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SUBJECT: Incorporating Resilience to Nonstationary Hydrometeorological Conditions in USACE Civil Works Studies, Designs, and Projects

CATEGORY: Guidance

1. **Purpose.** This Engineering and Construction Bulletin (ECB) supports the preparedness and resilience of U.S. Army Corps of Engineers (USACE) Civil Works (CW) projects (planned and existing), programs, missions, and operations by incorporating the potential for changing hydrometeorological conditions into hydrologic analyses. The ECB provides a framework to assess exposure to dynamic weather-related (DWR) threats and hazards tied to hydrologic processes. This guidance identifies actionable measures to reduce vulnerabilities and increase resilience. The steps in this document are meant to supplement, not replace, existing regulations and guidance related to hydrologic analyses for CW studies (e.g., EM 1110-2-1417, EM 1110-2-1415, ER 1105-2-101, EM 1110-2-1413).

2. **Applicability.** This guidance is effective immediately and applies to all USACE headquarters, division, and district components having responsibility for CW projects and programs.

3. **References.** See Appendix A.

4. **Required Integration of Resilience.**

a. USACE is required by statute to integrate preparedness and resilience into planning and actions to support USACE project performance under a wide range of potential weather-related disruptions; for example, Public Law (P.L.) 113-121, the Water Resources Reform Development Act (WRRDA) of 2014. Resilience is the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions. Per ER 1105-2-103, project delivery teams (PDTs) must assess the effects of DWR threats and hazards (e.g., wildfire, sea level, extreme storms, and floods) in the project area and incorporate the potential for long-term hydrometeorological variability into the decision-making process to strengthen resilience.

b. Given the long time horizons for most USACE projects and operations, the majority of USACE projects, studies, and management plans supported by hydrologic and hydraulic (H&H) analysis must assess the potential for long-term changes in hydrometeorological conditions as laid out in this guidance. For simplicity, this document uses “project” to refer to all USACE activities and “assessments” to indicate assessments of long-term hydrometeorological conditions (LHCs).

c. All projects require the assessment prescribed by this guidance when they include and/or rely on analysis that assumes hydrometeorological stationarity (e.g., flow-frequency, stage-frequency, flow-duration, and intensity-duration-frequency relationships). Stationarity assumes that the statistical characteristics of hydrologic time series data are constant through time, meaning that data collected in the past can characterize present and future conditions.

d. Projects that require LHC assessments include, but are not limited to, efforts characterizing hydrologic condition (i.e., watershed studies), activities that support planning, decision-making, project modification (i.e., structural or operational changes) and/or design, and evaluation or direction that supports long-term (i.e., greater than 10 years) water resources management (e.g., water reallocation studies, dredged material management studies, and new or significant updates to a water control manual).

e. Per ER 1110-2-8156, USACE water control manuals must summarize the effects of observed and future trends in hydrometeorological variables relevant to the project's authorized purpose. This content can be developed from applicable, already completed LHC assessments for the region. If no applicable assessment of hydrometeorological conditions has been completed, an abbreviated assessment can be developed. How a water control manual characterizes hydrometeorological conditions over time should be reviewed and updated following any change to the water control plan and at regular intervals along with the rest of the manual's content.

f. Activities supporting short-term (i.e., fewer than 10 years) water management decisions such as deviation requests and routine operations, maintenance, and repair are notable exceptions and do not require an assessment of project area hydrometeorology for evidence of nonstationarity. For all other activities, the USACE Infrastructure and Installation Resilience (IIR) Community of Practice (CoP) should be consulted before excluding an LHC assessment.

5. **Background.**

a. Since the USACE Resilience Initiative was initiated in 2015, USACE has been committed to mainstreaming resilience thinking throughout all its mission areas. By integrating resilience across the agency, USACE can reduce vulnerabilities and life cycle costs[1] associated with the infrastructure it designs and manages. Enhancing the resilience of our water resource infrastructure minimizes post-disaster damages and downtime.

b. To support resilience, understanding the current and future hydrometeorological conditions in which USACE projects must perform is critical. USACE projects, programs, missions, and operations are generally robust enough to accommodate the range of natural hydrometeorological variability over their operational life. In some places and for some impacts relevant to USACE operations, shifts in extreme weather patterns and modifications to watersheds are undermining the fundamental design assumption of hydrometeorological stationarity and can impact USACE's missions and business lines such as flood risk management, navigation, and aquatic ecosystem restoration. This ECB assesses hydrometeorological stationarity and characterizes dynamic, weather-related threats and impacts.

c. Where conditions are changing, relying on the stationarity assumption and solely basing water resource decision-making on analysis generated using the observed hydrometeorological

[1] Per ER 1110-2-8159, life cycle costs include the initial project investment and costs for operation, maintenance, repair, rehabilitation, and replacement.

records may no longer reliably characterize future risk. Over the past century, observed changes in various hydrometeorological conditions include changed rainfall extremes, snowmelt timing and volume, drought frequency and/or intensity, seasonal and annual water yield, wildfire frequency, and flood frequency.

d. Analysis of weather-related hazards, impacts, and vulnerabilities reflects best available, actionable science and leverages region-specific information from federal, Tribal, state, local, and nongovernmental partners. Actionable science provides data, analyses, or tools to support decisions regarding risk management. It is ideally co-produced by scientists and decision makers and creates rigorous and accessible products to meet stakeholder needs (ACCCNRS 2015).

e. As reflected in ER 1105-2-103, Policy for Conducting Civil Works Planning Studies, USACE incorporates the most up-to-date science, policies, and tools available. By understanding hydrometeorological conditions now and into the foreseeable future, USACE can understand the nation's water resource needs and how to address those needs.

f. All stages of project planning must identify and consider changes to observed and future hydrometeorological conditions. Changes in meteorology and the associated impacts to local-scale hydrology can be highly uncertain, requiring guidance on their interpretation and use. To the extent possible, uncertainties (both epistemic and aleatory) associated with evaluations of nonstationary hydrometeorology must be identified and described.

