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Global Changes

U.S. Army Corps of Engineers Guidance for Incorporating Study-Specific Projections of Climate-Changed Meteorology and Hydrology

FOR THE COMMANDER:

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Purpose. The purpose of this Engineer Circular is to provide a consolidated reference that will guide U.S. Army Corps of Engineers procedures for conducting climate change assessments beyond what is currently required by existing U.S. Army Corps of Engineers guidance. It is targeted at (1) increasing accessibility to and the appropriate use of climate change information relevant to U.S. Army Corps of Engineers Civil Works projects, programs, missions, and operations and (2) supporting the use of that information to inform the U.S. Army Corps of Engineers Civil Works planning process. This document lists relevant resources and general best practices to follow when a more in-depth analysis using projected meteorology and hydrology is pursued to complement the assessment required by Engineering and Construction Bulletin 2018-14. The steps described in this document are meant to supplement, not replace, existing regulations and guidance related to hydrologic analyses for Civil Works studies (Engineer Manual 1110-2-1417, Engineer Regulation 1105-2-101, and Engineering and Construction Bulletin 2018-14).

Applicability. This guidance is effective immediately and applies to all U.S. Army Corps of Engineers Civil Works Headquarters, Division, and District components having responsibility for Civil Works projects and programs.

Distribution Statement. Approved for public release; distribution is unlimited.

Proponent and Exception Authority. The proponent of this regulation is the CECW-EC. The proponent has the authority to approve exceptions or waivers to this regulation that are consistent with controlling law and regulations. Only the proponent of a publication or form may modify it by officially revising or rescinding it.

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Glossary of Terms

1. Purpose

The purpose of this Engineer Circular (EC) is to provide a consolidated reference that will guide U.S. Army Corps of Engineers (USACE) procedures for conducting climate change assessments beyond what is currently required by existing USACE guidance. It is targeted at (1) increasing accessibility to and the appropriate use of climate change information relevant to USACE projects, programs, missions, and operations and (2) supporting the use of that information to inform the USACE Civil Works planning process. This document lists relevant resources and general best practices to follow when a more in-depth analysis using projected meteorology and hydrology is pursued to complement the assessment required by Engineering and Construction Bulletin (ECB) 2018-14. The steps described in this document are meant to supplement, not replace, existing regulations and guidance related to hydrologic analyses for Civil Works studies (Engineer Manual (EM) 1110-2-1417, Engineer Regulation (ER) 1105-2-101, and ECB 2018-14).

2. Applicability

This guidance is effective immediately and applies to all USACE Headquarters, Division, and District components having responsibility for Civil Works projects and programs.

3. Distribution Statement

Approved for public release; distribution is unlimited.

4. References

References and document links are presented in appendix A.

5. Records Management (Recordkeeping) Requirements

The records management requirement for all record numbers, associated forms, and reports required by this regulation are addressed in the Army Records Retention Schedule – Army (RRS-A). Detailed information for all related record numbers is located in the Army Records Information Management System (ARIMS)/RRS-A at https://www.arims.army.mil. If any record numbers, forms, and reports are not current, addressed, and/or published correctly in ARIMS/RRS-A, see Department of the Army (DA) Pamphlet 25-403, Guide to Recordkeeping in the Army, for guidance.

6. Background

a. Since 2014, the USACE Climate Preparedness and Resilience Policy Statement has required the consideration of climate change in all studies to reduce vulnerabilities and enhance the resilience of our water resource infrastructure. In many locations, the assumption of stationary hydrologic conditions no longer applies. The climatological baseline and the range of natural climate variability is changing and will continue to change for the foreseeable future. Where climate is changing, solely basing long-term planning decisions on analysis generated using the observed record of climate and streamflow may no longer reliably characterize future risk.

b. There is resounding evidence that changes in climate are affecting USACE's missions. Changes in various hydroclimatic conditions have been observed including changes in rainfall extremes, snowmelt characteristics, drought frequency and/or intensity, seasonal and annual water yield, and flood frequency. Examples of how climate change is affecting USACE business lines (like flood risk management, water supply, navigation, and ecosystem restoration) include:

(1) Increases in precipitation may cause future flood volumes to be larger and more frequent than they were in the past. This may result in flood waters remaining elevated for longer durations, increasing the potential for damages.

(2) Increases in drought severity and/or frequency may result in decreases in water availability and quality, reductions in water supply, disruptions to navigation, and habitat loss over time.

c. USACE's overarching guidance for accounting for climate change impacts to inland hydrology is published in ECB 2018-14. ECB 2018-14 and this EC are relevant to all USACE civil works applications including assessments being applied in support of project design, watershed studies, and water management decisions.

d. Specific to project design, ECB 2018-14 requires that climate change and variability be characterized across a project's life cycle or lifetime. The long lifetime of water resources infrastructure requires that projects be designed to include the flexibility to adapt to changing conditions.

(1) As defined by ER 1110-2-8159, project service life is the length of time a project will remain in use to provide its intended function. This will often exceed the time period used for economic analysis of project benefits and costs as the basis for project authorization. Project service life is generally defined as 100 years for major infrastructure projects such as locks, dams, and levees.

(2) Within a project's lifetime, changes to factors (including agency policy, socioeconomic conditions, and the hydroclimatic environment) may affect project performance.

(3) Threats to future project performance driven by these factors, including climate change, should be considered using a risk-informed approach. Risk assessment is a useful tool to supplement evaluation of options to ensure life-cycle performance.

e. Potential climate change-induced hazards and resulting consequences should be identified using the latest actionable science. This document helps support assessments of potential climate change impacts relevant to USACE hydrologic analysis.

7. Overview

a. A multi-tiered, scalable approach will be taken to assess climate change impacts relevant to USACE inland hydrology applications. Given the state of climate science at the time of this publication, it would be premature to require in-depth analyses of climate-changed meteorology and hydrology for all USACE engineering and planning efforts. For the majority of USACE efforts, the USACE Climate Preparedness and Resilience (CPR) Community of Practice (CoP) will continue to require that teams perform a Tier 1 climate change assessment, which meets the requirements laid out in ECB 2018-14.

b. A Tier 2 in-depth climate change analysis may be pursued, in addition to a Tier 1 ECB 2018-14 assessment, when appropriate, on a case-by-case basis. An in-depth analysis may be performed when the results of that analysis can reasonably be expected to provide added insight, aid in decision-making, reduce vulnerabilities, and/or enhance resilience to climate change threats (see section 8 for more detail).

c. Projections of future, climate-changed meteorology and hydrology encompass a large range of plausible futures, each with associated uncertainties driven in part by natural climate variability, climate model structure, and assumed emissions pathways (including socioeconomic effects). The rigorous and statistically robust mechanisms available for quantifying the uncertainty associated with other design and planning factors cannot be applied to fully describe the uncertainty associated with projections of future climate-changed meteorology and hydrology. Thus, guidance on the interpretation and appropriate application of climate-changed projections to local-scale projects is required.

d. In-depth analysis will be conducted only with CPR CoP guidance and approval.

8. Objective of In-Depth Analyses

In-depth analysis can be used to better understand climate change vulnerability by exposing potential future hazards. Results can be applied to better understand the likelihood of climate-driven changes materializing in the future. This insight, along with an evaluation of the potential harms that could occur as a result of changing conditions, can support a better understanding of climate change risk. Study area specific, global climate model (GCM)-based projections of climate-changed meteorology and hydrology can be used to evaluate and compare alternatives and to aid in water resources management and decision-making.

a. An analysis of study area-specific climate-changed projections of meteorology and hydrology should not be used in isolation to support project design or other water resources applications. Output from in-depth analyses should be used in tandem with, not in place of, existing USACE standards of practice.

b. For project design, with and without project conditions should be defined by the most likely condition expected to exist in the future (ER 1105-2-100). By better understanding both the hazards posed by climate change and their likelihood of occurrence throughout a project's life cycle, steps can be taken towards making a project more resilient. However, modifying design parameters to reflect projected climate-changed meteorology and hydrology is often inadvisable due to the large uncertainty associated with climate projections and the fitness of climate-modeling techniques for providing many engineering design values. Thus, calculating an updated design value adjusted to reflect future conditions should not be the primary objective of an in-depth climate change analysis.

c. If there is strong evidence that an effect of climate change will have significant impacts to a planned project, the results of a supplemental analysis can be used to justify incorporating added resilience into a design or management plan.

(1) Significant climate change impacts can be driven by the magnitude of change in future conditions, the severity of the resulting consequences, or both. An evidence-based, consequence-driven approach will be taken to support the need for resilience planning. Conducting an in-depth climate change analyses will enable teams to better

understand and substantiate the level of risk that climate change poses to a given study area.

(2) Per USACE Engineer Pamphlet (EP) 1100-1-5, USACE defines resilience as the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions. To make USACE projects resilient to climate change, teams should look for opportunities to incorporate a degree of robustness into USACE designs and management plans so that they can absorb future climate change impacts. Robustness is the ability of a system to continue to operate effectively across a wide range of conditions.

d. One strategy for incorporating resilience into water resources planning is to apply an adaptive management approach. The results of an in-depth analysis can be used to formulate and justify adaptive management plans. Adaptive management effectively manages uncertainty and reduces the risk of overspending by supporting flexible designs and management frameworks that can appropriately evolve as future climate conditions become more certain (Choate et al., 2017).

