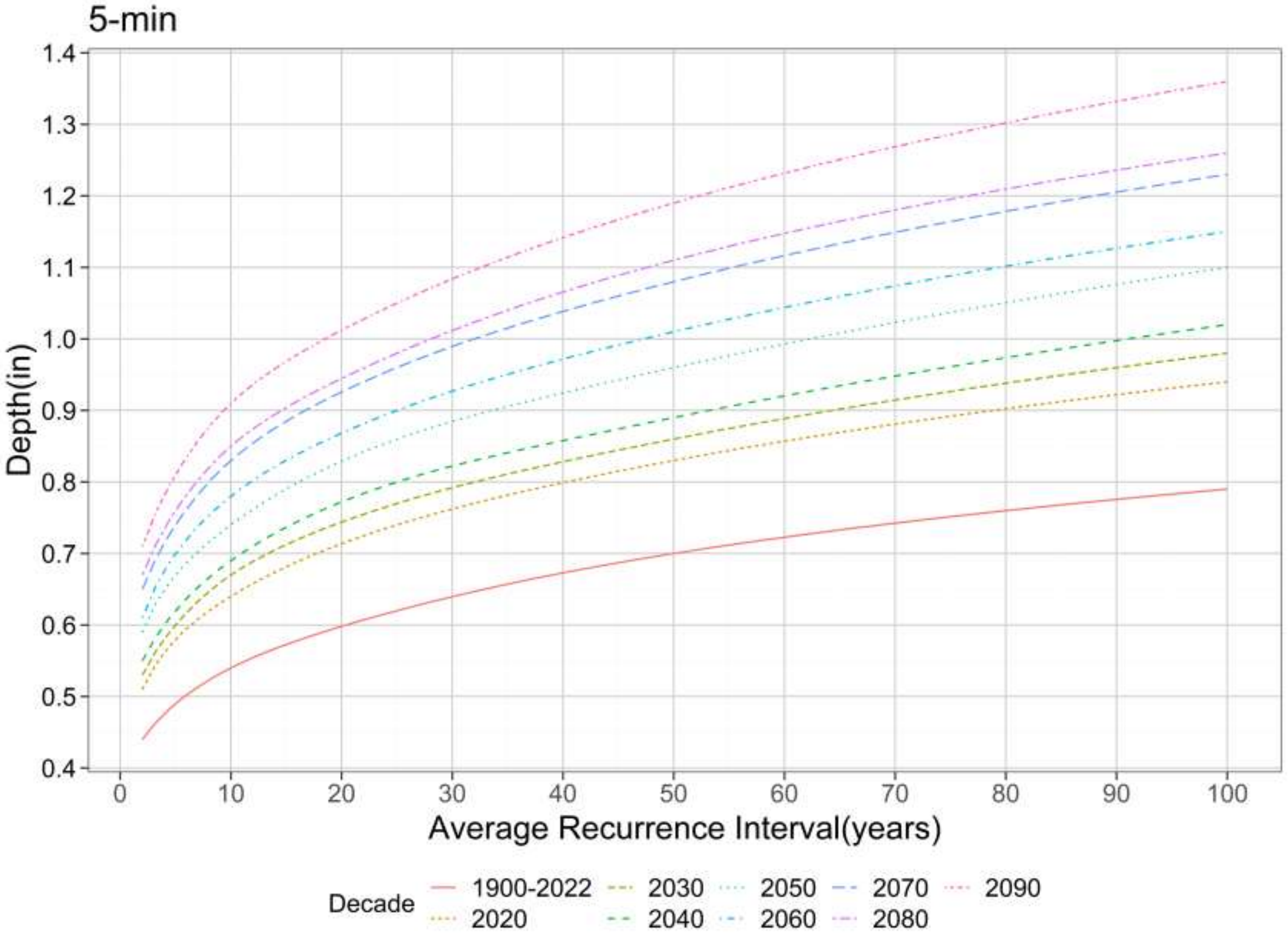

10-yr
Average Intensity (in/hr)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
2
4
6
8
10
12
14
16
18
20
22
24
Duration(hr)
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090

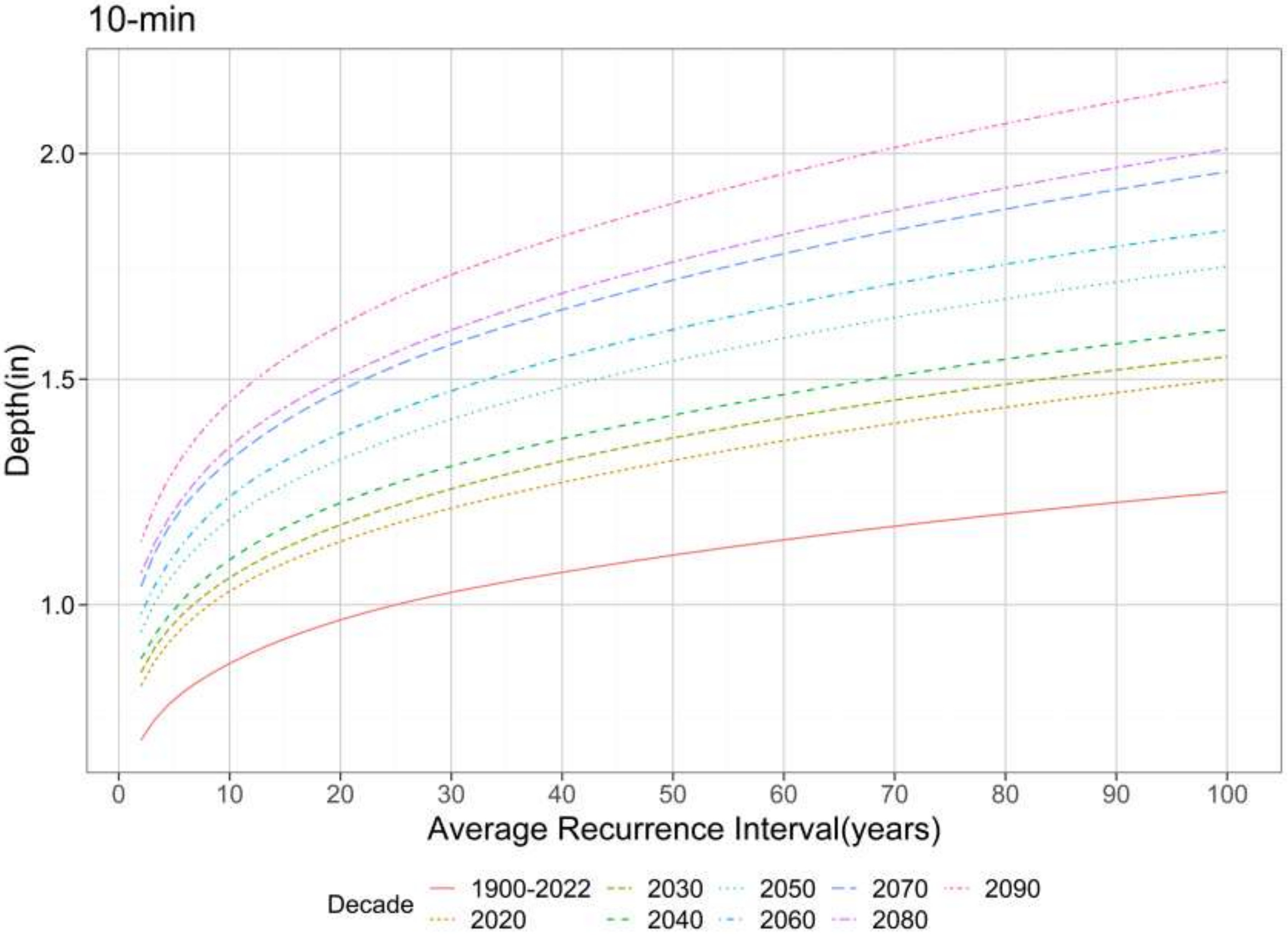

25-yr
Average Intensity (in/hr)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
2
4
6
8
10
12
14
16
18
20
22
24
Duration(hr)
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090