6. **Overview.**

a. Analysis incorporates a scalable, two-tier (Tier 1 and Tier 2) science-based approach to assess exposure to present and future extreme weather-related hazards tied to hydrologic processes. Analysis helps formulate, design, and construct resilient infrastructure; for existing USACE infrastructure, it supports resilient project operations and maintenance. This analysis provides a method and approach to understand and evaluate differences between current and future hydrometeorological conditions, and if they exist, to identify how these differences impact decision-making and characterizing risks to project performance.

b. The majority of USACE activities require a Tier 1 LHC assessment. Tier 1 assessments describe relevant hydrometeorological conditions throughout a project's service life, along with project-specific weather-related risks. Project service life is the length of time a project remains in use to provide its intended function (ER 1110-2-8159).

c. LHC assessments should help define future conditions (future without project [FWOP] and future with project conditions), support plan formulation, evaluate the performance of alternative plans, and inform other decisions related to project planning, engineering, and resource management, as well as long-term (>10-year) operations, maintenance, repair, rehabilitation, and replacement (OMRR&R) decisions/actions (e.g., equipment replacement, dam rehabilitation). IIR analysis can identify and justify adding resilience to a project by assessing weather-related risks to the project. Appendix B provides a flow chart outlining the analysis required by this ECB. Appendix C through Appendix F provide detailed guidance on how to perform the required analysis.

d. A Tier 1 LHC assessment uses multiple lines of evidence to characterize observed and future hydrometeorological change, impacts, and weather-related risk. The analysis focuses on compiling lines of evidence, which describe trends in observed and future hydrometeorological variables (e.g., temperature, precipitation, streamflow) pertinent to the project area, design, resource management approach, or operational change being considered. For a Tier 1 assessment, the information used as evidence to characterize potential hydrometeorological change is derived from literature review and analyses generated using USACE IIR CoP tools and resources.

e. A Tier 1 assessment cannot alter the numerical inputs used to perform quantitative hydrologic, hydraulic, and economic analyses (e.g., project-specific hydrologic/hydraulic/reservoir model inputs, flow/stage frequency relationships, economic model inputs and damage estimation, cost-benefit analysis). These objectives can be fulfilled by pursuing a Tier 2 assessment. However, a Tier 1 assessment can inform the decision-making process, as well as identify and justify the need for increased resilience. Components of a Tier 1 assessment are described in Appendix C.

f. Templates for small-scale, Tier 1 LHC assessments are available on the IIR CoP Knowledge Management Portal (KMP) site, and examples of completed Tier 1 assessments for applications of varying scope and scale are available via the web-based IIR CoP Library of Resilience Assessments (RAL).

g. In addition to a Tier 1 assessment, a Tier 2 in-depth analysis may be pursued when appropriate, on a case-by-case basis. A Tier 2 analysis generates quantitative, project-specific, model-based results that can support decision-making and justify added resilience by recommending actions and/or changes to design. Tier 2 assessments are more resource intensive. A Tier 1 assessment is required regardless of whether Tier 2 analysis is performed.

h. A Tier 2 in-depth analysis may be performed when the results of that analysis can reasonably be expected to add insight, aid in decision-making, reduce vulnerabilities, and/or enhance resilience to future, weather-related threats. Prior to pursuing a Tier 2 evaluation, the Tier 1 preliminary risk assessment should determine whether changing hydrometeorological conditions are likely to impact a given project area, water resources decision, and/or project feature. In-depth analysis can help illustrate vulnerability to future, weather-related hazards.

7. **Considering Combined Inland and Coastal Processes.**

a. Evaluating the hydrometeorological processes in this document also applies to coastal regions, but evaluation requires additional consideration due to interaction with coastal hydrologic processes (e.g., storm surges) and compounding impacts of factors contributing to total water levels.[2]

b. In coastal zones, analysis is required to determine if relative sea level change (RSLC) could impact hydraulic, hydrologic, and coastal analyses outcomes and the potential for coastal compound events driven by various combinations of pluvial, fluvial, and coastal processes. The determination of whether to evaluate coastal processes and whether an RSLC assessment is required should consider the altered extent of coastal forces (e.g., changes in water levels, wave action, tides, storm surge, coastal currents, and morphology due to RSLC) and their compounding impacts on upstream groundwater and surface water levels.

[2] Mean sea level is one component of total water level. Total water level consists of several other potential contributing factors, including wave runup, non-tidal residuals, wave setup, and astronomical tide. These vary in both space and time.

(1) Analysis of rivers in the coastal zone must include a determination of whether RSLC impacts upstream river stages. EM 1110-2-1416, River Hydraulics, offers one potential method to determine this by using "…the maximum predicted high tide, including wind-wave set up […] taken as the starting elevation at a station usually located at the mouth of the stream" to assess upstream impacts. How far RSLC impacts propagate upstream should be evaluated for the end of the project's period of economic analysis and for its project service life.

(2) USACE's Comprehensive Hydrology Assessment Tool (CHAT) can identify stream segments within the continental United States (CONUS) with a high potential to be tidally influenced and thus to be susceptible to coastal impacts. These segments are identified based on whether the minimum stream segment elevation is less than or equal to 50 feet North American Vertical Datum of 1988 (NAVD 88).

c. ER 1100-2-8162 provides USACE guidance for incorporating the direct and indirect physical effects of future sea level change across the project life cycle. EP 1100-21 provides instructional and procedural guidance to implement ER 1100-2-8162. If required, RSLC is evaluated as part of the risk assessment required by this guidance. The sea level scenario that characterizes risk should be consistent with the scenario that supports decision making (i.e., defines the tentatively selected plan [TSP] as part of USACE's plan formulation process).

d. In coastal regions, a Tier 1 assessment is required in addition to RSLC analysis when changes in hydrology (i.e., local runoff and cumulative streamflow), key hydrologic processes (i.e., sediment loads and compound events.), and meteorologic variables (e.g., precipitation and/or temperature) have the potential to impact the analyses and/or project area.

8. Assessing Long-Term Hydrometeorological Conditions and the USACE Planning Process.

a. Tier 1 LHC assessment must be performed throughout each phase of the USACE planning process to characterize future conditions (with and without project), inform decisions (e.g., alternative formulation), evaluate measures and alternatives under consideration, characterize DWR risk, and to determine whether to pursue a Tier 2 analysis. The project management plan must identify an IIR PDT member. The plan must also describe the process for assessing the impacts of nonstationary hydrometeorology to the project and considering resilience. PDT members from different disciplines must collaborate on the Tier 1 assessment.

b. For a feasibility study, the timing of the Tier 1 assessment must align with the feasibility study milestones laid out in EP 1105-2-61 (see Appendix B, Figure B–3). The Tier 1 assessment must be scoped up front, and many elements of the assessment need to be completed prior to the alternative milestone meeting (AMM) to meet the requirements in EP 1105-2-61.

(1) Aspects of the Tier 1 assessment that must be completed prior to the AMM include identifying relevant hydrometeorological factors (RHFs),[3] evaluating trends in observed and future hydrometeorology via the literature review, detecting statistical nonstationarities, evaluating future, modeled hydrometeorology using the USACE CHAT, conducting a vulnerability evaluation using the USACE Civil Works Vulnerability Assessment Tool

[3] A project's relevant hydrometeorological factors are hydrometeorological processes that affect watershed conditions and/or identified problems and opportunities.