9. Basis for Conducting In-Depth Analysis

a. Conducting study area-specific analysis of climate-changed, projected meteorology and hydrology is resource intensive. For the majority of USACE projects and studies, the Tier 1 assessment required by ECB 2018-14 is sufficient to support an assessment of the risk and uncertainty posed by climate change. Thus, teams should assess whether an in-depth Tier 2 climate change analysis, using study area-specific climate-changed meteorology and/or hydrology is warranted and of sufficient added value to justify its cost prior to pursuing such an approach.

b. The scale and level of risk tolerance associated with the study effort being undertaken should be considered when deciding what type of information should be incorporated into analysis and how that information should be used.

(1) *Scale*. The level of effort associated with characterizing the effect of climate change should be proportional to the study complexity. Study complexity is defined in terms of the type, size, location, scope, and overall cost of the project/study effort. Complexity increases when a project finding or water resources management decision impacts other state or local water resources agencies and/or where there is significant public interest.

(2) *Risk Tolerance*. If the decision being made reflects a high degree of risk averseness an in-depth analysis may be justified. For example, a decision impacting a recreational feature is unlikely to warrant additional investigation. Conversely, decisions related to a high consequence flood risk reduction project are more risk averse and may warrant additional analysis to better quantify climate change impacts.

c. The sensitivity of the project/decision to the variability and uncertainty associated with climate change relative to other risk factors should be taken into consideration. Climate change sensitivity can be evaluated by identifying the critical variables to the study area/decision/project being assessed and determining if climate change could impact these variables in the future. Prior to pursuing in-depth analysis, the study team should take the following steps:

(1) Establish a basic understanding of how climate hazards (such as changes in streamflow, extreme temperatures, seasonality) may impact a given location, design feature, management decision, etc.

(2) Determine the magnitude of change relative to current conditions which would necessitate a change in the design/decision-making/management approach.

(3) Evaluate the sensitivity to relevant climate stressors by taking into consideration the practitioner's existing understanding of how the system and relevant assets have been impacted by extreme weather conditions experienced in the past. Teams should also consider problems that might arise if climate stressors become more severe in the future. Where there is substantial evidence that the effects of climate change have been observed and/or are projected to influence project performance in the future, in-depth analyses can be appropriately applied.

d. The complexity of the climate assessment should mirror the risk associated with climate change impacts on the study area, decision being made, and/or proposed project features. USACE refers to risk as a combination of the magnitude of the potential consequence(s) and the probability that the consequence(s) will occur. To justify the need for a Tier 2 in-depth analysis, the risk that climate change might pose to a project should be appreciable in terms of the likelihood of climate change presenting a hazard and the degree of harm it would induce. A hazard is a circumstance that increases the likelihood of danger or peril to life, property, resources, or assets.

e. There is generally more confidence in GCM-based projections of hydrologic changes directly related to certain variables like temperature change (for example, snowmelt timing, streamflow seasonality) or annual precipitation than for variables with higher variability (extreme precipitation, peak rainfall flood events). Thus, GCM output-based, in-depth analysis can provide greater value for projects sensitive to changes that result from changes in variables with stronger climate signals and linkages to warming.

f. The Tier 1 ECB 2018-14 framework should be used to perform a preliminary risk assessment to determine whether there is evidence that climate change is likely to have an impact on a given study area, water resources decision, and/or project feature (see appendix E for more detail).

10. Initial Scoping of In-Depth Analysis

The level of detail associated with the proposed climate assessment and the intended application of results must be clearly defined before developing an in-depth analysis of the effects of climate change. Appendix C provides key criteria and guidelines for developing in-depth analyses. As noted in section 9, the meteorological and/or hydrologic variable(s) to which the project or study is potentially sensitive to should be identified. The approach to characterization and evaluation of these changes in climate, hydrology, and project impacts using projected meteorology and hydrology should be detailed.

a. The proposed scope of analysis must document the data products and projections to be applied, the modeling approaches to be used, computational requirements, and the proposed workflow. Projections of future meteorology and hydrology generally require selecting assumed greenhouse gas (GHG) emissions pathways, an ensemble of GCMs, a mechanism for downscaling GCM output to spatial and temporal scales relevant to water resources planning, and the selection and implementation of a hydrologic model. Appendix B includes references to the typical components of an in-depth analysis of projected meteorology and/or hydrology and can be used as a reference during the scoping process.

b. The study team should consider the availability, relevance, and credibility of existing projected meteorology and hydrology applicable to the study area.

c. As part of scope development, the project delivery team (PDT) must consider whether a modeling approach or dataset is fit for the intended application. “Fit-for-purpose” is a concept that is increasingly used to describe the degree to which a method or tool is designed and applied to accomplish reliable outcomes for the information needs of a particular study. Modeling tools and methods are typically constructed and applied to meet one set of objectives—but then may be applied to settings with different objectives, including those for which they are not suitable or fit to provide reliable information. It is important to identify if a model or data source is reliable or actionable for a particular decision. A review of past applications and use, expert consultation, and/or a preliminary reliability evaluation of the modeling datasets based on the intended application should be conducted to ensure reliable outcomes. If considerations or adjustments need to be made to a data product in order to make the product “fit-for-purpose,” these must be documented.

d. As indicated in appendix B, each component of the modeling chain introduces uncertainty into the resulting projections. How the uncertainty associated with each component of the modeling chain will be conveyed as part of the analysis being proposed needs to be addressed within the scope. The resulting product needs to address how uncertainty will be evaluated over the model time period and the implications of these uncertainties to how results are interpreted (Vano et al., 2020).

e. The scope should describe how the team intends to evaluate the projected meteorology and/or hydrology and define what types of conclusions will be made. Given the uncertainty associated with projected meteorologic and hydrologic response, results representing different plausible futures should be incorporated into a risk-based approach. Appendix D outlines some best practices that can be applied to support the interpretation of GCM-based projected meteorology and hydrology. The final product should characterize confidence in projection information, indicating the weight it will be given in a design or plan.

f. It is strongly recommended that PDTs consult with the CPR CoP lead or delegate throughout the scoping process. Some options for engaging the CPR CoP include scoping workshops and/or interim review of the scope.

(1) The CPR CoP can provide advice and direction on appropriate sources of relevant climate change information for the project under analysis and on the appropriateness and applicability of processes and methods of analysis being proposed by the project team.

(2) The CPR CoP can advise the project team on the general type of conclusions that can be made based on the analysis being proposed.

(3) The CPR CoP can also ensure the proposed work complies with existing USACE guidance and incorporates the latest best practices for analyzing projections of meteorology and hydrology.

11. Climate Preparedness and Resilience Community of Practice Scope Approval

The PDT will submit a scope of work to the USACE CPR CoP. The scope of work should establish the basis for conducting analysis (section 9), the proposed workflow, and how results will be applied. The CPR CoP will review the submission and indicate whether a study area-specific, in-depth, Tier 2 analysis can and should be performed. An overview of the steps required to receive CPR CoP scope approval are detailed in the flowchart displayed in appendix E. Outcomes and decisions from the CPR CoP consultation must be documented prior to continuing with a Tier 2 analysis.

12. Application to Planning Process

a. Elements of the Tier 1 ECB 2018-14 assessment necessary to support the need for an in-depth Tier 2 climate change analysis should be conducted at the earliest stage possible.

b. If the team determines that an in-depth analysis of climate change impacts is warranted in support of a feasibility study, a scope of work should be drafted and be approved by the CPR CoP prior to the Alternatives Milestone Meeting (AMM) presentation. Both the Tier 1 ECB 2018-14 assessment and the Tier 2 in-depth analysis (if applicable) should be carried out before alternatives are fully formulated or evaluated.

(1) As part of the AMM, the PDT should briefly discuss the primary meteorologic, hydrologic, and/or coastal processes related to study area problems and opportunities. A brief overview of the basis for conducting the in-depth analysis and the proposed scope should be presented at the AMM.

(2) Between the Alternatives Milestone and the Tentatively Selected Plan (TSP) Milestone, the in-depth analysis should be generated in order to support the PDT in evaluating and comparing the focused array of alternatives in order to identify the TSP.

c. Once the USACE CPR CoP has reviewed and approved the proposed scope of work for an in-depth climate change analysis, the outcome of the proposed analysis can be used to support planning and engineering decisions. Analyses can be applied to support components of established USACE project decision-making procedures and to evaluate project performance.

d. Climate change assessments, resulting in the derivation of project-specific, projected meteorology and hydrology can directly alter the numerical calculations and results of hydrologic analysis. However, because there is a great deal of uncertainty associated with projected meteorology and hydrology, it is necessary to apply numerical results appropriately. This includes effectively communicating the uncertainty associated with these results. As described in greater detail in section 7, the numerical data generated by in-depth climate analyses does not provide a complete depiction of climate uncertainties. This implies that climate projection data will not usually be directly applied as part of economic analysis because it cannot be used to generate future flow-frequency relationships with defined confidence limits reflective of the true range of uncertainty.

e. Some examples and methods by which projections of meteorology and hydrology can be incorporated into the USACE planning process are described in appendix D.

13. Documentation

a. An in-depth Tier 2 climate change analysis may be undertaken as an independent study effort. In such cases, the study should be documented as a stand-alone report. When an in-depth climate change analysis is being conducted to support a larger study effort (such as the Design Documentation Report, Feasibility Report, or Environmental Assessment), it is expected that the analytical detail of the analysis will be documented in a separate climate change appendix to the main report, while summaries of the analyses and key findings will be integrated into the relevant sections of the main document.

b. Whether the analysis is being presented as a stand-alone report or an appendix to a larger study effort, the justification for an in-depth analysis, as well as the strategies for characterizing climate change impacts and how these results are integrated in a study's design and/or decision-making process should be introduced early in the report.

c. The appendix or independent climate change report must describe the datasets, models, and methods applied to define future meteorologic and hydrologic conditions. Documentation should include visualizations of projected meteorology and/or hydrology that supports the interpretation of the uncertainty associated with these data products. The appendix or independent report should describe the ensemble of GCMs applied, assumptions related to GHGs (for example, Representative Concentration Pathways [RCPs] or Shared Socioeconomic Pathways [SSPs]), GCM downscaling method(s), hydrologic model(s) used, hydrologic modeling assumptions and calibration, and any bias-correction or post-processing techniques applied.