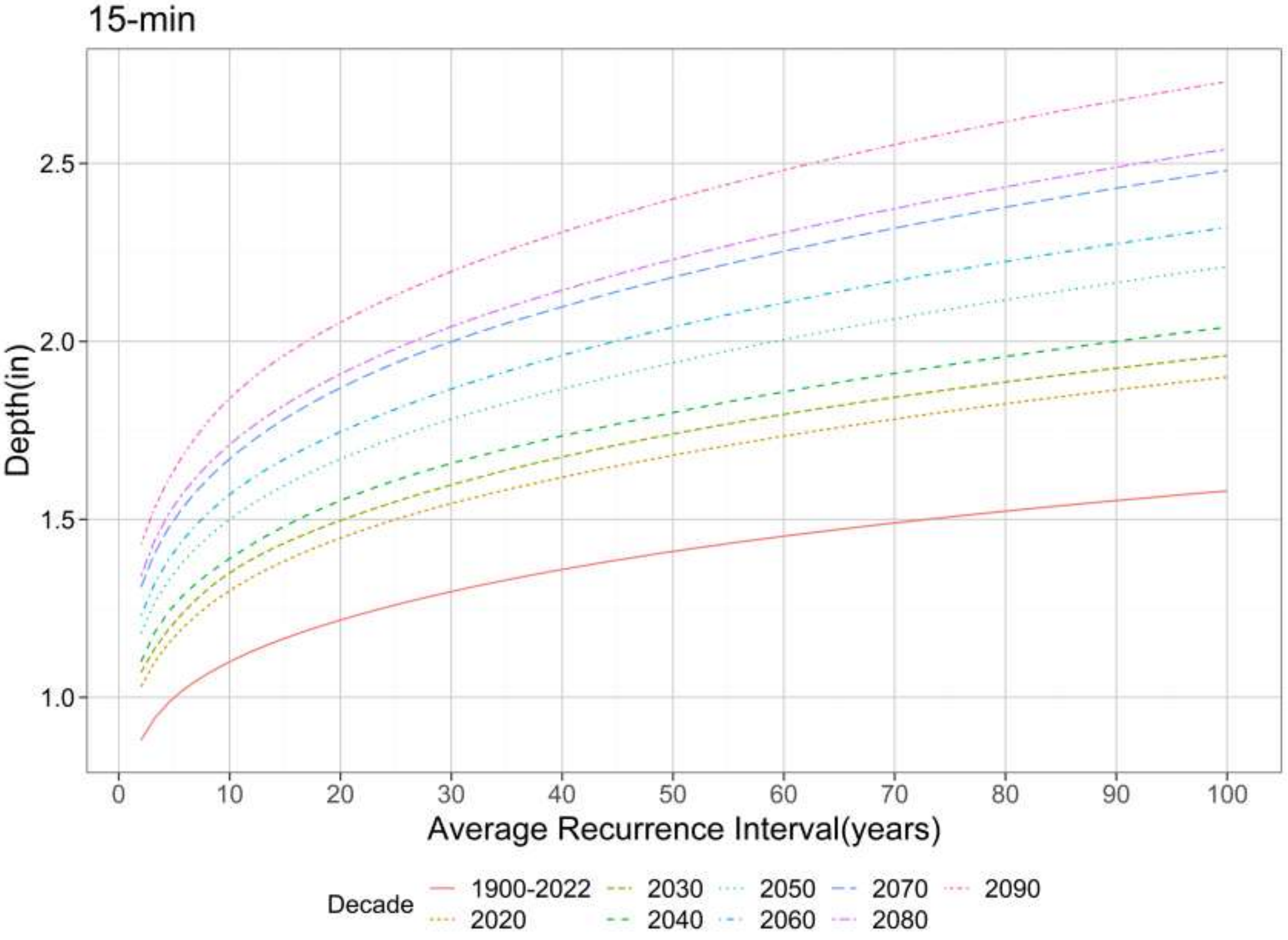

50-yr
Average Intensity (in/hr)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
2
4
6
8
10
12
14
16
18
20
22
24
Duration(hr)
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090

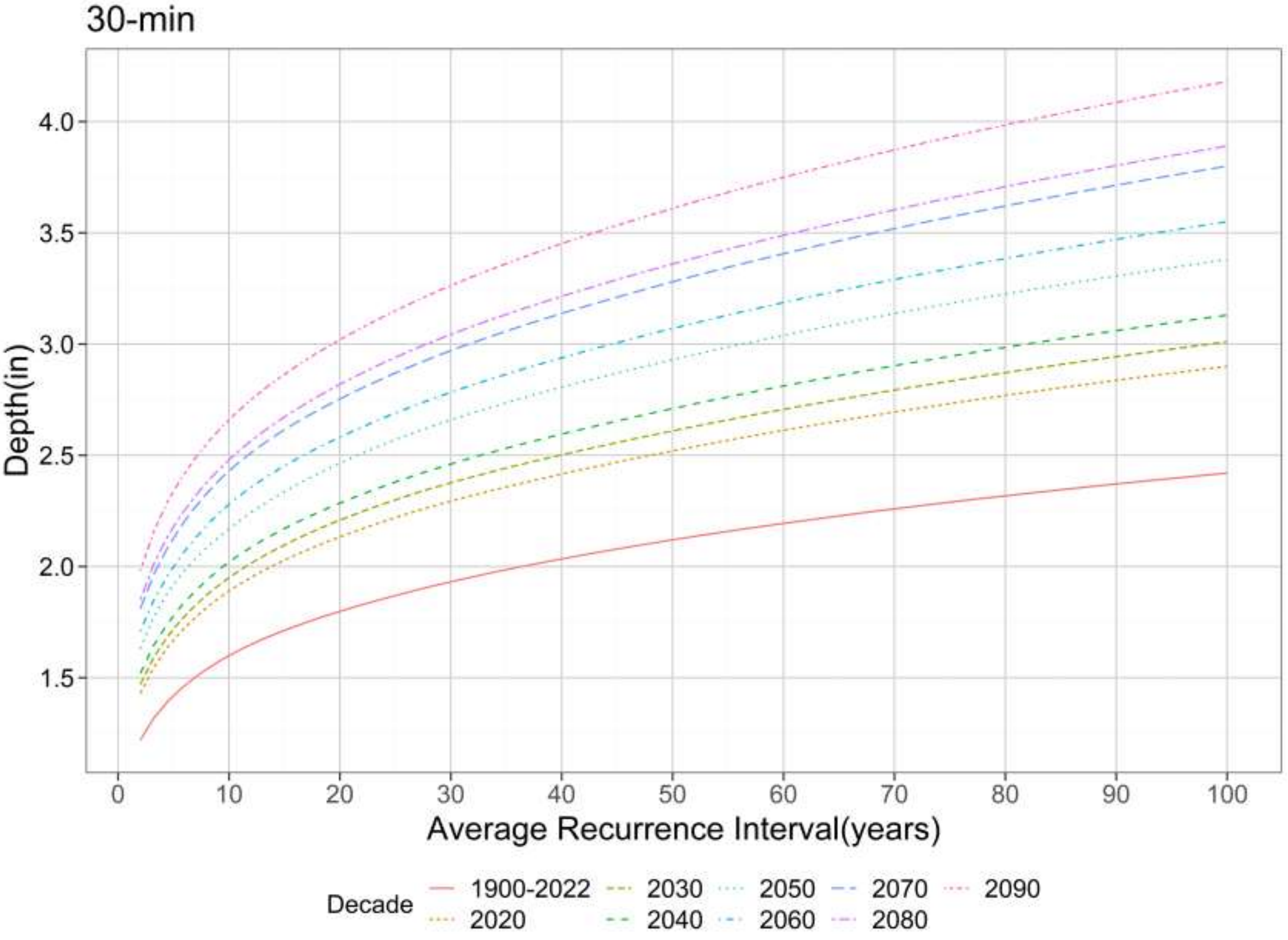

100-yr
Average Intensity (in/hr)
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
2
4
6
8
10
12
14
16
18
20
22
24
Duration(hr)
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090