(CWVAT), assessing RSLC (if applicable; see section 8), and identifying potential weather-related triggers, hazards, and harms (THHs).

(2) This analysis supports characterizing the future condition and formulating the focused array of alternatives required by the AMM. Analysis also helps determine whether a Tier 2 analysis is required.

c. The decision to pursue a Tier 2 analysis must be made prior to or shortly after the AMM. The PDT should start working with the IIR CoP leadership to develop the scope for the Tier 2 analysis prior to the AMM and must receive IIR CoP leadership approval of the scope shortly after the AMM. This is imperative because the decision to conduct a Tier 2 analysis must receive concurrence from the vertical team. The vertical team includes decision makers and technical experts from the district, major subordinate command (MSC), and headquarters (e.g., IIR CoP leadership). It can also include representatives from the appropriate planning centers of expertise. The decision to pursue a Tier 2 analysis must be documented in the vertical team alignment memorandum (VTAM) due to potential impacts to schedule and budget.

d. Between the AMM and TSP milestones, the PDT evaluates and compares an array of alternatives through additional iterations of the planning process to identify a TSP and, potentially, a locally preferred plan (LPP). Analysis of hydrometeorological nonstationarity during this period of the study helps to characterize uncertainty related to future conditions and differentiate between alternatives, including how RHFs influence each alternative in terms of weather-related risk.

e. The Tier 1 and Tier 2 (if pursued) assessments must be completed prior to the TSP milestone. The TSP presents the first opportunity for public review. An analysis of current and foreseeable future hydrometeorology enables the PDT to identify opportunities to add resilience to recommended measures and features. The analysis also helps communicate to the public how weather-related risk may change with time and offers the public an opportunity to provide input on how to address this risk. The potential for nonstationary weather-related risk should be consistently and continually communicated with the USACE vertical team.

f. Between the TSP and the command validation milestone (CVM), the PDT optimizes measures and features in the recommended plan. At this point, the study focuses on reducing uncertainties and optimizing engineering effectiveness to reduce environmental, social, and economic impacts. The analysis required by this guidance reduces the uncertainty in potential future performance by providing an understanding of the RHF influencing the decision.

g. During the Pre-Construction Engineering and Design (PED) phase, the PDT should revisit the assessment of current and future hydrometeorological conditions and the DWR risk evaluation to verify that elements of the underlying analysis reflect the latest actionable science, policy, and guidance and to assess whether to add additional resilience to changing hydrometeorological conditions to the project.

h. During the PED phase, if the PDT identifies a need to add more resilient features to the authorized plan, the PDT must provide the analysis to determine whether proposed modifications alter project cost and/or performance beyond the original authorization. The division commander has some discretion to approve changes to authorized projects if such changes meet certain criteria, but generally, a post-authorization report or study must justify changes to authorized projects, or elements thereof (ER 1105-2-100).

9. **Scaling and Scoping Assessments of Long-Term Hydrometeorological Conditions.**

a. An LHC assessment should be scaled to the project's complexity and sensitivity to changing hydrometeorological conditions to the degree known at the time of the analysis. Scoping an assessment should consider the level of risk tolerance associated with the overall effort. The level of effort for assessing LHCs should generally mirror the project complexity and risk associated with impacts driven by changing hydrometeorological conditions on the project area, decision(s) being made, and/or proposed project features.

b. Complexity is defined in terms of the type, size, location, scope, and overall cost of the effort. Complexity increases when a project finding or water resources management decision has the potential to impact other federal, state, or local water resources agencies and/or where public interest is significant.

c. ER 1105-2-101, Risk Assessment for Flood Risk Management Studies, refers to risk as the product of the magnitude of the potential consequence(s) and the probability (likelihood) that the consequence(s) occur. If the decision being made reflects a low risk tolerance, the LHC assessment should take a more comprehensive approach. For example, decisions related to a high-consequence flood risk management project are typically risk-averse and may warrant additional analysis to characterize the impacts driven by nonstationary conditions. Conversely, a decision solely impacting a recreational feature is less likely to warrant additional investigation. Examples of additional analysis include extended literature review, assessing more sites/variables using USACE tools, and Tier 2 analysis.

d. The assessment should consider the sensitivity of the project to the variability and uncertainty associated with changing hydrometeorological conditions relative to other risk factors. Sensitivity to changing conditions can be evaluated by identifying the variables critical to the project and determining if changes in long-term weather and hydrologic response could impact these variables within the project's service life. This determination is made by analyzing LHCs, which includes coordinating with the PDT and local and regional technical experts.

10. **Tier 1 Assessments of Long-Term Hydrometeorological Conditions.**

a. A Tier 1 assessment (as further detailed in Appendix C) has five required components: (1) establish decision context, (2) identify RHFs, (3) evaluate multiple lines of evidence, (4) assess DWR risk, and (5) consider opportunities to add resilience and dynamic adaptation. A Tier 1 assessment considers both past (observed) changes as well as future (modeled) changes in hydrometeorological conditions.

b. Step 1, establishing decision context, identifies all tasks to decide which RHFs have the potential to impact the project's problems, opportunities, objectives, and constraints over a project's service life. This step includes identifying key project components, decisions, and performance objectives. Defining the decision context should characterize and consider existing hydrometeorological conditions, associated sensitivities, important decision timeframes (see Appendix F, section F–4), and key hydrologic processes. Professional judgment is necessary to identify which hydrometeorological drivers affect project conditions now and in the future.

c. Step 2 identifies the RHFs for the project. Not all factors impacting the hydrologic cycle are relevant to all USACE projects and applications. Starting at the scoping phase, the PDT must identify and consider which hydrometeorological processes, if any, are exacerbating or ameliorating watershed conditions and/or identified problems and opportunities. These critical processes are the project's RHFs. RHFs are categories of hydrometeorological variables (e.g., temperature, precipitation, streamflow) or processes (e.g., snowmelt, wildfire) that reflect potential changes to hydrology.

(1) The Tier 1 assessment should evaluate RHFs that are critical to describing the future condition and understanding DWR risk in the context of the project's problems, opportunities, objectives, and constraints. RHFs are evaluated by analyzing measurable variables (e.g., annual maximum flow, 7-day annual minimum temperature).