14. Review

At a minimum, an in-depth Tier 2 climate analysis must undergo District Quality Control Review (DQCR) and an Agency Technical Review (ATR). At least one member of the ATR team for projects covered by this EC must be certified for review of climate hydrology impacts and adaptation by the CPR CoP in the Corps of Engineers Review Certification and Access Program (CERCAP). Outcomes of the CPR CoP consultation must be included as part of the study's review documentation.

Appendix A
References

Required Publications

USACE Publications

Unless otherwise indicated, all U.S. Army Corps of Engineers publications are available on the USACE website at https://publications.usace.army.mil. Army publications are available on the Army Publishing Directorate website at https://armypubs.army.mil.

ECB 2018-14 Rev 1
Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects. (Available at https://www.wbdg.org/ffc/dod/engineering-and-construction-bulletins-ecb/usace-ecb-2018-14).

ECB 2020-6
Implementation of Resilience Principles in the Engineering and Construction Community of Practice. (Available at https://www.wbdg.org/ffc/dod/engineering-and-construction-bulletins-ecb/usace-ecb-2020-6).

EM 1110-2-1417
Flood-Runoff Analysis

ER 1105-2-100
Planning Guidance Notebook

ER 1105-2-101
Risk Assessment for Flood Risk Management Studies

ER 1110-2-8159
Life Cycle Design and Performance

EP 1100-1-5
USACE Guide to Resilience Practices

EP 1100-2-1
Procedures to Evaluate Sea Level Change: Impacts, Responses, and Adaptation

For references available from the USACE library please use the following link: https://usace.contentdm.oclc.org/.

USACE Climate Preparedness and Resilience Policy Statement
USACE Climate Preparedness and Resilience Policy Statement.

USACE Adaptation Policy Statement
USACE Climate Preparedness and Resilience Policy Statement.

USACE Climate Change Adaptation Policy Statement
USACE Climate Preparedness and Resilience Policy Statement.

Private Sector Publications

Intergovernmental Panel on Climate Change (IPCC) (2014)
Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri, and L.A. Meyer (eds.)]. IPCC. Geneva, Switzerland. pp. 151. Available at https://www.ipcc.ch/report/ar5/syr/.

IPCC (2021)
Summary for Policymakers. In: Climate Change 2021: The Physical Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. [V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. In Press. Available at https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf.

International Joint Commission (IJC) (2017)
A Climate Change Guidance Framework for IJC Boards. Available at https://www.ijc.org/sites/default/files/IWI_CAWG_2017_02.pdf.

IJC (2018)
Climate Change Guidance Framework for IJC Boards: A Highlights Report 2018. Available at https://www.ijc.org/en/climate-change-guidance-framework-ijc-boards-highlights-report-2018

River Management Joint Operating Committee (RMJOC) (2018, 2020)
Climate and hydrology datasets for RMJOC long-term planning studies: Second Edition (RMJOC-II) Part I: Hydroclimate projections and analyses. Portland, OR. River Management Joint Operating Committee: Bonneville Power Administration, United States Army Corps of Engineers, United States Bureau of Reclamation. Available at https://usace.contentdm.oclc.org/digital/collection/p266001coll1/id/10562/rec/3.

Public Sector Publications

A Comparison of Statistical Downscaling Methods Suited for Wildfire Applications
Abatzoglou, J.T., and Brown, T.J. 2012. “A comparison of statistical downscaling methods suited for wildfire applications.” *International Journal of Climatology*. (Available at https://doi.org/10.1002/joc.2312)

A Decision-Analytic Approach to Managing Climate Risks: Application to the Upper Great Lakes
Brown, C., Werick, W., Leger, W., and Fay, D. 2011. "A decision-analytic approach to managing climate risks: Application to the upper Great Lakes." *Journal of the American Water Resources Association*. 47:524–534. Available at https://doi.org/10.1111/j.1752-1688.2011.00552.x.

A Process – Conditioned and Spatially Consistent Method for Reducing Systematic Biases In Modeled Streamflow
Bennett, A., Stein, A., Cheng, Y., Nijssen, B., and McGuire, M. 2022. "A process – conditioned and spatially consistent method for reducing systematic biases in modeled streamflow." *Journal of Hydrometeorology*. (Available at https://journals.ametsoc.org/view/journals/hydr/23/5/JHM-D-21-0174.1.xml)

A Workshop on Improving Our Methodologies of Selecting Earth System Models for Climate Change Impact Applications
Newman, A.J., et al. (2022). "A workshop on improving our methodologies of selecting Earth System Models for Climate Change Impact Applications." *Bulletin of the American Meteorological Society*. 103.4:E1213–E1219. Available at https://journals.ametsoc.org/view/journals/bams/103/4/BAMS-D-21-0316.1.xml.

An Overview of CMIP5 and the Experiment Design
Taylor, K.E., Stouffer, R.J., Meehl, G.A. 2012. "An Overview of CMIP5 and the experiment design." *Bulletin of the American Meteorological Society*. 93:485–498. Available at https://doi.org/10.1175/BAMS-D-11-00094.1.

Comparing Downscaled LOCA and BCSD CMIP5 Climate and Hydrology Projections
Vano, J., Hamman, J., Gutmann, E., Wood, A., Mizukami, N., Clark, M., Pierce, D.W., Cayan, D.R., Wobus, C., Nowak, K., and Arnold, J. 2020. "Comparing Downscaled LOCA and BCSD CMIP5 Climate and Hydrology Projections." Release of *Downscaled LOCA CMIP5 Hydrology*. p. 96. Available at https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/LOCA_BCSD_hydrology_tech_memo.pdf

Characterizing Uncertainty of the Hydrologic Impacts of Climate Change
Clark, M.P., Wilby, R.L., Gutmann, E.D., Vano, J.A., Gangopadhyay, S., Wood, A.W., Fowler, H.J., Prudhomme, C.. Arnold, J.R., and Brekke, L.D. 2016. "Characterizing uncertainty of the hydrologic impacts of climate change." Current Climate Change Report 2. No. 2:55–64. Available at https://doi.org/10.1007/s40641-016-0034-x.

Climate Risk Informed Decision Analysis (CRIDA)
Mendoza, G.F., et al. 2018. "Climate Risk Informed Decision Analysis." UNESCO and ICIWaRM: Paris, France and Alexandria, USA. p. 162. Available at https://unesdoc.unesco.org/ark:/48223/pf0000265895.

Decision Scaling: Linking Bottom-Up Vulnerability Analysis with Climate Projections in the Water Sector
Brown, C., Ghile, Y., Laverty, M. and Li, K. 2012. "Decision scaling: Linking bottom-up vulnerability analysis with climate projections in the water sector." *Water Resource. Research*. 48(9). W09537. Available at https://doi.org/10.1029/2011WR011212.

Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections: Release of Hydrology Projections, Comparison with Preceding Information, and Summary of User Needs
Reclamation. 2014 "Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections: Release of Hydrology Projections, Comparison with Preceding Information, and Summary of User Needs." U.S. Department of the Interior. Bureau of Reclamation. Technical Services Center. Denver, CO. pp. 110. Available at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/BCSD5HydrologyMemo.pdf.

Evaluation of CMIP5 20th Century Climate Simulations for the Pacific Northwest USA
Rupp, D.E., Abatzoglou, J.T., Hegewisch, K.C., and Mote, P.W. 2013. "Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA." *Journal of Geophysical Research: Atmospheres*. 118:10,884–10,906. Available at https://doi.org/10.1002/jgrd.50843.

Evaluation of Bias-Correction Methods for Ensemble Streamflow Volume Forecasts
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Appendix B
Components of an In-Depth Climate Analysis and Available Resources

A series of models, modeling decisions, and data processing techniques is applied to generate projections of climate and hydrology and the potential effects on resources (Figure 1). The development of climate projections typically utilizes an ensemble approach due to the range of hydroclimate outcomes represented by different models or modeling decisions, a lack of consensus on any single most appropriate method or model, and uncertainty in future human actions and policy decisions. This appendix describes the common components of the modeling chain.

B–1. Emissions Scenarios

a. The Intergovernmental Panel on Climate Change (IPCC) produces assessment reports on an approximate 7-year cycle. A common set of scenarios of future GHG emissions is developed for the basis of each report. An emission scenario is a plausible outcome of societal actions and represents relationships between human choices, land use changes, and those effects on GHG concentration in the atmosphere. These include multiple representations of potential policy change and mitigation, energy source contribution, afforestation/deforestation, and other influences. These scenarios are not predictions of the future, but rather can be used to represent a range of plausible outcomes given today's knowledge.

b. Given the large uncertainty in the choice of future policy and mitigation efforts, multiple emissions scenarios should be considered for in-depth analyses. However, it is also recognized that some scenarios are exceedingly unlikely and should not form the sole basis of planning activities (for example, RCP 2.6 from CMIP5) without appropriate prior consideration. A review of the current best practices and scenarios used in recent national climate assessments is necessary. Recent scenarios developed by the IPCC have included:

(1) Representative Concentration Pathways (RCPs) – scenarios for 2014 IPCC Fifth Assessment Report (AR5).