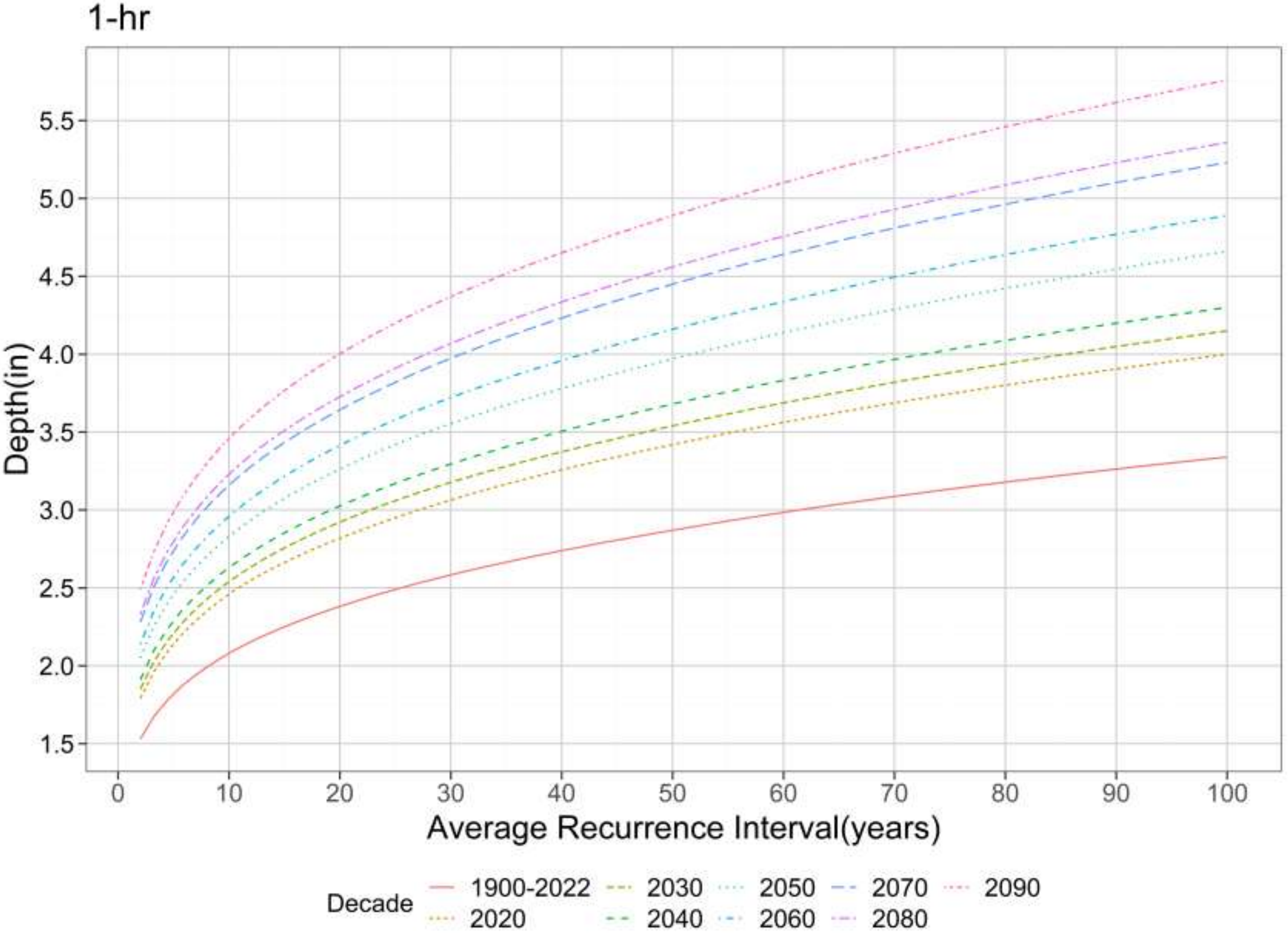
Appendix C-4 Observed and Future Depth-Duration-Frequency Plots

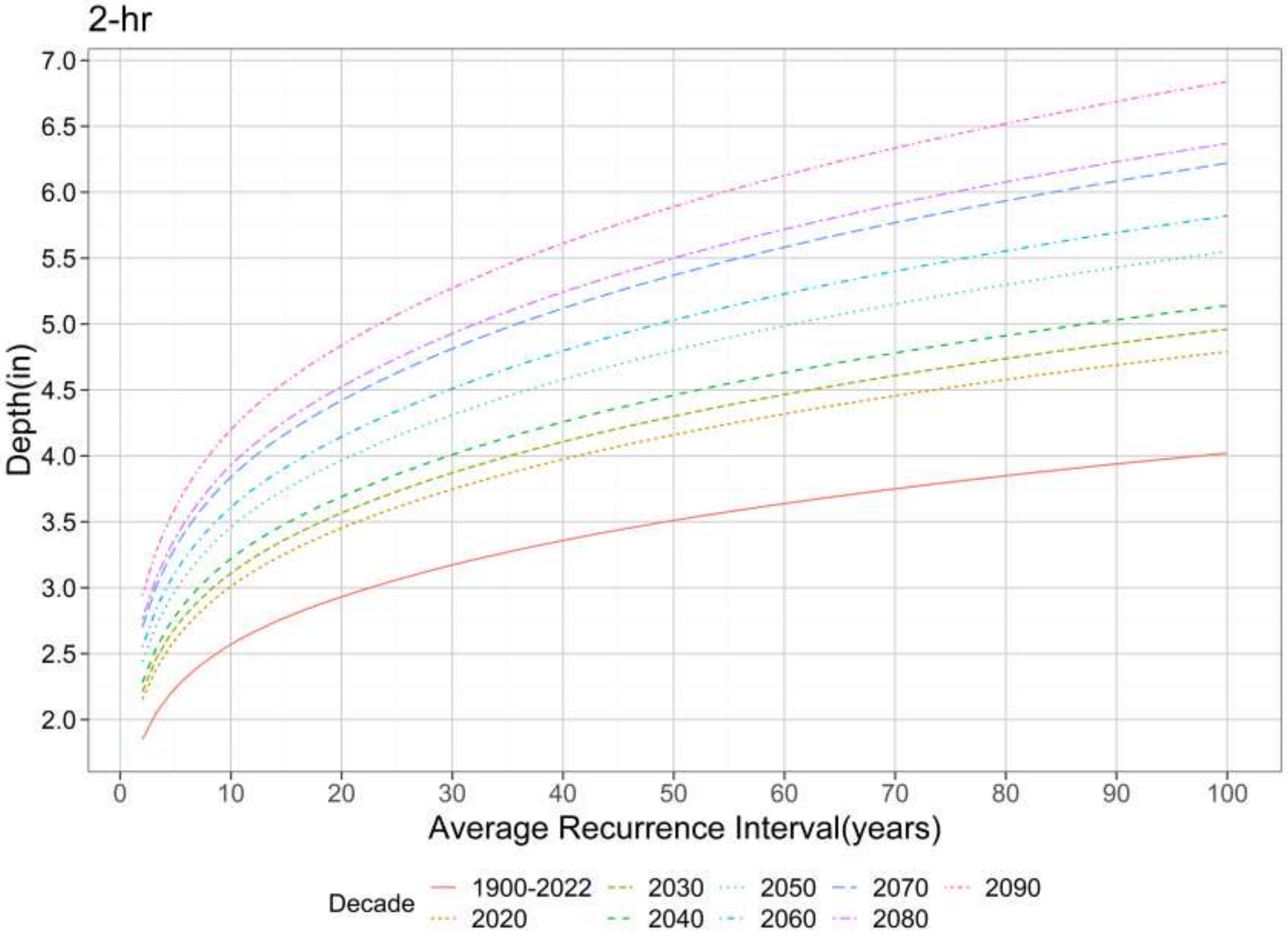

5-min
Depth(in)
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0
10
20
30
40
50
60
70
80
90
100
Average Recurrence Interval(years)
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090