(2) Typically, RHFs important to USACE hydrologic analyses relate directly to temperature, precipitation, and streamflow, but the project location and purpose could require that additional RHFs be evaluated, such as wildfire, sediment transport, and drought. For example, in a flood risk management project, RHFs include streamflow and precipitation, and analyzing annual maximum peak flows and annual maximum 24-hour precipitation is appropriate. For water supply and navigation projects, potential increases in drought frequency and intensity are important, and evaluating drought indicators like changes in the maximum number of consecutive dry days may be of interest.

d. Step 3 evaluates multiple lines of evidence to investigate trends in observed and future hydrometeorology and resulting shifts in weather-related vulnerabilities. Analysis generally consists of applying the methods in the suite of USACE IIR CoP tools that are available via USACE's IIR CoP Applications Portal. Tools include the Time Series Toolbox (TST), the CHAT, and the CWVAT. Use of USACE IIR tools (CHAT, TST, CWVAT) should be scaled and limited to critical variables tied to the identified RHFs. This aspect of the Tier 1 assessment consists of the following four elements and is covered in greater detail in Appendix C, Appendix D, and Appendix E.

(1) *Literature Review*. At minimum, the literature review should cover trends in observed and future changes in temperature, precipitation, and the hydrologic response (e.g., streamflow) most relevant to the project's RHFs. The number of references summarized and level of detail presented should be commensurate with the scale of the LHC assessment and the project scope and purpose. Resources to support the literature review are in Appendix C.

(2) *Trend and Nonstationarity Detection Statistical Analysis*. Critical hydrometeorological variables associated with the RHFs should be evaluated for evidence of nonstationarity using observed time series data. Analysis should use the approach prescribed by the USACE TST. Applying the TST is covered in more detail in Appendix C, and statistical nonstationarity analysis is further covered in Appendix D.

(a) The TST supports exploratory data analysis (EDA), monotonic trend analysis, and other statistical methods to evaluate the stationarity (i.e., change point analysis) of both preloaded observational datasets (i.e., U.S. Geological Survey [USGS] annual maximum peak flows) and user-supplied datasets.

(b) Evaluating hydrometeorological stationarity using the approach described herein is limited to analyzing meteorological, riverine, and lacustrine observational records. Due to the complexity of underlying coastal processes, evaluating the stationarity of coastal time series data like tidal records is beyond the scope of this guidance.

(3) *Future Hydrometeorology Evaluation*. Future hydrometeorology associated with critical hydrometeorological variables tied to RHFs can be assessed in support of Tier 1

assessments using the USACE CHAT. Note: The potential for future changes in sea level and compound coastal flood/precipitation frequency are not currently captured by the CHAT streamflow outputs.

(a) CHAT allows users to visualize unregulated, hydrologically modeled streamflow outputs, as well as precipitation, temperature, and other future simulations of Coupled Model Intercomparison Project (CMIP)-designated[4] model outputs (e.g., CHAT relies on 32 of the model experiments for CMIP Phase 5 [CMIP5] at the time of publication).

(b) The tool displays the ensemble range of CMIP model-based outputs for a simulation period of 1951–2099 and includes robustness metrics that provide insight into the inter-model agreement and the robustness of the change signal modeled for a selected variable relative to historic variability.

(c) Trend evaluation is performed on the annual, inter-model means for both a historic period (e.g., for CMIP5, water years 1951–2005) and a future period (e.g., for CMIP5, water years 2006–2099). Additionally, the tool visualizes epoch-based differences in simulated monthly and annual historic versus future period streamflow, precipitation, and temperature model outputs.

(4) *Screening-Level Vulnerability Assessment*. The USACE CWVAT can evaluate vulnerability to changing hydrometeorological conditions across a given USACE business line or weather-related hazard. The CWVAT provides a nationwide, screening-level assessment of hazard- and weather-related vulnerabilities associated with USACE missions, operations, programs, and projects.

(a) Within the CWVAT, indicator variables define exposure and sensitivity to hydrometeorological hazards, which are applied to perform vulnerability assessments related to USACE business lines between a baseline historic period and two future epochs.

(b) The CWVAT facilitates project-based vulnerability assessments to support a Tier 1 assessment and comparative vulnerability assessments to inform strategic national- and regional-level decision-making.

e. Step 4 of a Tier 1 assessment evaluates DWR risk and is required for all inland and coastal studies. Risk driven by nonstationary hydrometeorological conditions can present a new risk or increase existing risks to project performance, management and/or operations. DWR risk must be considered in conjunction with other risks to identify opportunities to add resilience and to define and communicate residual risk due to nonstationary hydrometeorology. Risk driven by changing hydrometeorological conditions along with associated, known uncertainties should be characterized using the approach described in Appendix E. The DWR risk assessment process involves the following elements.

(1) The DWR risk assessment framework illustrated by the workflow in Appendix B, Figure B–2 and described in greater detail in Appendix E prescribes a methodology for performing a semi-quantitative assessment of the likelihood of THHs occurring as a result of future changes in hydrometeorological conditions. Triggers are tied to the project's RHFs.

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[4] Throughout this guidance CMIP-designated model outputs and CMIP5, as a specific example, illustrate the functionality of USACE tools that rely on model-based outputs (CHAT and CWVAT). USACE will continue to update its suite of tools as new data or methods become available.

Hazards are potential sources of harm driven by a given trigger. Harms capture the consequences of potential decreases in project performance such as life safety concerns, socioeconomic impacts, and environmental impacts.

(2) The DWR risk assessment approach determines the likelihood of a hazard and harm occurring because of changed hydrometeorological conditions in a project's service life, as well as the consequences of the harm via an impact rating. The assessment approach translates the combined likelihood and impact scores into a risk determination.

(3) Triggers tied to RHFs and hazards are included to characterize the future condition. Identified THHs inform alternative evaluation and formulation, help identify the TSP, and characterize residual DWR risk associated with each element of the recommended plan. Residual risk to the performance of elements of the TSP, any LPPs, and the recommended plan sensitive to changing hydrometeorological conditions must be presented in a risk table (see Appendix E, Table E–6). The table identifies the likelihood and impacts of the THHs translated into the overall DWR risk to each project feature.

(4) While a risk table (Table E–6) is only required for the TSP, LPPs (as applicable) and recommended plan, the DWR risk assessment process prescribed in Appendix E can be applied to all alternatives being evaluated to select the TSP. In some cases, it may be advantageous to evaluate all alternatives using the risk table to support a comprehensive benefits-based approach to incrementally justify resilient features (see Appendix F).

(5) The DWR risk assessment process should be iterative, as the PDT modifies elements of the project under consideration. If DWR residual risk is Moderate or High for a given project feature in the TSP, LPPs (if applicable), or recommended plan, the PDT should determine whether the residual risk is acceptable and engage the vertical team if necessary. Appendix E defines tolerable/acceptable versus unacceptable DWR risk in more detail.