(2) Shared Socioeconomic Pathways (SSPs) – scenarios for 2021/22 IPCC Sixth Assessment Report (AR6).

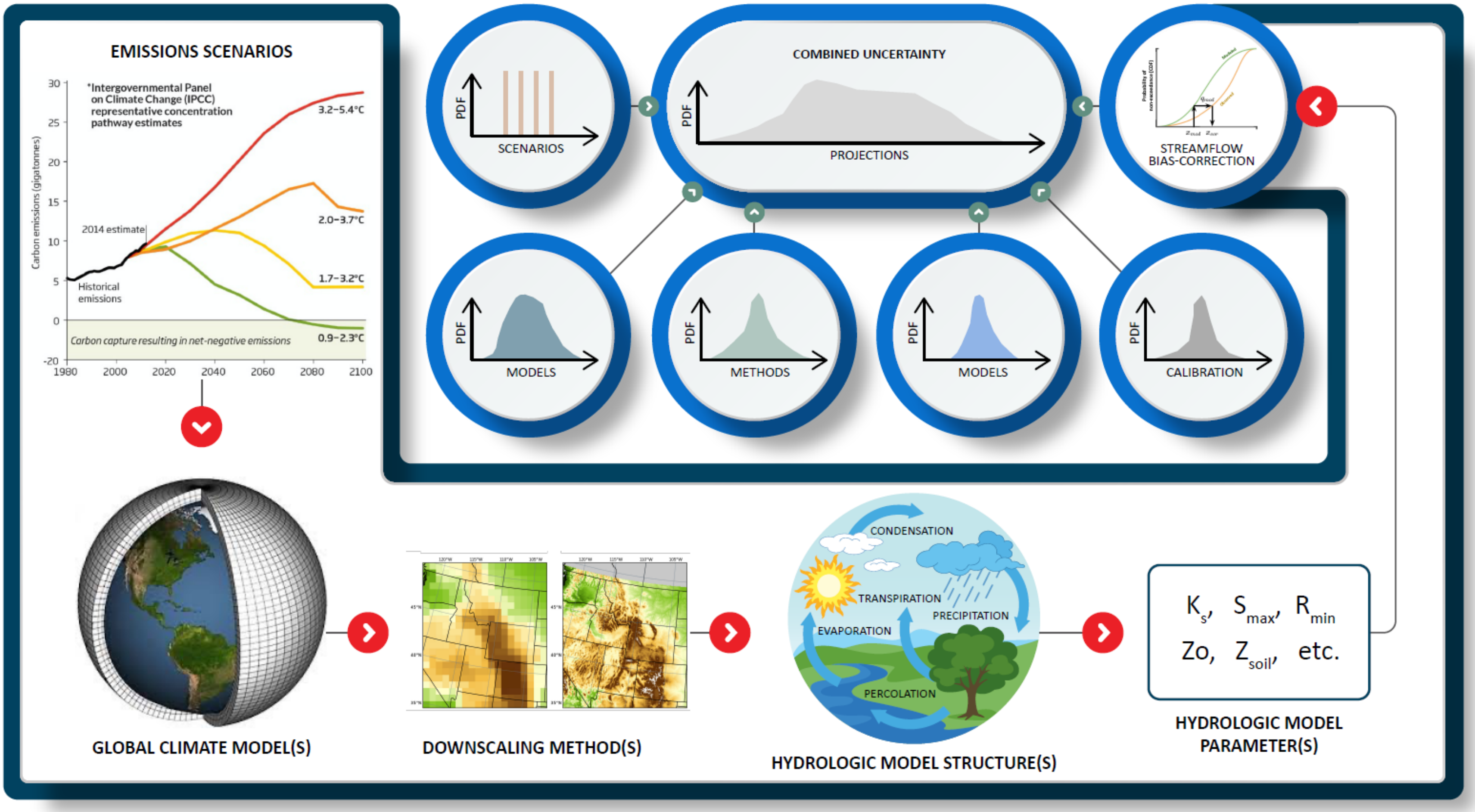

Figure 1: Graphical depiction of the models and methods used to predict the effects of global climate change on local resources (adapted from Clark et al., 2016)

B–2. Global Climate Models and Earth System Models

a. Global Climate Models (GCM) simulate global weather patterns through interactions of the atmosphere with the ocean, sea ice, and land surface for periods of up to hundreds of years. GCMs are configured to simulate the Earth's climate at a global scale and have considerable computational requirements. Consequently, the models are coarse in spatial resolution (~25–300 km grid). Model output includes simulations of a historical time period, as well as the future.

(1) Simulations of the historical period represent known human-driven emissions over that period and other factors, such as volcanic eruptions, as atmospheric boundary conditions. However, historical simulations should not be considered "hindcasts" of historically observed weather. For instance, GCMs are not targeted at replicating observed, annual, or sub-annual temperature or precipitation records. Historical GCM output reflects weather patterns that are driven by the same general constraints (boundary conditions) inherent to the Earth's climate system, however, result in different evolutions of land surface and ocean states that lead to unique sequences of weather (internal variability). The skill of a GCM can be evaluated in terms of its representation of historical climate and the statistical properties of historical meteorology.

(2) The complexity of GCMs has evolved over time. GCMs were originally referenced as global circulation models and only included the physics needed to simulate the circulation of the ocean and atmosphere. Newer models now also account for atmospheric chemistry and aerosols, land surface interactions, land and sea ice, and increasingly, interactive biochemical cycles.

(3) Those models that include the latter are referenced as Earth System Models (ESMs). ESMs are an evolution of GCMs that include more physical, chemical, and biological processes and even the impact of human systems, such as water management and irrigation. In this EC, the acronym GCM is adopted to mean both GCMs and ESMs.

b. GCM simulations of future climate are made as a part of the Coupled Model Intercomparison Projects (CMIPs) administered by the World Climate Research Programme (WCRP) to develop, share, and apply information for better understanding the Earth's climate system. Climate models developed by research centers around the world are run with sets of agreed upon experiments using inputs derived from projections of future socioeconomic conditions that determine future GHG concentrations in the atmosphere. The results of the CMIP experiments are published in IPCC Assessment Reports.

c. Climate modeling initiatives also exist outside of the CMIP. These efforts are supported by academic institutions, government agencies, or reputable science organizations.

B–3. Downscaling

Downscaling is required to translate the coarse spatial-scale weather patterns simulated by GCMs to a finer scale that better represents the influence of the local land surface and is at a resolution that is more applicable to regional and local scale resource assessments. Downscaling from the coarse spatial resolution associated with the GCMs to a higher spatial resolution provides more detailed insight into local climate change impacts, capturing the effects of fine-scale features such as coastlines and orographic effects (Vano et al., 2020). Even with downscaling, GCM-based outputs are generally more reliable for larger watersheds (Choate et al., 2017). There are three general types of downscaling: Statistical, Dynamical, and Hybrid Statistical-Dynamical downscaling.

a. Statistical Downscaling. Statistical downscaling techniques transform the spatially coarse projections of GCMs to a finer resolution. Statistical downscaling consists of applying statistical relationships developed between modeled climates with an observational dataset (such as gridded or station-based temperature and precipitation). In the process of downscaling, systematic biases in modeled temperature and precipitation are removed.

(1) One advantage of statistical downscaling is that it is computationally efficient; however, these approaches typically include a gradient of stationarity assumptions in the statistical transforms used to convert the coarser data to a finer resolution. A distinction is often made between methods that downscale from nearest GCM output location and those that that downscale from GCM circulation features.

(2) Users may encounter various statistical downscaling methods such as the Bias-Correction and Spatial Disaggregation (BCSD) method and methods that rely on constructed analogs (for example, Localized Constructed Analogs [LOCA]; Multivariate Adaptive Constructed Analogs, [MACA]). Many additional methods exist, and users should take care to consider the “fit-for-purpose” of any method before selecting it.

b. Dynamical Downscaling. Dynamical Downscaling uses the output of GCMs as boundary conditions to force a finer scale regional climate model (RCM). RCMs resolve the mesoscale interaction of the atmosphere with the land surface, in addition to other physical processes, through the explicit representation of physical processes at resolutions that are typically 10 to 20 times higher than a GCM. Dynamical downscaling is computationally intensive, which has made its application in comprehensive ensemble-based regional applications infeasible to date. With increases in computational power and newer models, such data may be more common in the future. However, even high-resolution RCMs can contain biases that may prevent their use without further correction or adjustment.

c. Hybrid Statistical-Dynamical Downscaling. Hybrid Statistical-Dynamical Downscaling is a method that uses both simulations of RCMs and statistical downscaling techniques. This method usually relies on the application of 12–25 km spatial scale RCMs forced with GCM boundary conditions. The output from the RCM simulations is then subsequently translated to an even finer spatial resolution using empirical statistical methods, which also correct for any biases in the RCM.

B–4. Hydrologic Modeling

Hydrologic models are often used to translate downscaled, GCM-based meteorological outputs (for example, precipitation and temperature) into the response of the land surface state and runoff response of the watershed. Hydrologic models are ideally constrained using observational datasets to represent an accurate, process-based relationship between input meteorology, internal states (such as soil moisture, groundwater, and snow water equivalent), and output fluxes (such as runoff, streamflow, and evapotranspiration).

a. Hydrologic models simulate water transport through and storage within the vegetation canopy, the snowpack (if any), the soil column, and often a shallow aquifer layer. Simulated runoff and subsurface flow from the hydrologic model can be routed through a drainage (channel) network to simulate discharge or streamflow. Hydrologic models vary in structure and process representation.

b. Several important model attributes should be considered when determining whether a hydrologic model is appropriate for climate change applications.