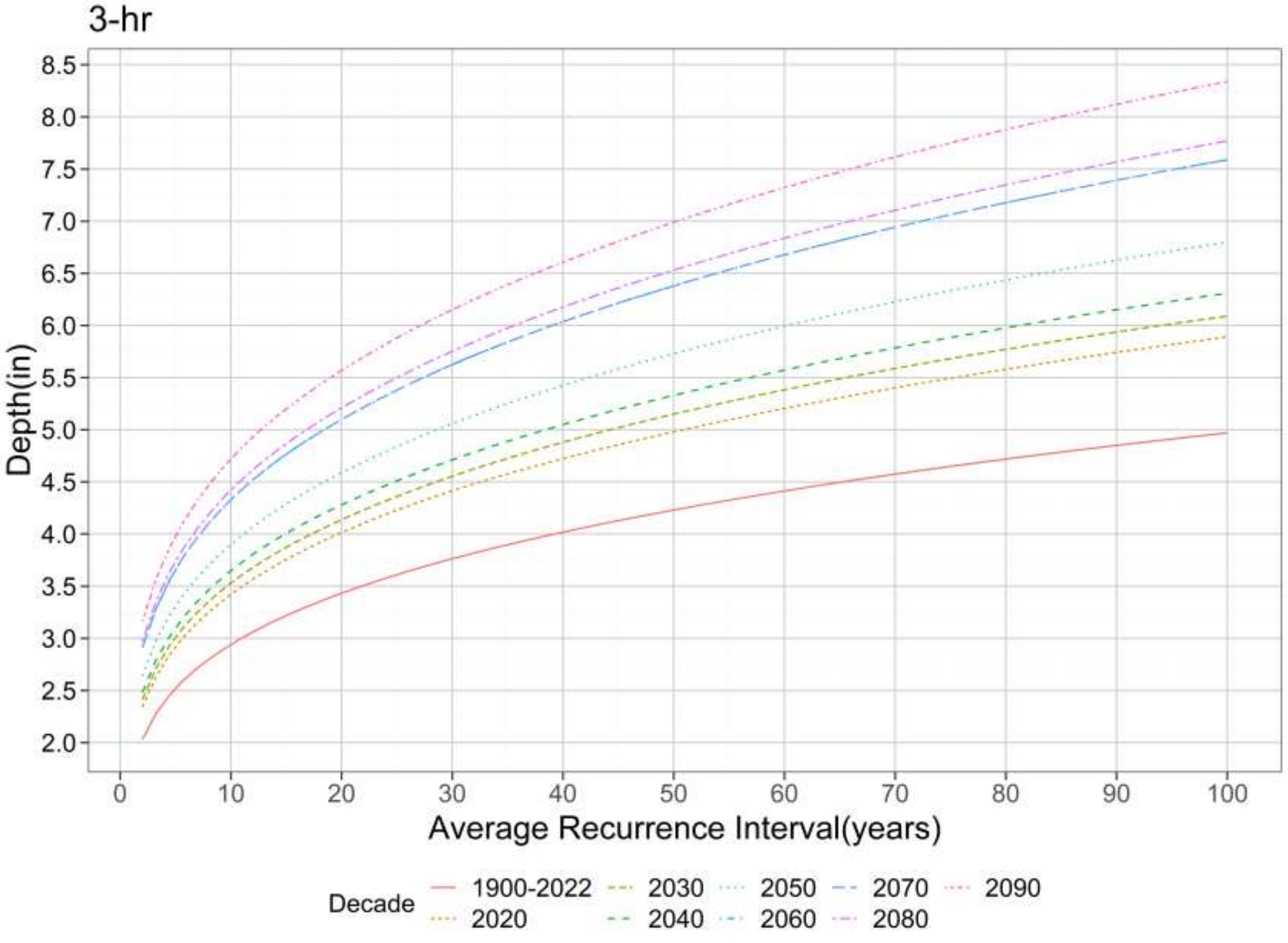

10-min
Depth(in)
2.0
1.5
1.0
0
10
20
30
40
50
60
70
80
90
100
Average Recurrence Interval(years)
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090

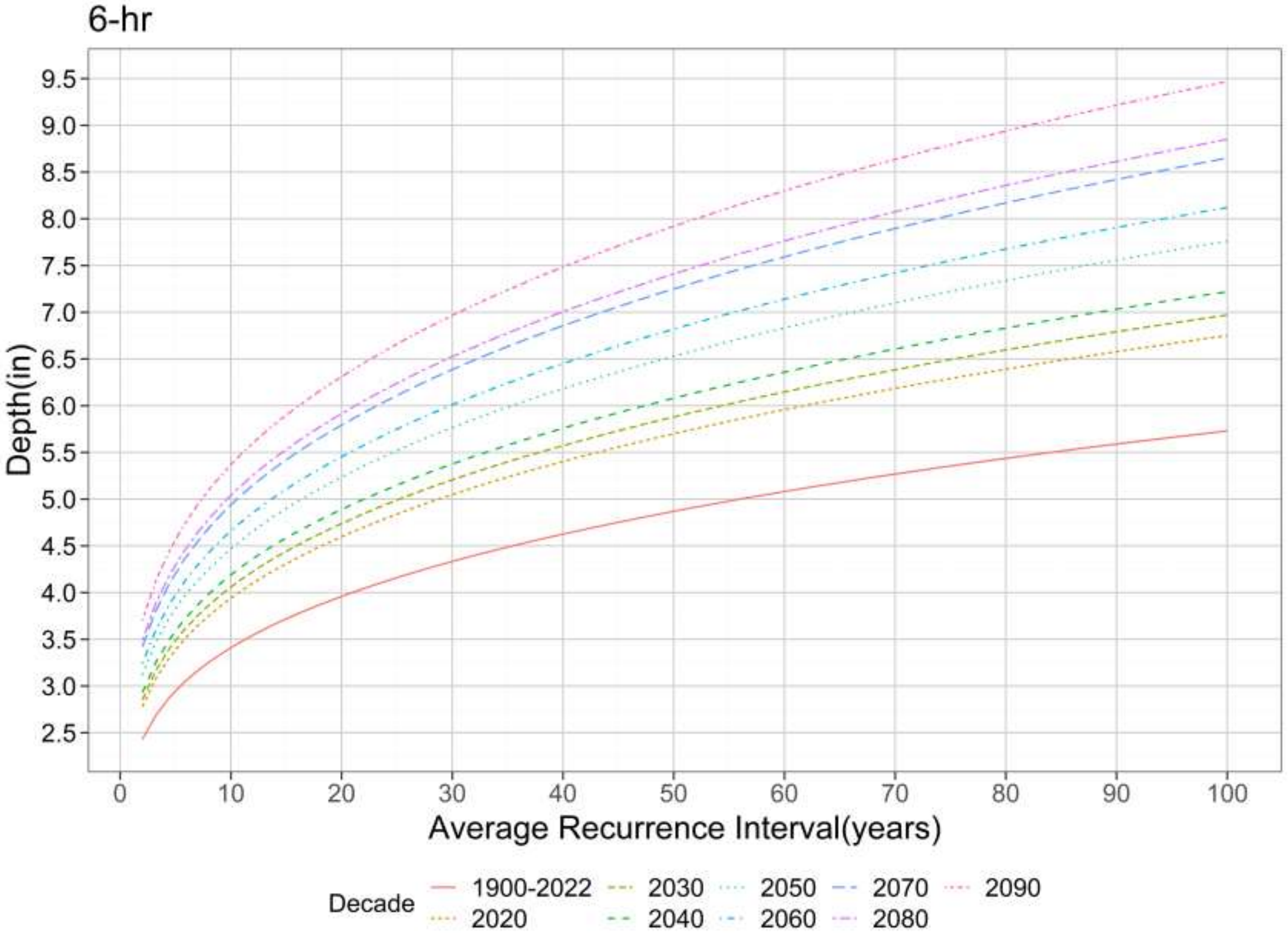

15-min
Depth(in)
2.5
2.0
1.5
1.0
0
10
20
30
40
50
60
70
80
90
100
Average Recurrence Interval(years)
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090