(6) If the risk is unacceptable, the PDT must either make modifications to manage or alleviate that risk or describe and justify why no action is taken. The determination as to whether a risk is tolerable or unacceptable to the project should be made in close coordination with all PDT members and requires consulting project partners and stakeholders. The USACE vertical team can help identify risk tolerance levels (Hilleary et al. 2024).

(7) Risks due to the potential for changing hydrometeorological conditions are nearly impossible to eliminate due to the high uncertainties associated with the simulating future realizations of RHFs; therefore, DWR risks, including residual risks, should be documented both as part of the Tier 1 assessment and in the project risk registry, as appropriate. Uncertainties associated with each step of the risk evaluation must be qualitatively characterized and communicated (for more detail see Appendix E).

f. Step 5 of a Tier 1 assessment considers resilience and the potential for applying a dynamic adaption strategy. Adding resilience supports a project, system, and/or community's ability to anticipate, prepare for, and adapt to changing conditions and to withstand, respond to, and recover rapidly from disruptions. Increasing resilience to potential impacts driven by changes in hydrometeorological conditions can reduce unacceptable DWR risk. Strategies and steps that can add resilience and adaptive capacity to reduce the potential for impacts driven by nonstationary hydrometeorology are briefly summarized below and further detailed in Appendix F.

(1) Resilience to DWR risk can be achieved through various approaches or combinations of approaches by accepting and monitoring, avoiding, transferring, controlling, or burning-down risk (OUSD(R&E) 2023). These strategies can be applied during project design or can be deployed stepwise through dynamic adaptation.

(2) Alternatives should incorporate dynamic adaptation, where warranted, to address risk and uncertainty. When adopted, an adaptive approach requires a monitoring framework that identifies thresholds indicating nonperformance and triggers initiating preplanned actions that consider the lead time required for implementation (i.e., planning, design, and construction).

g. The first Tier 1 assessment in a geographic area generally requires additional time due to lack of familiarity with pertinent literature and resources available. Once analysis is complete for a specific geographic area and/or for a given USACE business line, elements of the analysis can be directly incorporated into future assessments for the same region and/or project type. The IIR CoP has generated a series of resources to increase familiarity with conducting a Tier 1 assessment and to leverage existing content.

(1) The USACE RAL, available via the IIR CoP's application portal, enables users to search completed LHC assessments by various geographic identifiers, keywords and USACE business lines.

(2) The IIR CoP KMP and IIR CoP Applications Portal sites provide web-based training, fillable small-scale Tier 1 assessment templates, and additional reference documents to support the current guidance (e.g., case studies, external references).

(3) When elements of an already completed evaluation are applied to a different project, the assessment must be tailored to the analysis it supports, and the Tier 1 assessment should reflect results based on the most up-to-date USACE tools and guidance.

11. **Tier 2 Assessments.**

a. A Tier 2 assessment consists of using future, model-based scenarios of hydrometeorology generated, evaluated and/or fine-tuned for use within a defined area/region and/or for a specific application. Tier 2 analysis can be applied in support of numerical modeling. Tier 2 evaluations augment a PDT's understanding of foreseeable changes in future hydrometeorological conditions and vulnerability to weather-related hazards over a project's service life. Tier 2 analysis can be applied to support adding resilience and/or dynamic adaptability to a project.

b. Modeled scenarios representing future hydrometeorology encompass a large range of plausible conditions, each with associated uncertainties driven in part by natural variability in long-term weather patterns, model structure, and assumed hydrometeorological and socioeconomic effects. However, the rigorous and statistically robust mechanisms available for quantifying the uncertainty associated with other design and planning factors cannot fully describe the uncertainty associated with simulations of future hydrometeorology.

c. The IIR CoP provides standards of practice and guidelines for conducting Tier 2 assessments as resources (e.g., supporting datasets and options for incorporating analyses). This includes best practices for addressing and communicating the large uncertainty associated with CMIP model-based outputs (Taylor, Stouffer, and Meehl 2012). These resources are available on the IIR CoP KMP site.

d. Proposing and applying a Tier 2 analysis requires IIR CoP leadership approval. To acquire approval, IIR CoP leadership must review the proposed technical, Tier 2 analysis scope of work. The Tier 2 scope must document available data products to apply, the modeling approaches, the computational requirements, the proposed workflow, and how to interpret and apply output.

(1) The PDT should consider the availability, relevance, and credibility of existing modeled scenarios representing future hydrometeorology applicable to the project area.

(2) As part of scope development, the PDT must consider whether a modeling approach or dataset is fit for the intended application. "Fit-for-purpose" describes the degree to which a method or tool is designed and applied to accomplish reliable outcomes for the information needs of a particular project.

e. Steps required to receive Tier 2 approval are detailed in F–10. For the majority of USACE projects, a Tier 1 LHC assessment is sufficient to assess the risk and uncertainty posed by changing hydrometeorological conditions to deliver a resilient project.

12. **Life Cycle Design Considerations.**

a. The hydrometeorological conditions for which a project is designed, or formulated on, can change over a project's service life. Thus, considering DWR risks and evaluating for long-term impacts should be an ongoing iterative process integrated across the entirety of the project's planning horizon. The planning horizon begins at the start of a USACE planning study and continues throughout a project's service life. Considering LHCs in decision-making is achieved by taking a life cycle design approach.

b. Life cycle design consists of selecting project elements (or applying a given management approach) based on combined life cycle costs (including OMRR&R) and long-term performance. Considering these criteria as part of decision-making related to DWR risks is required and supports long-term resilience and project performance throughout a project's service life.

(1) Once USACE projects are constructed, they often last in perpetuity when properly maintained unless deauthorized, so the planning horizon and project life are effectively infinite. However, life cycle design must assume a finite period for analysis.

(2) The period of economic analysis adopted as part of the USACE plan formulation process is typically 50 years. The analysis to consider LHCs as part of life cycle design should span a longer period over which impacts and benefits could foreseeably accrue.

(a) Both ER 1110-2-8159 and ER 1105-2-103 specify that for major infrastructure projects such as locks, dams, and levees, performance (benefits) and projected OMRR&R costs over an additional 50 years (beyond the 50-year economic period of analysis) must be analyzed to support effective life cycle design. For some applications (e.g., some ecosystem restoration projects) project service life can justifiably be assumed to be shorter.

(b) Unless another project service life is specified and justified in project documentation, a minimum 100-year period of analysis must be assessed to evaluate LHCs in a life cycle approach to design and decision-making.

(3) Both the economic period of analysis and longer life cycle period of analysis start with the project base year. The base year (i.e., analysis year zero) is the year at which full

expected project benefits begin to accumulate (i.e., the end of construction, though some benefits may begin to accrue during construction). Consistent with ER 1105-2-103, social, economic, environmental, and other physical impacts of changing LHCs should be evaluated over the 100-year (or otherwise specified) analysis period.