(1) *Process Fidelity*. A model must have accurate and realistic representation of the physical processes that govern hydrological response. This is referred to as "process fidelity." Process fidelity is especially important because the accurate projection of a basin's runoff response to climate change is predicated on the model's ability to correctly represent the sensitivity of hydrologic states and fluxes to meteorological inputs. Climate change can affect the processes that govern the transport, storage, and fate of water throughout the watershed. Capturing the hydrologic response under climate change requires continuous simulation for long timeframes: multi-season/year/decade, depending on memory processes of the land surface being represented.

(a) Typically, models that are used for non-continuous, event-based applications or for short-term forecasting rely on empirical parameters and conceptual approaches that require tuning (calibration) to event-specific conditions. While all hydrology models require some parameter estimation to represent watershed behavior, the event-based or short-term forecasting models may lack the process fidelity required to describe the watershed's climate sensitivity beyond the current climate, and/or the parameters may have been estimated to meet a narrow objective (such as peak flow simulation) rather than a comprehensive effort to constrain state/flux relationships to represent broader climate sensitivities. Event-based models are generally not suitable for climate change studies. Short-term forecasting models must be carefully assessed to gauge their fidelity and climate sensitivity

(b) In many instances, antecedent conditions can be as or more important than the short-term atmospheric forcings in generating hydrologic response. A model used to simulate climate-changed hydrology must be able to capture changes in all of the watershed processes to represent potential changes in basin state and responses to changes in atmospheric forcings. Some of the processes that drive hydrologic response include long-term, seasonal, or interannual dependencies. For example, spring snowmelt runoff can be amplified when preceded by a wet fall. The assumptions of different process parameterizations should reflect our best understanding of their climate sensitivities. For example, an evapotranspiration parameterization that is dependent only on temperature, versus other forcings including wind speed, humidity, and radiation, will likely cause biases in projected climate impacts for the watershed.

(2) The approach to model calibration and evaluation should prioritize process fidelity and climate sensitivity-related evaluations over a narrow use of univariate, single-objective, or event-specific metrics. For modeling hydrological response in novel, rare, or historically unseen future environmental conditions, it is important to place a strong emphasis on the hydrologic model's ability to accurately model governing processes and climate sensitivity for critical variables (such as runoff or streamflow), while also considering the performance of the critical variables for observed, impactful

events. For both considerations (process and performance), the ramifications of uncertainty and error in model inputs, outputs, and supporting observations should be recognized.

c. Computational Efficiency. Computational efficiency should be considered when selecting a hydrologic model. To represent uncertainty, it is important to simulate a large ensemble of future conditions. Some hydrologic models' computational requirements make the modeling of large numbers of long-term simulations infeasible within the scope of a study. These computational constraints are usually due to a model's detailed representation of complex processes at fine spatial and temporal scales or a computationally intensive computing framework, interface, or analysis workflow. Such hydrologic models impose constraints on the number of ensemble members that can be generated and assessed to represent future conditions. Relying on only a sampling of the available projections can imply false precision of the projected future. Characterizing uncertainty should be prioritized over highly precise model outcomes.

B–5. Streamflow Bias-Correction

a. Hydrologic models are calibrated by adjusting model parameters to improve their simulation of key processes in a physically reasonable manner. No matter how well a model is calibrated, there are often remaining systematic biases in model process representation, especially in outcomes that were not specific objectives of the calibration.

b. Hydrological biases are identified by comparing simulations over historical periods to observationally derived datasets. For applications specific to modeling projected streamflow, it is beneficial to perform these comparisons using observed datasets reflective of relatively pristine watershed conditions (uninfluenced by water management activities such as river regulation, irrigation withdrawals, and returns).

(1) Some hydrology models lack representation of the effects of water management practices. When models include the effects of managed hydraulic structures, this introduces another source of model uncertainty. Thus, "natural" or "unimpaired" flows best facilitate this comparison because systematic biases related to hydrological processes can be diagnosed and accounted for.

(2) In some water resources applications, where decisions are made around specific thresholds in flow, volume, or stage (for example, water management and reservoir operations analyses), it can be important to reduce these biases for meaningful interpretations (for example, Hashino et al., 2007; Guo et al., 2020).

(3) Caution should be taken in applying bias-correction where there are significant deficits in performance for a streamflow characteristic of interest for the study. In these cases, bias-correction can introduce spurious elements into the climate signal.

c. A common streamflow bias-correction method is based on quantile mapping of observed and simulated flow duration probability distributions. It is assumed that biases in the historical period will also be present in the future projection period. This assumption can be a limitation for these methods in cases where bias is nonstationary. Multiple approaches have recently been developed to address this limitation connecting biases to physical processes, and conserving mass when applied to multiple sites within a river network (for example, Bennett et al., 2022).

B–6. Impact Assessment Modeling

a. In cases where the effects of climate change on specific resources are difficult to determine from meteorologic and hydrologic projections alone, due to complex interactions of hydroclimate change in space and time with human and ecological systems, additional impact modeling is necessary (for example, Harrell et al., 2022). Meteorological and hydrological projections are used as inputs to impact models that represent complex systems that function as a product of atmospheric and hydrological forcing. These models include, but are not limited to, biogeochemical (water quality modeling), ecosystem (habitat/fish life-cycle modeling), geomorphic, and water resource systems (multi-objective reservoir modeling).

b. Often assumptions based on historical hydroclimatic conditions are embedded in these impact models. If these embedded assumptions could be affected by climate change, they should be updated or explicitly described to adequately interpret their potential influences on model outcomes.

c. For example, in the modeling of a reservoir system in a snowmelt basin, current seasonal operating objectives may be tied to the timing of snowmelt as defined by historical observations. These operating objectives may be reflected in operating requirements specified in a project's water control manual and integrated into the impact model's decision-making logic. While the assumption of not updating the seasonal operating criteria as snowmelt regime changes is appropriate for identifying vulnerabilities under present-day operational objectives, changes in the timing of snowmelt could foreseeably necessitate a change in operation sometime in the future that would not currently be captured by the impact model's future year output.

B–7. Supporting Datasets

As a first step to analyzing projected meteorology and hydrology specific to a study area, an effort should be made to inventory available, GCM-based, downscaled projection products providing coverage of the study extent. Most readily available, downscaled, climate projections typically end in 2099 or 2100. Therefore, at present, projections for year 2099/2100 provide the most insight into how climate change may affect project performance in the long-term. As longer modeled projections become available, they should be incorporated into analyses to better inform risk-based decision-making over the full 100-year service life assumed for major USACE infrastructure projects.

a. Numerous government science agencies, private science organizations, and academic institutions host libraries of climate-changed meteorology and hydrology and resource hubs (for example, https://toolkit.climate.gov/).

b. One example of an available database is the Lawrence Livermore National Laboratory (LLNL) Green Data Oasis (GDO). USACE collaborates with science agencies, academic institutions, and science organizations to maintain this database. The GDO site hosts meteorologic and hydrologic projections at spatial and temporal scales (daily, monthly) relevant to water resources planning. USACE's publicly available CPR tools like the Climate Hydrology Assessment Tool (CHAT) and the Vulnerability Assessment (VA) tool apply LLNL GDO data products. The data are housed in the Downscaled Climate and Hydrology Projections archive, publicly accessible at the

Lawrence Livermore National Laboratory (LLNL) Green Data Oasis (GDO) website: https://gdo-dcp.ucllnl.org.

c. The GDO archive provides climate projections from the WCRP's CMIP3 multi-model dataset referenced in the IPCC Climate Change Fourth Assessment Report and the CMIP5 multi-model dataset referenced as part of the IPCC Fifth Assessment. Projections are available for the contiguous United States and Canadian portions of the Columbia River and Missouri River Basins. In addition to providing access to the data, the GDO website provides an interface and tutorials for extraction of projections for a specific location.

d. Meteorological projections developed using multiple statistical downscaling techniques are available via the GDO site. Projected future hydrology model simulations forced by downscaled outputs from selected CMIP models are also available for the continental United States (CONUS). Additionally, regionally developed hydrological datasets may be available for large river basins. For example, USACE and other federal partners have produced basin-specific datasets and analyses (Federal Columbia River Power System, RMJOC-II, 2018, 2020; Reclamation WaterSMART studies, https://www.usbr.gov/watersmart/bsp/).

e. Climate data resources that are not clearly documented, have not been supported in peer-reviewed literature, or were produced by organizations with limited demonstrated experience should be avoided.

Appendix C
Considerations for Developing In-Depth Analyses

The following appendix outlines key criteria for developing in-depth Tier 2 analyses of climate change that extend beyond the Tier 1 requirements described in ECB-2018-14. These considerations serve as guidelines for developing and evaluating analyses that rely on the application of study-specific, climate-influenced meteorology and/or hydrology.

C–1. Uncertainty and the Ensemble Based Approach

Projections of the future hydrologic variables include a large range of uncertainty. The uncertainty in future warming is attributed to (1) natural variability in the climate system, (2) scientific uncertainty in the response of climate system to emissions, and (3) uncertainty in future emissions due to unknown human actions and policy decisions (Hawkins and Sutton, 2012).

a. Natural variability is the largest source of uncertainty in the near term (years to decades). Imperfect knowledge of the response of the climate system, also characterized as climate model uncertainty, is the most influential source of uncertainty in the range of the next 30 to 50 years. Over the next 60 to 100 years, human actions and policy decisions (as captured by emission scenarios) are the largest source of uncertainty.

b. Multi-model ensembles represent these sources of uncertainties but cannot fully characterize future uncertainty. This is because our current knowledge is imperfect. For example, unforeseen large-scale natural (volcanic eruptions) and human (war, global pandemics) influences on the global climate are not represented. However, multi-model ensembles are accepted for characterizing risk given the current knowledge of the climate system and a range of potential human actions and policy decisions.

c. Climate change analyses should not rely on small subsets of simulations. Analyses based on a single GCM or even small subsets of GCM outputs result in a false degree of precision and do not provide insight into the uncertainty of potential future project-relevant conditions. Instead, an ensemble of GCMs and modeling methods should be applied to generate a range of projected futures. Furthermore, ensembles are essential for understanding internal variability and extremes.