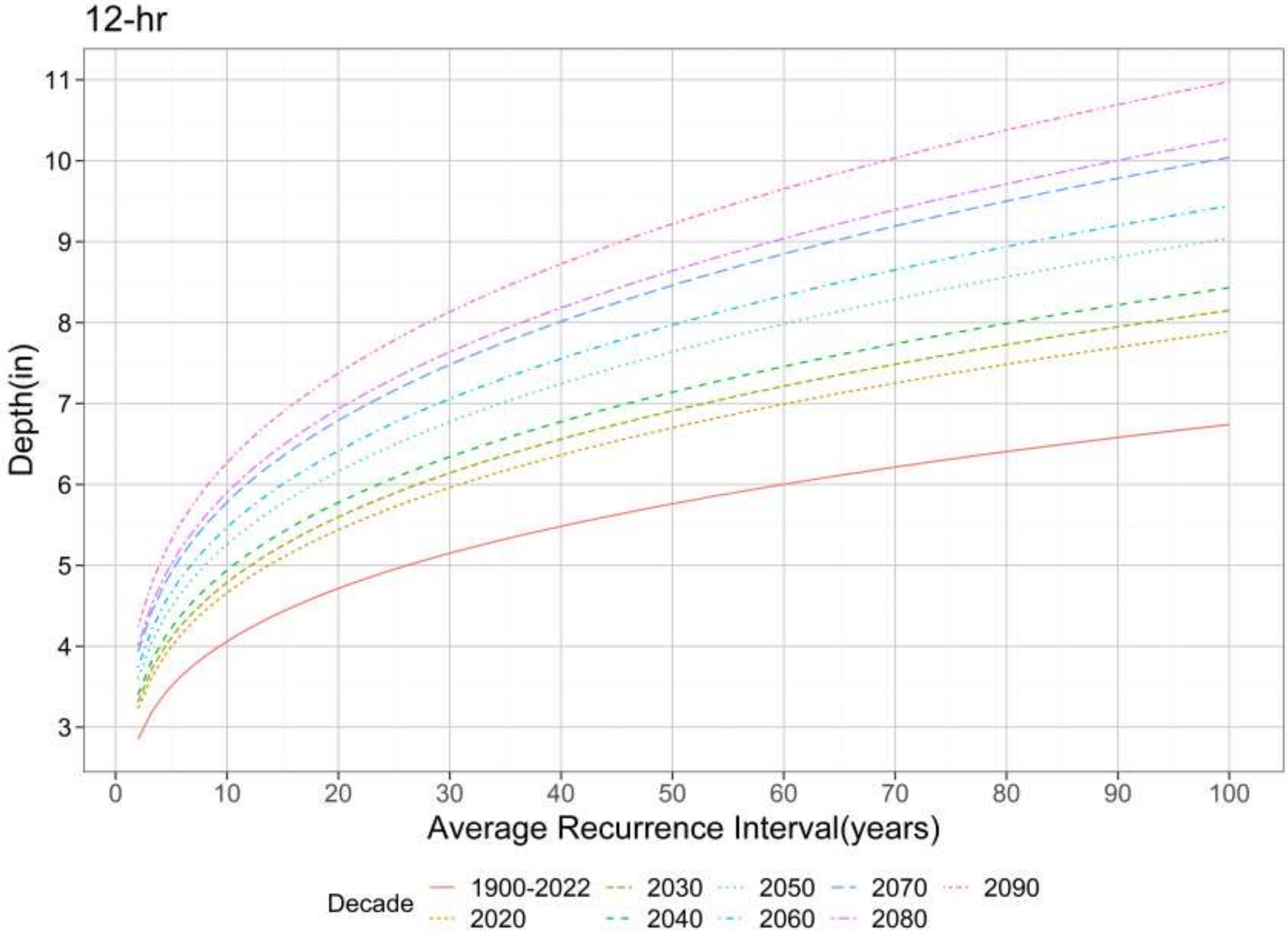

30-min
Depth(in)
4.0
3.5
3.0
2.5
2.0
1.5
0
10
20
30
40
50
60
70
80
90
100
Average Recurrence Interval(years)
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090

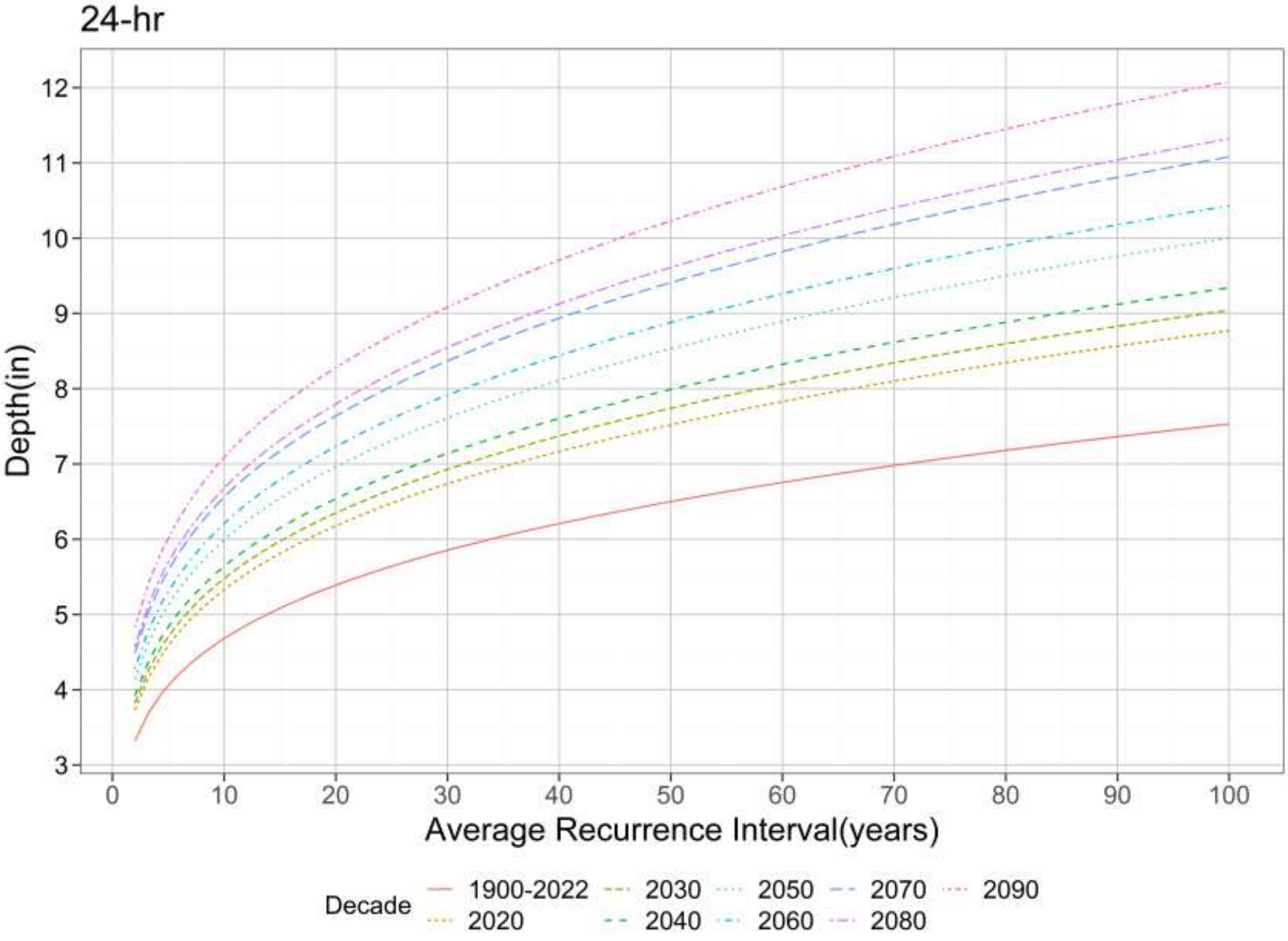

1-hr
Depth(in)
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
0
10
20
30
40
50
60
70
80
90
100
Average Recurrence Interval(years)
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090