(4) CMIP-model-based products currently in USACE tools and resources have a period of analysis ending in 2099. Therefore, 2099 approximates future impacts to a project's performance over its service life until longer datasets become available and are incorporated into USACE tools and resources. This limitation must be clearly documented, since the 100-year period for most projects extends well into the first half of the 22nd century.

c. As part of a life cycle approach to project design and decision making, the DWR residual risk discussion, including how to manage it through the service life of the project (e.g., through monitoring and periodic reevaluation), must be part of design and OMRR&R documentation. Foreseeable future performance risks and long-term OMRR&R impacts should be conveyed to the nonfederal sponsor (NFS), when applicable. Depending on USACE's authority, either USACE or the NFS (or both) monitors the risk to inform future needs for reevaluation.

13. **Documentation.**

a. Each applicable element of the LHC assessment should be presented, along with supporting tables and figures. A narrative of assessment results, including at minimum a brief, qualitative characterization of uncertainty associated with analysis and findings, should be summarized and applied to determine and communicate DWR risk.

b. Documentation, including the recommendations provided by the IIR PDT member, should clearly illustrate that DWR risks are considered as part of the overall project and are appropriately mitigated so that the project is resilient to DWR risks over its service life.

c. In most cases, the LHC assessment (Tier 1, Tier 2, and RSLC analysis, as is applicable) are documented in a separate appendix to the main report. Brief summaries of the analyses, key findings, DWR risk discussion, residual risk, and resulting recommendations, should be integrated into the relevant sections of the main project report documentation.

14. **Review.**

a. Per ER 1165-2-217, LHC assessments require district quality control (DQC) reviews, and often agency technical reviews (ATRs) and policy and legal compliance (P&LC) reviews. The LHC assessment should, at minimum, receive a level of internal (i.e., DQC, ATR, P&LC) review commensurate with the highest level of internal review that the hydrology, hydraulics, and coastal (HH&C) analyses receive. The IIR CoP's review guide is available on the CoP's KMP site and includes review checklists to support DQC, ATR, and P&LC reviews.

b. The project review plan should identify an IIR reviewer for both the ATR and P&LC reviews. The IIR reviewer must have the required expertise (e.g., coastal, Tier 2 analysis). The project review plan should specify whether a Tier 2 scope review is required, as well as the assigned IIR CoP leadership reviewer(s). The review plan specifies the required review schedule. Per ER 1165-2-217, the project schedule must provide sufficient time to complete all reviews. The IIR and HH&C reviewers can be the same person, but to perform the IIR DQC, ATR or P&LC reviews, the reviewer must have experience specific to conducting and evaluating LHC assessments and DWR risk. At least one member of an ATR team for efforts covered by this

ECB must be certified by the IIR CoP in the Corps of Engineers Review Certification and Access Program (CERCAP).

15. **Nonstationary Extreme Precipitation and the Probable Maximum Precipitation.**

a. Extreme precipitation, such as 1-day and 3-day annual maximum precipitation with annual exceedance probabilities (AEPs) in the range of 10^{-3} to 10^{-6}, are used to estimate floods for levee and dam safety risk assessments. These extreme precipitation and probable maximum precipitation (PMP) estimates support flood risk management applications, including floodplain studies, planning and alternatives for dam rehabilitation designs, and risk reduction measures to address hydrologic potential failure modes (PFMs).

b. Robust evidence within the scientific literature indicates an increase in the frequency and severity of extreme precipitation by the end of the century (Diffenbaugh, Singh, and Mankin 2018; Kirchmeier-Young and Zhang 2020; Marvel et al. 2023). Extreme rainfall events have become heavier and more frequent across most of the U.S, especially over the last three to five decades. Based on simulations of future meteorology over the U.S., these observed trends will continue (Marvel et al. 2023). Therefore, PMP event magnitudes are likely to increase in the future (NASEM 2024). The National Academies of Sciences, Engineering and Medicine (NASEM) concluded that the potential for nonstationary hydrometeorological conditions and their effect on extreme rainfall must be considered to avoid underestimating both present-day and future risk of extreme rainfall.

c. USACE is collaborating with various research groups, national laboratories, and the National Oceanic and Atmospheric Administration (NOAA) to develop the best actionable science approaches to account for changes in extreme precipitation and PMP quantitatively. Examples include the ongoing revision to national precipitation frequency estimates known as NOAA Atlas 15 (NWS OWP 2022) and investigations to update PMPs that account for changes and nonstationarity. Information from these studies could be considered in Tier 1 and Tier 2 assessments, as appropriate, in consultation with IIR CoP leads.

d. Where dam safety modification studies use extreme precipitation estimates and/or PMPs as input for risk-informed design alternatives and risk reduction measures, information from Tier 1 assessments and Tier 2 assessments, when performed, should be used, as appropriate. Any quantitative adjustments applied to characterize extreme precipitation should follow the guidelines for Tier 2 assessments and require consultation with the IIR CoP leads. All dam safety analyses should be consistent with ER 1110-2-1156 and subsequent revisions.

16. **OCONUS Applications.** For areas outside the continental United States (OCONUS), data, information, and resource sparsity may present a challenge; analyses must be coordinated with the IIR CoP leadership.

17. **Date of Applicability.** This ECB is effective immediately.

18. **Update.** This guidance and any new methods will be incorporated into the next appropriate guidance document update. The next update is anticipated to be an engineer circular with a projected publication date of fiscal year 2028.

19. **Point of Contact.** The Headquarters USACE point of contact for this ECB is Dr. William Veatch, CEEC, (202) 761-7755.

//S//
Thomas P. Smith, P.E., SES
Director of Engineering and Construction
U.S. Army Corps of Engineers

Encl.

Appendix A ECB Main Body References

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Appendix F Resilience and Dynamic Adaptation

Appendix G Tier 2 Assessment Scoping and IIR CoP Approval Process

Glossary of Terms

ECB Appendix Table of Contents

Appendix A
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River Hydraulics.
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EM 1110-2-1417
Flood-Runoff Analysis.
https://www.publications.usace.army.mil/USACE-Publications/Engineer-Manuals/.

EP 1100-2-1
Procedures to Evaluate Sea Level Change: Impacts, Response, and Adaptation.
https://www.publications.usace.army.mil/USACE-Publications/Engineer-Pamphlets/.

EP 1105-2-61
Planning: Feasibility and Post-Authorization Study Procedures and Report Processing Requirements.
https://www.publications.usace.army.mil/USACE-Publications/Engineer-Pamphlets/.