(1) It is important to characterize and describe uncertainty by using the spread of projections from multi-model ensembles for a future condition of interest. If there is little spread among ensemble members in the direction and relative magnitude of change, there is higher confidence in those projections of the future. If the spread among ensemble members is large, and there is limited consensus on the direction or magnitude of change, there is higher uncertainty in projected conditions. The agreement on the sign of change and the magnitude of change relative to historical variability can be used to determine the robustness of projected climate change signals. Following these general concepts, the ensemble spread can be described statistically, thereby characterizing some of the uncertainty associated with projections of future conditions.

(2) In some cases, it may be necessary to evaluate results derived from a subset of projections selected from a larger ensemble (Newman et al., 2022). This must be done carefully, and the process by which a representative subset of projections is selected, or by which models are discounted or removed, must be described in detail and be technically defensible.

(3) A smaller subset of projections can be identified by evaluating the skill of individual models in reproducing the retrospective, regional-scale climatic processes, or teleconnections that may be most relevant to climate risks being evaluated (Rupp et al., 2013). Subsets of model outputs must be selected in a manner that maintain the spread of the full set of meteorological and/or hydrological projections relevant to the application of interest (RMJOC-II, 2018).

(4) When identifying which subsets of ensemble members to use for analysis, it is important to recognize that solely selecting ensemble members using criteria based on mean changes in study-domain precipitation and temperature will not always capture the range of changes in hydrologic response relevant to a project. Note that the appropriate minimum number of ensemble members for a given application must be determined on a case-by-case basis.

C–2. Design of Modeling Chains

a. The hydroclimate projection modeling chain includes multiple components (appendix B). Each component of the modeling chain carries with it associated uncertainty. The typical hydroclimate projection modeling chain consists of the following key elements:

(1) Emission scenarios.
(2) The GCMs selected and their initial conditions.
(3) Applied downscaling method(s).
(4) The hydrologic model(s) selected and their input parameters.

b. The spread in projections of certain hydrological conditions can be predominantly driven by elements of the hydrologic modeling approach (Chegwidden et al., 2019). For example, the choice of hydrologic model and hydrologic model parameters could greatly influence the prediction of low flows because different parameterizations of the soil column and subsurface flow can vary greatly between models. Characterizing the uncertainty in low flows could require considering multiple hydrologic models and/or hydrologic model parameter sets. Another example is applications where precipitation variability is known to be a dominant driver of vulnerabilities. To more fully capture the uncertainty associated with projected precipitation, a relatively wider range of GCMs, initial GCM conditions, and multiple downscaling methods should be considered.

C–3. Comparative Approach

a. Model simulations are used to project or characterize the effects of climate change. Each model and data analysis technique used to translate the output of GCMs to a scale that can be used in support of decision-making introduces its own set of biases. For this reason, it is often necessary to conduct climate change analyses using a comparative framework. Relative comparisons of modeled future to the modeled past limit the influence of model-based biases on the interpretation of the climate change signal. This contrasts with an approach that would compare a simulated future to the observed past, for which model biases would influence the interpreted climate change response.

b. Comparative analyses require that the historical reference period be simulated using the same modeling methodology as the future period. The determination of relative changes through time is based on the comparison of the future modeled outcomes against the historical modeled outcomes. These differences are often referred to as “change factors.” The future modeled outcomes may be for one or more multi-decadal periods (referred to as “time slices” or epochs) or to outcomes generated across a longer, continuous future period.

Appendix D
Application and Interpretation of Climate-Changed Meteorology and Hydrology in Impact Modeling

Climate change analysis, when generated using projections of study area-specific meteorology and hydrology, can be appropriately applied to evaluate how future climate change may affect the project features, measures, and/or operational changes being proposed. Analysis, as described in this EC, can provide additional context to the decision-making process, such as analysis being used to select a given alternative or being applied to justify selecting a more resilient project configuration or management option even at a higher cost. This appendix discusses several options for incorporating in-depth climate change analyses.

D–1. Impact Modeling Assessments

a. One of the most sought-after applications of climate projections in water resources is their usage as a direct input to impact assessment models. As part of such applications, impact model simulations are conducted for historical and future periods through direct use of meteorological and hydrological projection time series. Based on these simulations, project performance can be evaluated under future conditions. Results can be analyzed over long time periods, using a transient approach (continuous changes in time) or by using epoch-based comparisons. Both cases require comparison to a historical condition simulated using the same modeling framework to separate the influence of underlying model-based biases (appendix C).

b. Such evaluations facilitate quantification of project performance under nonstationary hydroclimatic conditions and provide for an assessment of relative changes in performance in time (flood risk, water supply reliability, habitat vulnerability, flood consequences). This change in performance be compared to performance estimates derived from traditional historical observationally based inputs.

D–2. Perturbation-Based Sensitivity Analysis

a. One approach to evaluating the effects of changes in meteorology and hydrology is to conduct sensitivity analysis to assess the differences between the outcomes (meeting performance objectives, alternative impacts, etc.) derived using historical observation-based inputs versus historical observation-based inputs that are perturbed based on assumptions of potential future changes. For example, the historical record can be made wetter/drier or warmer by a prescribed set of shifts and scalars applied to time series, or particular historical statistics can be perturbed. These approaches can be informative for understanding project performance under a wider range of conditions than was observed historically; however, these are not considered comprehensive climate change assessments because the types of conditions, weather patterns, and sequences are still limited by those that have been observed in the past.

b. These sensitivity analyses can be informative for understanding what types of changes the project or system may be sensitive to. Sometimes, these perturbations are informed by coarse interpretations of projected changes extracted or derived from climate change projections, while not directly using the entire climate projection-based modeling chain. Most of the data and statistics used in these analyses remain based on the historical record, and consequently, these analyses do not capture the feedback mechanisms and complexities of how the climate and hydrological systems could evolve with a changing climate.

c. Examples of more complex approaches incorporating sensitivity analysis are illustrated by vulnerability assessments included in water system planning decision frameworks (International Joint Commission Climate Change Guidance: [IJC 2017, IJC 2018], Climate Risk Informed Decision Analyses (CRIDA): [Mendoza et al., 2018], among others). These sensitivity analyses are often referred to as bottom-up vulnerability assessments or “decision-scaling” (Brown et al., 2012). The general framework for analysis first focuses on framing the decision for which the analysis is being conducted. Study-specific vulnerabilities to climate uncertainty are recognized by identifying key performance targets that may be undermined in the future by changes to climate. For example, for a reservoir this might consist of climate-sensitive operating objectives or critical thresholds related to flow or lake levels.

d. Climate sensitivity (or stress) tests are carried out with impact models to assess what kinds of climatic conditions significantly affect the decision being made. The development and assumptions of the underlying hydrological inputs for these sensitivity analyses are critical for meaningful interpretations. Sensitivity tests are targeted at answering the question: How might changes to the climate and hydrology in a study area affect the vulnerabilities? These stress tests can be applied to define how much change from historical conditions a system or designed feature can handle before becoming vulnerable through non-performance. This knowledge can be combined with meteorological and hydrological monitoring to inform implementation of adaptation actions.

e. After identifying climatic conditions that would present a risk to the system via the sensitivity tests, outcomes can be linked back to GCM-based projections to identify the future conditions and timing of the greatest concern. In this way, projections of climate-changed variables like precipitation, temperature, and streamflow can provide context into the likelihood of occurrence associated with identified vulnerabilities given the current understanding of the plausible range of future conditions.

D–3. Lead Time/Adaptation Trigger Assessment

a. Although projects are often justified in part using economics based on a 50-year period of economic analysis, it is necessary to build systems so they can perform their authorized purpose for their designated service life (usually 100 years per ER 1110-2-8159 and ER 1105-2-100). Implementing or changing water resources infrastructure generally requires a long planning, engineering, and construction process. Consequently, building lead time for adaptation to changing conditions is important.

b. Whether affected by climate or non-climate changes, USACE projects must be prepared to perform for their full range of reasonably plausible future conditions. One way to accomplish this is to consider a wide range of potential future conditions generated using projections of climate change conditions and to identify triggers or thresholds at which adaptation decisions will need to be made. This concept is incorporated into USACE’s existing guidance for adapting to sea level change (EP 1100-2-1) and is valid for inland applications as well. Consideration should be given to the feasibility of changing the level of project functionality or performance when changes in hydrology begin to require action. When adaptable modifications are infeasible, this provides an additional rationale for adding resilience to a design upfront.

Appendix E
Stepwise Description of Scoping and CPR Coordination Process

The following appendix provides an overview of the steps required to outline a scope and document its coordination with and approval by the CPR CoP. See Figure 2 for a visual representation of the process.

E–1. Step 1. Resource Availability

Verify that the scale of the study supports conducting an in-depth climate analysis. Ensure that the considerable resources (including scheduled study duration, expertise, funds, etc.) required to support an in-depth analysis and associated required review (DQC and ATR) are available. USACE management staff, project managers, planners, and stakeholders/external partners associated with the project or study should be engaged to verify that there is support for pursuing an analysis using projected meteorology and hydrology. The availability of resources and the support of the District(s), product development team leadership, and stakeholders/study partners (if applicable) must be documented.