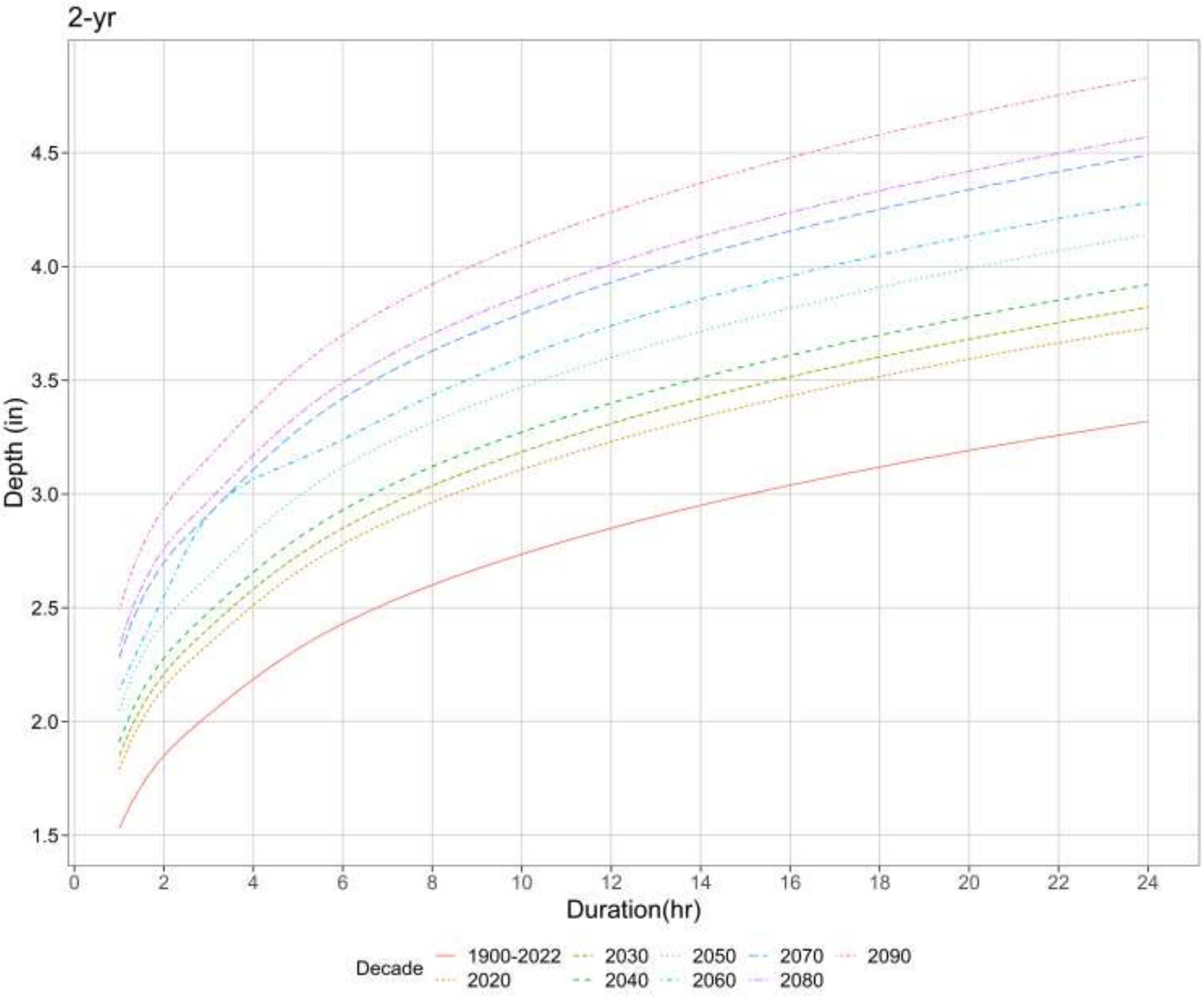

2-hr
Depth(in)
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
0
10
20
30
40
50
60
70
80
90
100
Average Recurrence Interval(years)
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090

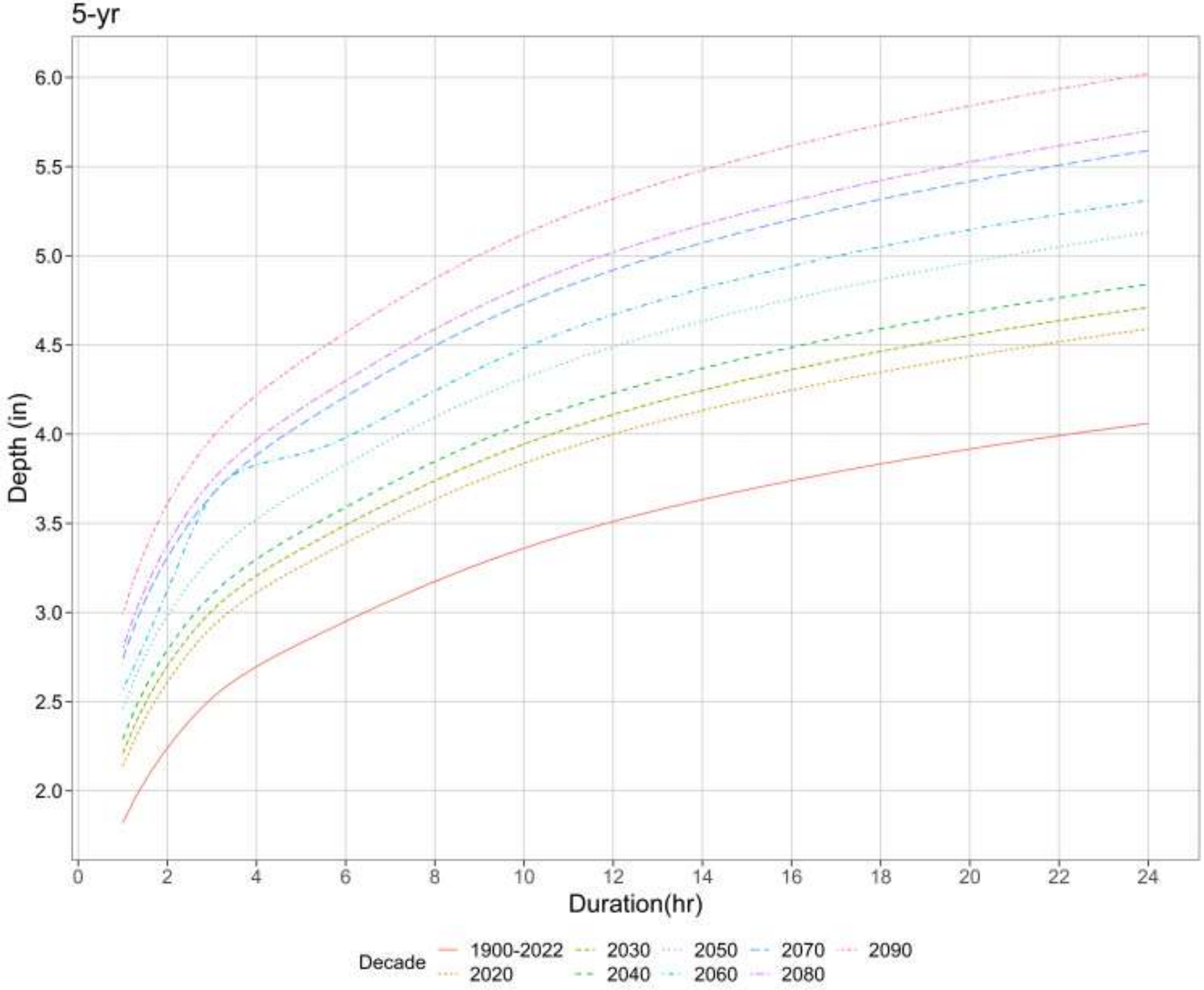

3-hr
Depth(in)
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
0
10
20
30
40
50
60
70
80
90
100
Average Recurrence Interval(years)
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090