ER 1105-2-100[5]
Planning Guidance Notebook.
https://www.publications.usace.army.mil/USACE-Publications/Engineer-Regulations/.

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[5] ER 1105-2-100, the Planning Guidance Notebook, will be superseded by several different pieces of new guidance, including EP 1105-2-61. The December 2023 version of the ER contains elements of the Planning Guidance Notebook that are still in effect (Chapter 4 and Appendixes C, D, E, and G).

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Appendix B
Workflow and Planning Process Alignment Figures

B–1. LHC Assessment Workflow. The flow chart in Figure B–1 illustrates the five required components of an LHC assessment (green boxes), as well as the multiple lines of evidence that can be analyzed to evaluate DWR risk (to include risk due to RSLC if applicable) (gray boxes). Lines of evidence required for most assessments are shown by a solid outline, while additional analyses that are only included where necessary/applicable are indicated by a perforated outline. (EM 1110-2-1416, River Hydraulics; ER 1100-2-8162, Incorporating Sea Level Change in Civil Works Programs; and EP 1100-2-1, Procedures to Evaluate Sea Level Change: Impacts, Response, and Adaptation)

B–2. DWR Risk Assessment Framework. Figure B–2 shows the DWR risk assessment framework prescribed by this guidance to evaluate risk driven by changing hydrometeorological conditions, described in greater detail in Appendix E. (EP 1105-2-61, Planning: Feasibility and Post-Authorization Study Procedures and Report Processing Requirements)

B–3. Alignment with Planning Process. Figure B–3 provides a crosswalk between the activities mandated in this ECB and the CW project milestones as specified by EP 1105-2-61. Key planning milestones include the AMM, TSP, and CVM. As laid out in EP 1105-2-61, the feasibility phase begins with distributing federal feasibility funds, following the execution of a feasibility cost sharing agreement.