E–2. Step 2. Define Study Objectives

Identify study/design/assessment objectives and determine which watershed components and/or study features/measures would likely be sensitive to the impacts of climate change. During this step, the study-specific meteorologic and hydrologic variables that will be analyzed to assess climate change vulnerability should be identified. The purpose of this step is to establish the context within which climate change should be considered. This context should be incorporated into the scope of work generated, subsequently in Step 3.

E–3. Step 3. Define Study Scope of Work

Prior to dedicating substantial resources to executing an in-depth analysis of climate-changed meteorology and hydrology specific to a study area or project, the PDT must generate a well-formulated scope of work. The scope of work needs to be produced with consultation from the CPR CoP prior to starting analysis. It is strongly recommended that PDTs consult with CPR CoP leadership throughout the scoping process. The scope of work should include a description of the study objectives as determined in Step 2, as well as text detailing the following four components:

a. Preliminary Risk Assessment.

(1) As part of the scoping process, all Tier 1 ECB 2018-14 requirements should be fulfilled except for the final table of residual risks due to climate change. ECB 2018-14 requirements include:

(a) Literature review.

(b) Nonstationarity analysis and monotonic trend analysis of historically observed time series.

(c) Application of the USACE Climate Hydrology Assessment Tool (CHAT).

(d) Application of the Vulnerability Assessment (VA) tool.

(2) Based on the output of the ECB 2018-14 assessment, a qualitative, preliminary determination of the risk that climate change poses to the study objectives as defined in Step 2 should be made. An in-depth analysis should only be performed if:

(a) Climate change presents a significant risk to the watershed and/or performance of study/design features/measures being evaluated.

(b) When the results of an in-depth analysis can reasonably be expected to help reduce vulnerabilities or enhance resilience to climate change threats and impacts.

b. Inventory Available Data Products. This consists of inventorying relevant data products, which may include:

(1) Observed, historic hydrologic and meteorologic time-series data.

(2) Readily available, GCM-based, downscaled meteorology.

(3) Off-the-shelf climate-changed projections of streamflow response.

(4) Available hydrologic models configured to support long-term simulations of runoff response.

c. Define Approach. Based on the inventory conducted in Step 2, the workflow for assessing climate-changed meteorology and hydrology will be defined and described for the study. The application of the proposed tools and datasets should be "fit-for-purpose," meaning modeling tools and methods proposed must align with the study objectives identified in Step 2.

d. Evaluation. The team should outline how analysis results will be evaluated and how the conclusions will be incorporated into the decision-making process. The scope will include how the analysis endpoints will be interpreted and applied to address study objectives.

E–4. Step 4 CPR CoP Scope Approval

a. The PDT will submit the scope to the USACE CPR CoP.

b. The CPR CoP will review the submission and indicate whether a study area-specific, in-depth analysis can and should be performed using projected meteorology and hydrology. Once the scope has been reviewed by the USACE CPR CoP and that coordination and approval is documented, the proposed analysis can be used to support planning and engineering decisions.

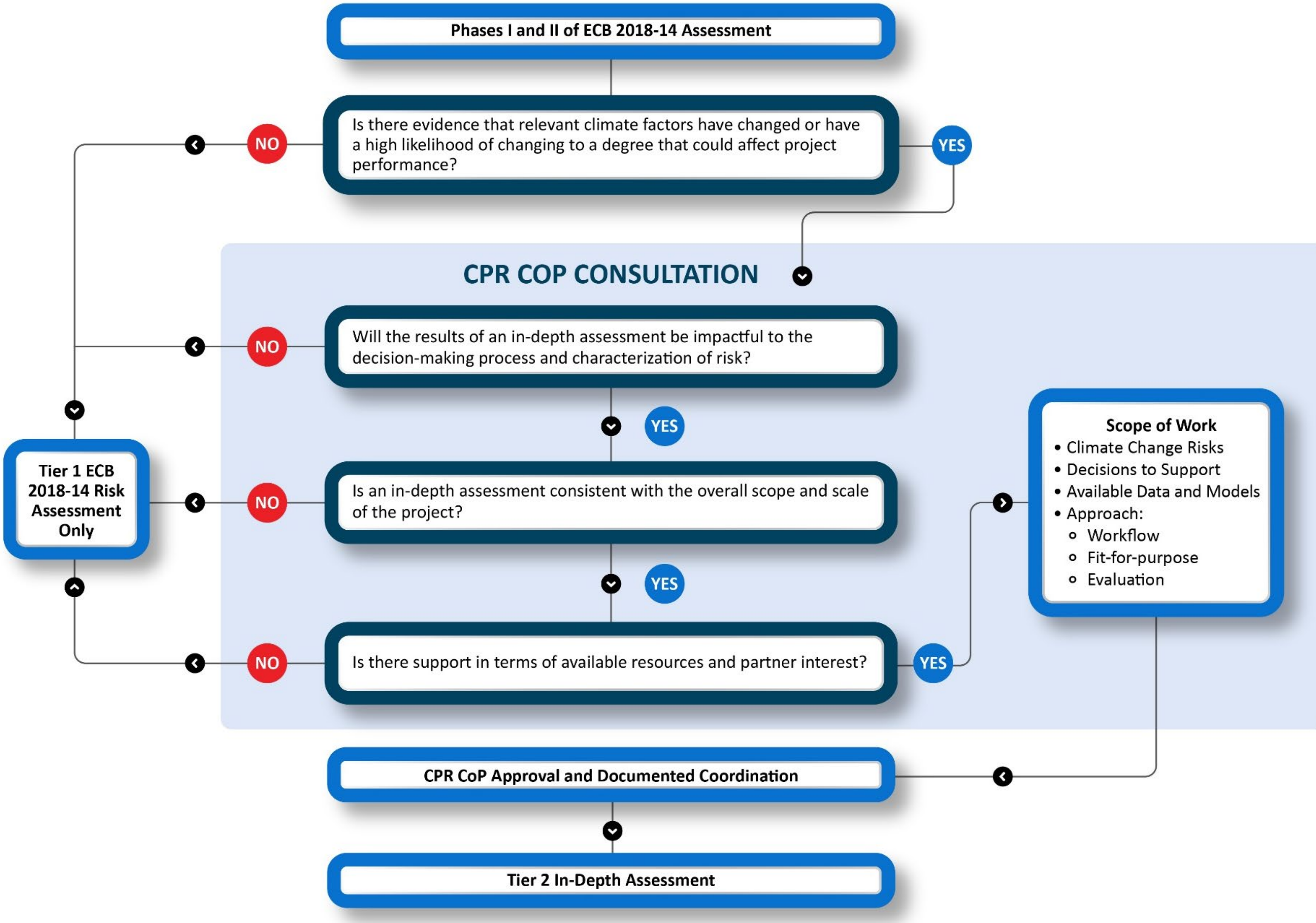

Figure 2: Stepwise description of scoping/approval process

Glossary of Terms

Actionable Science

Theories, data, analyses, models, projections, scenarios, and tools that are: (1) relevant to the decision under consideration and (2) reliable in terms of its scientific or engineering basis and appropriate level of peer review. Additionally, to support application in this context, climate change science needs to be (3) understandable to those making the decision, (4) supportive of decisions across wide spatial, temporal, and organizational ranges, and (5) co-produced by scientists, practitioners, and decision-makers and result in rigorous and accessible products to meet the needs of stakeholders.

Adaptation

Adjustment in natural or human systems in anticipation of or response to a changing environment in a way that creates beneficial opportunities or reduces negative effects.

Adaptive Capacity

The ability of an entity to take action to reduce exposure or sensitivity (see definitions) to climate or other change. Capacity may include financial, institutional, educational, cultural, or any other structure that affects an entity's ability to act.

Adaptive Management

An approach to resource management that emphasizes learning through management where knowledge is incomplete, and when, despite inherent uncertainty, managers and policymakers must act. Unlike a traditional trial and error approach, adaptive management has explicit structure. This structure includes a careful elucidation of objectives, the identification of alternative management measures and/or hypotheses of causation, the monitoring of outcomes, and the prescribed procedures for evaluating these outcomes. Adaptive management is iterative and serves to reduce uncertainty, build knowledge, and improve management over time in a goal-oriented and structured process.

Bias-correction

The process of adjusting climate and hydrology model outputs to account for systematic errors.

Climate

Usually defined as the "average weather," or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time. Relevant quantities are most often surface variables such as temperature, precipitation. The classical time period is 30 years, as defined by the World Meteorological Organization (WMO).

Climate Change
Climate change refers to a long-term change in average weather conditions that is projected to persist for multiple decades or longer over the entire earth. These changes encompass increases and decreases in temperature, changes in precipitation, as well as shifts in the frequency and intensity of severe weather events. Climate change will cause changes to atmospheric circulation patterns that will radically alter climate in some locations. Human (anthropogenic) greenhouse gas emissions are the driving force of this change.

Climate Change Signals
In the context of climate change adaptation, the climate change signal refers to the amplitude of change due to human-driven climate change relative to natural variability in climate. The climate change signal emerges when the associated trend becomes significantly different relative to "noise" associated with naturally occurring interannual variability.

Climate Variability
Variations of climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural, internal processes within the climate system, or due to variations in external natural or human-driven (anthropogenic) forcing.