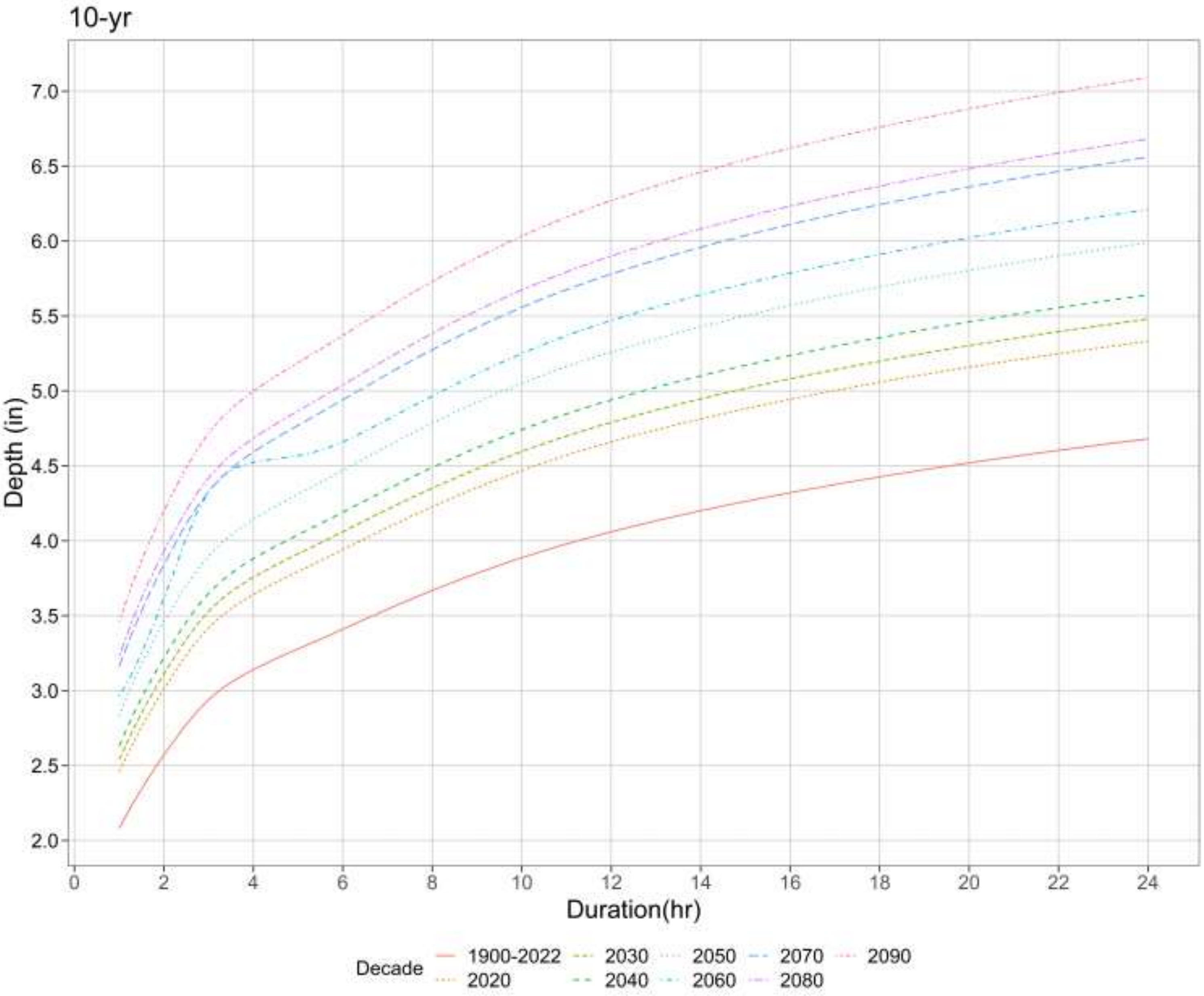

6-hr
Depth(in)
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
0
10
20
30
40
50
60
70
80
90
100
Average Recurrence Interval(years)
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090

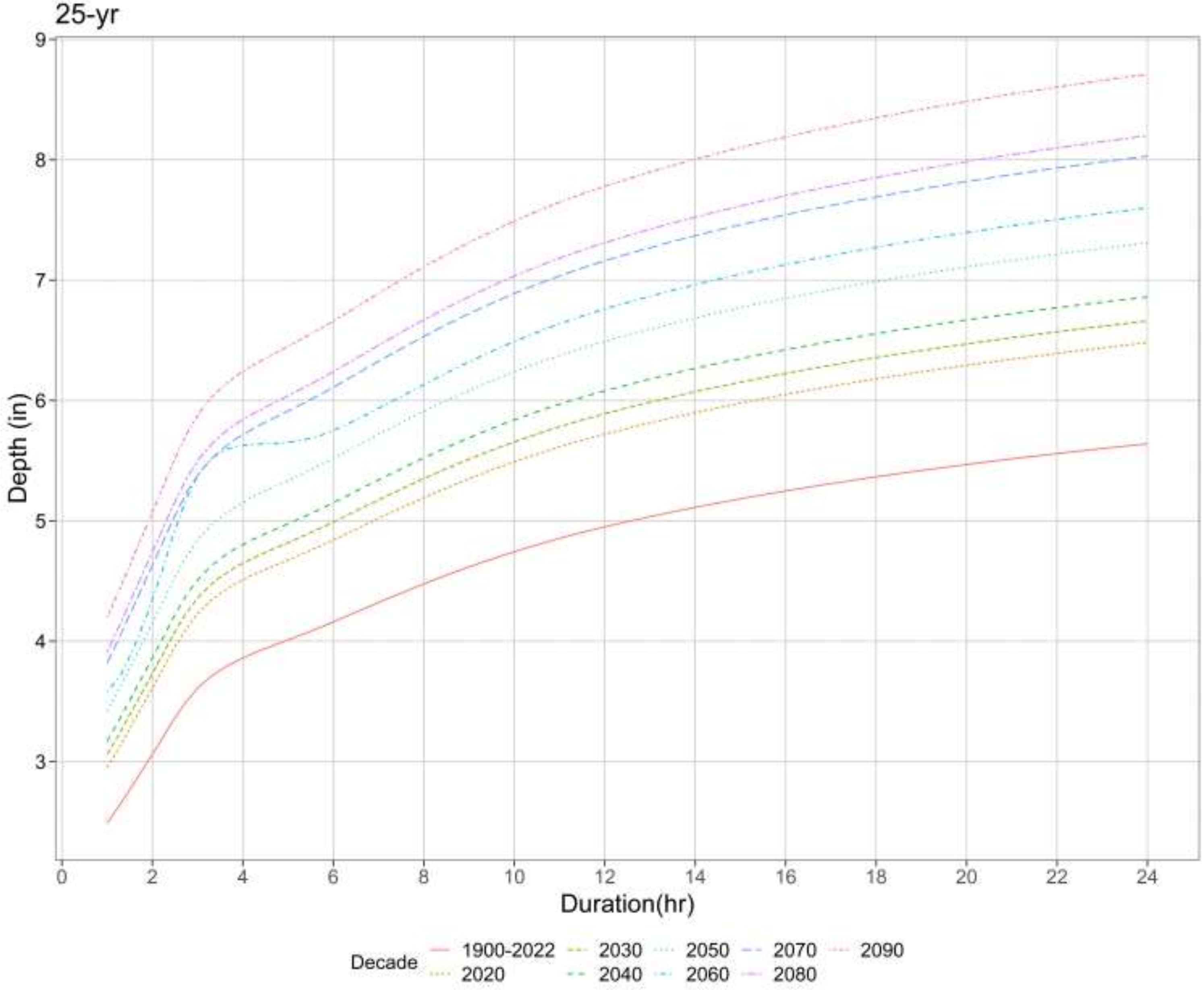

12-hr
Depth(in)
11
10
9
8
7
6
5
4
3
0
10
20
30
40
50
60
70
80
90
100
Average Recurrence Interval(years)
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090

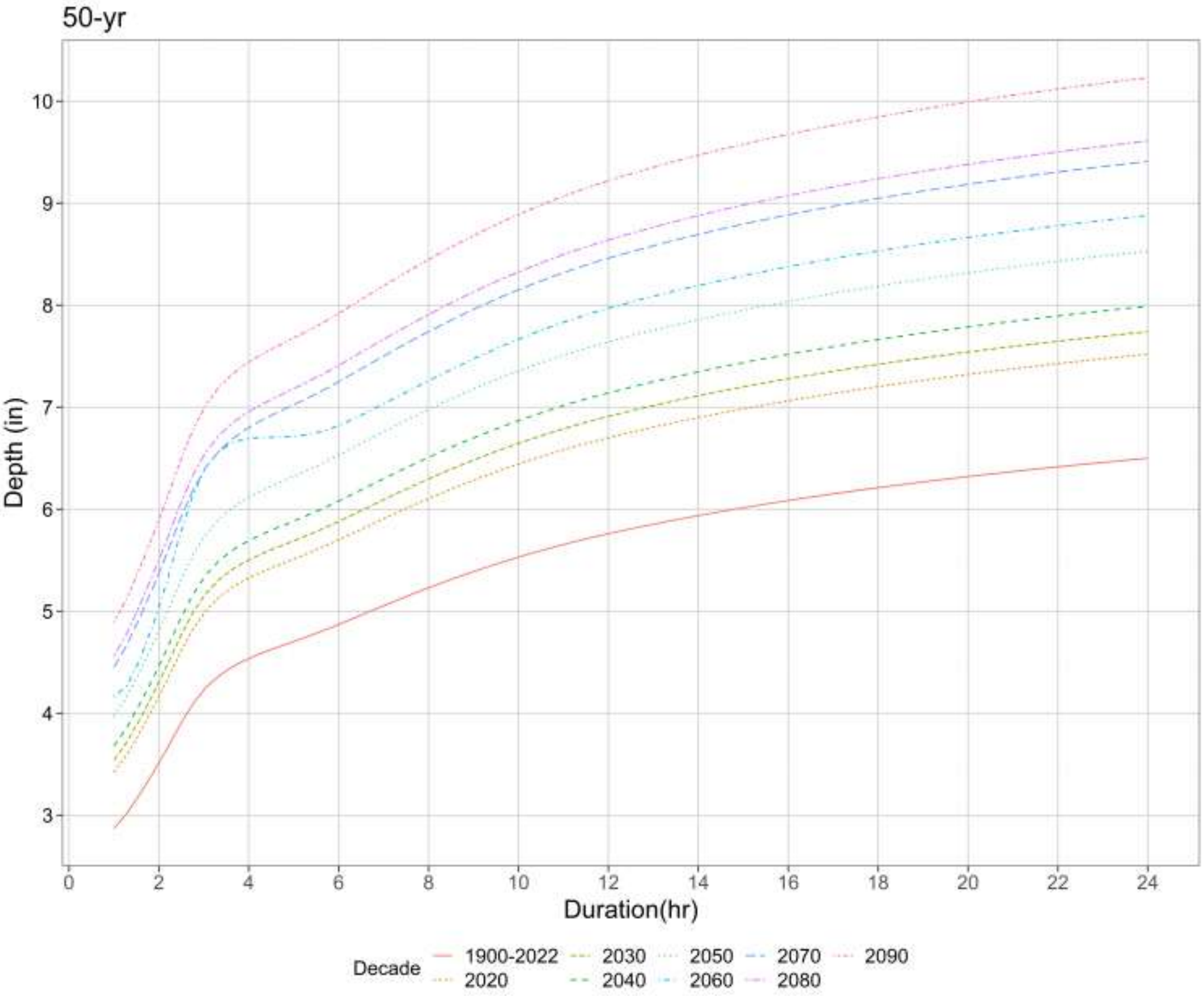

24-hr
Depth(in)
3
4
5
6
7
8
9
10
11
12
0
10
20
30
40
50
60
70
80
90
100
Average Recurrence Interval(years)
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090

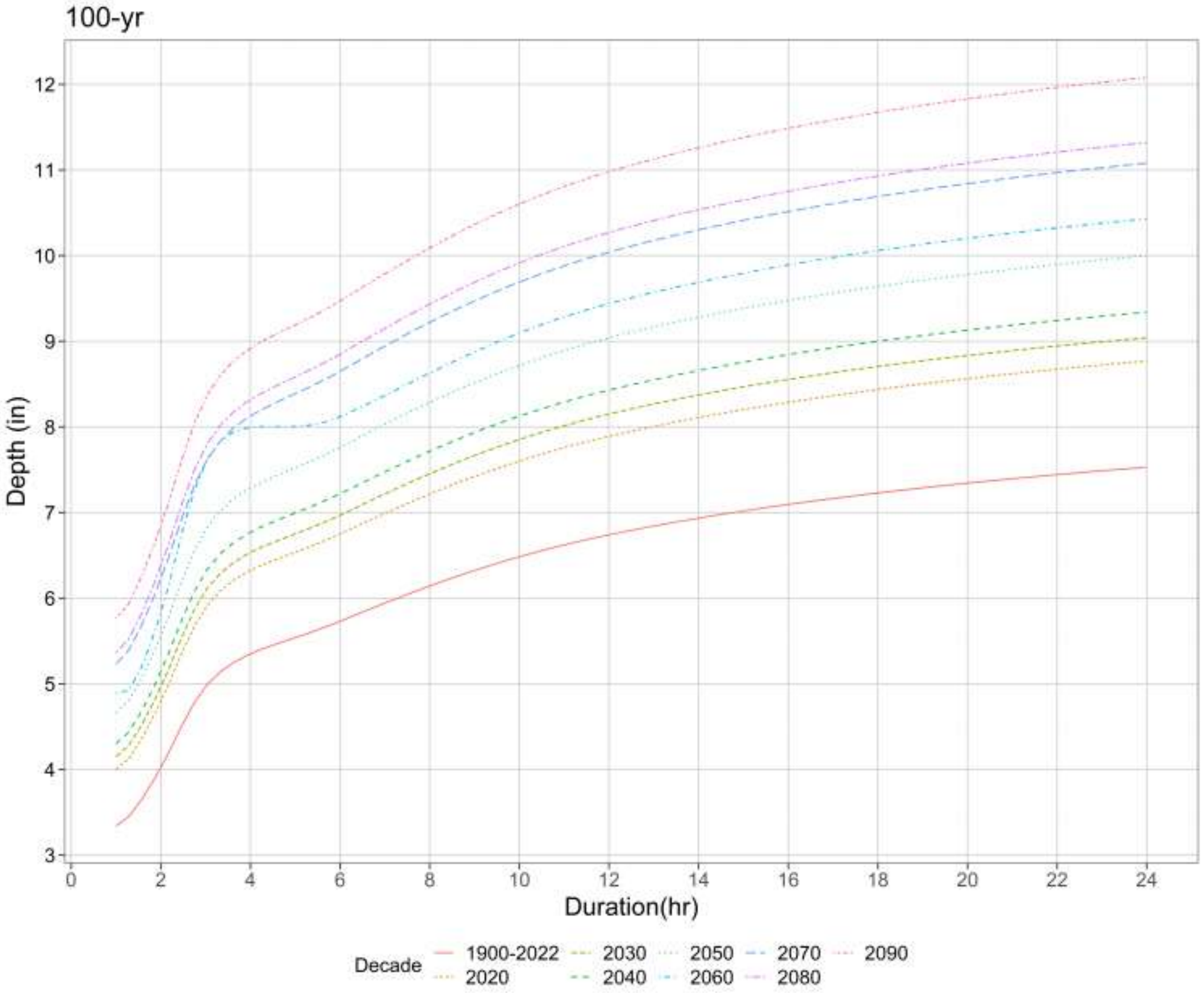

2-yr
Depth (in)
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Duration(hr)
0
2
4
6
8
10
12
14
16
18
20
22
24
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090


5-yr
Depth (in)
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
Duration(hr)
0
2
4
6
8
10
12
14
16
18
20
22
24
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090


10-yr
Depth (in)
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
0
2
4
6
8
10
12
14
16
18
20
22
24
Duration(hr)
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090


25-yr
Depth (in)
9
8
7
6
5
4
3
0
2
4
6
8
10
12
14
16
18
20
22
24
Duration(hr)
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090


50-yr
Depth (in)
3
4
5
6
7
8
9
10
Duration(hr)
0
2
4
6
8
10
12
14
16
18
20
22
24
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090


100-yr
Depth (in)
3
4
5
6
7
8
9
10
11
12
Duration(hr)
0
2
4
6
8
10
12
14
16
18
20
22
24
Decade
1900-2022
2020
2030
2040
2050
2060
2070
2080
2090