Coupled Model Intercomparison Project (CMIP)
A collaborative framework designed to improve knowledge of climate change by fostering the development and review of Earth System and coupled climate models. The CMIP is an initiative that was started in 1995 by the Working Group on Coupled Modelling (WGCM). The WGCM is part of a collaboration with many groups and partners within the World Climate Research Programme (WCRP), which oversees the ongoing CMIP. The project is being carried out in phases and seeks to encourage climate model improvements and to support assessments of climate change by making multi-model output publicly available in an accessible format.

Critical Threshold or Tipping Point
For infrastructure, the structural or operational limit beyond which function will be impaired or lost. For example, the height of a levee intended to provide protection against flooding is considered a critical threshold. The term can be applied more broadly to the functioning of any system (ecological, navigational, hydrologic) to identify the point at which it ceases to function in its current (or desired) fashion.

Downscaling
Method that derives local- to regional-scale (typically 5 to 100 kilometers) information from larger scale models or data analyses. For climate information, downscaling can be accomplished by either statistical or dynamical (regional climate model) means.

Earth System Model (ESM)
The latest generation climate models that account for atmospheric chemistry and aerosols, land surface interactions, land and sea ice, and increasingly interactive biochemical cycles, in addition to physical atmospheric and oceanic processes included in earlier generation global climate models (see definition).

Emissions Scenario or Pathway
Modeled, future trajectories of greenhouse gas emissions based on projected political, social, demographic, technological, and other changes resulting from different degrees of collective action with respect to climate change (called storylines). Typically, the storylines range from strong collective action (SSP1) that strongly reduces emissions (RCP 1.6, 2.6) to weak collective action (SSP5) that increases emissions (RCP 8.5). Emission scenarios are used as inputs to climate models and show how much change to expect from each course of action. Emissions are typically reduced to carbon dioxide equivalent, but derive from the total range of greenhouse gases (see definition).

Ensemble
Grouping of models or model runs, often done to represent plausible ranges of potential future conditions.

Epoch
A period of time. Climate is typically defined in 30-year epochs (called “climate normals”).

Exposure
The nature and degree to which a system is impacted by significant climate variations or climate change.

Extreme Event
Extreme events are occurrences of unusually severe weather or climate conditions that can cause devastating impacts on communities, and agricultural and natural ecosystems. Weather-related extreme events are often short-lived and include heat waves, freezes, heavy downpours, tornadoes, tropical cyclones, and floods. Climate-related extreme events either persist longer than weather events or emerge from the accumulation of weather or climate events that persist over a longer period of time. Examples include drought resulting from long periods of below-normal precipitation or wildfire outbreaks when a prolonged dry, warm period follows an abnormally wet and productive growing season.

Fit-for-Purpose
A concept that describes the degree to which data, methods, models, or other tools are developed to be useful for a particular application. The data, method, model, or tool should promote reliable production of the desired output and should meet the information needs of a study.

Forcing
In hydrological modeling, the variables (such as meteorological inputs) that are required as input to mass and energy conservation equations that are used to simulate land surface states and fluxes. Climate models use inputs representing the effects of greenhouse gases as a forcing. These are referred to as radiative forcings.

General Circulation Model
See Global Climate Model.

Global Climate Model (GCM)
A model that simulates global weather patterns through interactions of the atmosphere with the ocean, sea ice, and land surface for periods of up to hundreds of years. GCMs are configured to simulate the Earth's climate at a global scale and have considerable computational requirements. Consequently, the models are coarse in spatial resolution (~25–300 km grid). GCMs originally were referenced as global circulation models and only included the physics needed to simulate the circulation of the ocean and atmosphere. Compared to Earth System Models (see definition), GCMs have reduced land and ocean representation and provide a less exhaustive treatment of the physical, chemical, and biological interactions between the atmosphere, land, and oceans.

Greenhouse Gases (GHGs)
Gases that absorb heat in the atmosphere near the Earth's surface, preventing it from escaping into space. As the atmospheric concentrations of these gases rise, the average temperature of the lower atmosphere will gradually increase, a phenomenon known as the greenhouse effect. Water vapor, carbon dioxide, nitrous oxide, methane, and ozone are the primary GHGs in the Earth's atmosphere.

Impact
The positive or negative effect on the natural or built environment caused by exposure to a hazard (such as flooding). Climate hazards can have multiple impacts on people and communities, infrastructure and the services it provides, as well as on ecosystems and natural resources. Impact can be described as the combination of exposure and sensitivity (see definitions).

Impact Assessment
Practice of identifying and evaluating, in monetary and/or non-monetary terms, the effects of climate variability or change on natural and human systems. It is often a quantitative assessment, in which some degree of specificity is provided for the associated climate, environmental (biophysical) process, and impact models.

Intergovernmental Panel on Climate Change (IPCC)
The IPCC is the intergovernmental body of the United Nations focused on assessing the science related to climate change (https://www.ipcc.ch/).

Mitigation of Climate Change
Intervention to reduce the magnitude of climate change by reducing its causes, such as through reducing emissions of greenhouse gases to the atmosphere and enhancing greenhouse gas sinks.

Model Perturbation
Incremental changes in model inputs to assess response in simulated outcomes.

National Climate Assessment
A periodic summary report by the U.S. Global Change Research Program that collects, integrates, and assesses climate-related observations and research from around the United States to assist federal planning for climate change adaptation and mitigation. The report includes analyses of impacts on sectors and regions of the United States.

Natural Variability
Variation in climate parameters due to nonhuman causes. There are two types of natural variability: external and internal. External variability is attributed to forces outside of the earth's climate system (such as solar variability, volcanic eruptions, earth's orbital patterns). These represent longer term variations in climate (decades to century scale). Internal variability includes interactions of the oceans, land surface, and atmosphere. The timescales of these interactions are shorter (monthly, annual, or decadal).

Nonstationarity
The case where the statistical characteristics of a time series cannot be considered constant through time.

Process Fidelity
Realistic representation of key physical processes in a model.

Projection
A modeled climate future forced with a specific trajectory of greenhouse gas concentrations and other constituents derived based on assumptions or scenarios concerning; for example, future natural, pollical, socioeconomic, and technological developments. There is uncertainty associated with the various steps used to derive climate projections (from emissions to climate response).

Quantile Mapping
A common method of bias-correction in hydroclimate applications that involves adjusting the distribution of modeled data based on the differences between the modeled distribution and the distribution of a given, historically observed hydroclimatic variable.

Radiative Forcing
Measure of the influence a factor has in altering the balance of incoming and outgoing energy in the earth-atmosphere system. The units are typically reported as W/m^2 (Watts per square meter).

Regional Climate Model (RCM)
A numerical climate prediction model forced by specified lateral and ocean conditions from a global climate model or observation-based dataset (reanalysis) that simulates atmospheric and land surface processes, while accounting for high-resolution topographical data, land-sea contrasts, surface characteristics, and other components of the Earth-system.

Representative Concentration Pathway (RCP)
A greenhouse gas concentration trajectory adopted by the IPCC. Four pathways were used for climate modeling and research for the IPCC Fifth Assessment Report (AR5) in 2014. The pathways describe different climate futures, all of which are considered possible depending on the volume of greenhouse gases emitted in the years to come. The RCPs—originally RCP2.6, RCP4.5, RCP6, and RCP8.5—are labelled after a possible range of radiative forcing values in the year 2100 (2.6, 4.5, 6, and 8.5 W/m^2, respectively).

Resilience
The ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions.

Risk
Combination of the magnitude of the potential consequence(s) of climate change impact(s) and the likelihood that the consequence(s) will occur.

Robustness
The ability of a system to continue to operate correctly across a wide range of operational conditions with minimal damage, alteration, or loss of functionality, and to fail gracefully outside of that range; the wider the range of conditions allowing good performance, the more robust the system.

Scenario
A situation that details future plausible conditions in a manner that supports decision-making under conditions of uncertainty, but does not predict future change that has an associated likelihood of occurrence.

Sensitivity
The degree to which exposure to climate variability and change impacts or degrades USACE projects, programs, missions, and operations. Measures can be implemented to reduce sensitivity; for example, a building’s sensitivity to flooding could be reduced by constructing a ring dike.

Sensitivity Analysis
Sensitivity analysis is used to systematically investigate the possible or potential effects of climate change as part of a risk assessment. Sensitivity analysis is sometimes called a “what if” analysis. Values for variables and parameters can be changed one at a time, or in combination, to assess variation in risk due to sources of knowledge uncertainty and natural variability. The exercise can reveal the most important assumptions upon which the analysis is based and reveal those to which the outcome is most sensitive.

Shared Socioeconomic Pathways (SSPs)
Scenarios of projected socioeconomic global changes used in the IPCC Sixth Assessment Report (AR6). SSP narratives (storylines) quantify and make assumptions about multiple socioeconomic drivers such as population growth, gross domestic product, and urbanization. SSPs serve as the basis of scenarios for estimating plausible greenhouse gas emissions.

Spread
The range in outcomes from a large set of models that is indicative of the uncertainty driven by modeling assumptions (such as assumed emission scenarios) and methods (such as downscaling method[s]).

Stationarity
The case where the statistical characteristics of time-series data may be considered constant through time.

Unimpaired Flow
The natural streamflow of a watershed that would have occurred under current land use but without dams or diversions. This is often referred to as natural flow. Streamflow observations that have been adjusted to remove the effects of dams, diversions, and land use changes are referred to as naturalized streamflow records.

Vulnerability
The degree to which built infrastructure or other assets could be exposed to climate change, their sensitivity to this change, and their adaptive capacity.

Vulnerability Assessment
The process of measuring susceptibility to harm by evaluating the exposure, sensitivity, and adaptive capacity of systems to climate change and related stressors.