Figure B–1. LHC assessment workflow

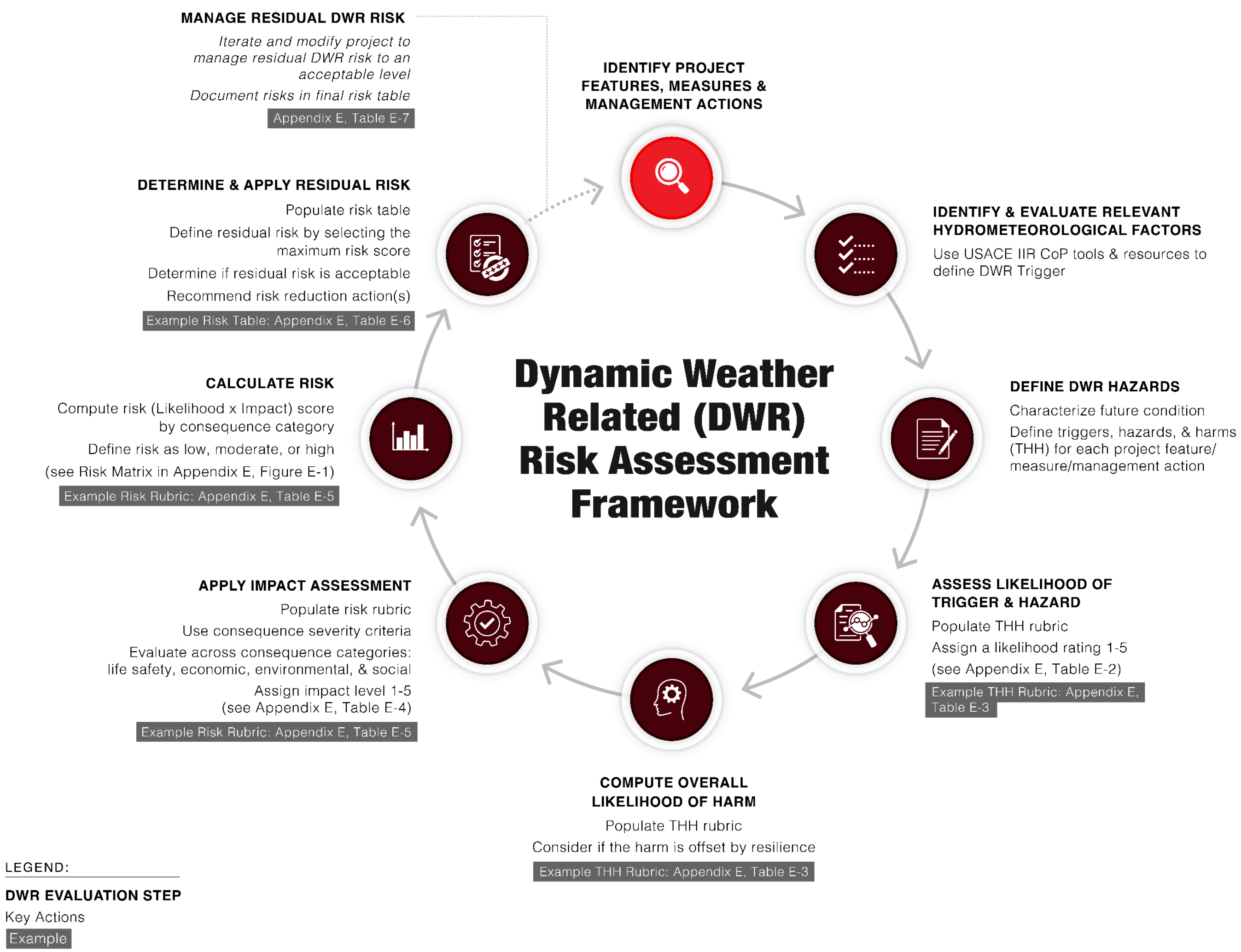

Figure B–2. DWR risk assessment framework

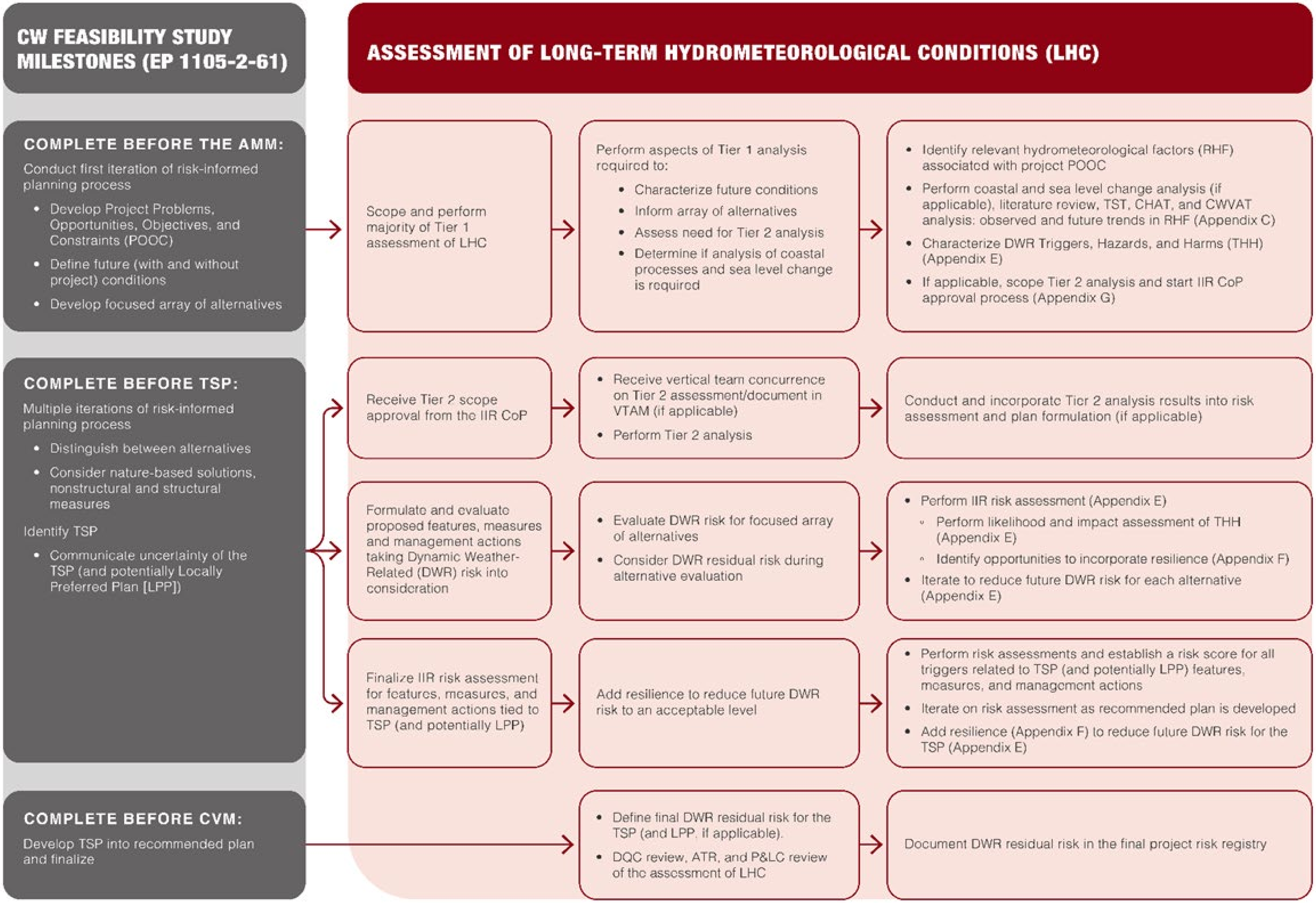

Figure B–3. Alignment of LHC assessments with the USACE planning process

Appendix C
Components of a Tier 1 Assessment

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C–1. Overview.

a. The effects of long-term variability in hydrometeorology are important for all USACE CW projects[6] because weather-related events play a role in modulating the hydrological conditions that underpin the flood risk management, aquatic ecosystem restoration, navigation, water supply, hydropower, and emergency management services that USACE provides to the nation. The required Tier 1 analyses identify changes in meteorological conditions that have the potential to substantially affect project hydrology and assess their potential impacts to project performance over its intended project service life.

b. This analysis relies on the best available science and professional judgment to address the DWR risks associated with changing hydrometeorological conditions. A Tier 1 assessment should be appropriately scaled to the project's complexity and sensitivity to nonstationary hydrometeorology to the degree known at the time of the analysis.

C–2. Approach.

a. A Tier 1 assessment consists of five required components: (1) establishing decision context, (2) identifying RHFs, (3) evaluating multiple lines of evidence, (4) conducting a DWR risk assessment, and (5) assessing the need for resilience features and dynamic adaptation strategies. This appendix discusses these components in more detail. Templates for small-scale Tier 1 assessments are available on the IIR CoP KMP site, and examples of completed Tier 1 assessments for applications of varying scope and scale are available on the web-based IIR CoP RAL.

b. A Tier 1 assessment uses multiple lines of evidence to understand whether changes (nonstationarities) are already impacting baseline hydrometeorological conditions and whether expected changes in future hydrometeorology could result in performance demands that significantly differ from what is presently required.

c. A Tier 1 assessment seeks to understand the following: (1) current conditions in terms of the RHFs, (2) observed and future trends in seasonality/timing, duration, frequency, and intensity of RHFs, to include qualitatively communicating the uncertainty associated with characterizing future hydrometeorological conditions; and (3) identifying DWR risk presented by nonstationary hydrometeorological conditions.

d. Evaluating both observed and future hydrometeorological information is important. Recent changes in hydrometeorology as captured by statistically significant trends in the observed record are more relevant for present-day and near-future outlooks (e.g., within 20 years). Modeled, future hydrometeorology (i.e., CMIP simulations) is relevant for longer term outlooks (e.g., 20 years or more into the future) (CEMA and CNRA 2012). Both must be used to characterize the future condition (FWOP and future with project conditions) as lines of evidence to evaluate DWR risk and to justify adding resilience to projects.

e. When evaluating modeled future information, analysis representing different scenarios and or/timeframes can more fully describe the range of plausible future conditions at different points throughout a project's service life. The range of different model-scenario

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[6] The Tier 1 risk assessment applies to all USACE activities that include hydrologic analysis, including but not limited to projects, studies, and management plans. For simplicity, "project" describes all USACE activities.

combinations can characterize uncertainty in modeled future hydrometeorology. How many scenarios and future timeframes are evaluated should be tailored to the scale and purpose of the assessment.

(1) Examples of CMIP-modeled future scenarios include CMIP5 representative concentration pathways (RCPs) 4.5 and 8.5, as well as the more recently published CMIP Phase 6 (CMIP6) shared socioeconomic pathways (SSPs) 2-4.5, 3-7.0, and 5-8.5.

(2) Model outputs are often evaluated for a historic timeframe, as well as future timeframes such as midterm (centered around 2050) and long term (centered around 2085).

f. USACE online tools should support the assessment required by this ECB, including the TST, the CHAT, and the CWVAT. All three tools are available via the USACE IIR CoP Applications Portal.

g. This analysis evaluates any differences between current and future hydrometeorological conditions, if they exist. The analysis considers DWR risks to project performance to identify how these differences impact decision-making. Identifying an unacceptable level of risk may necessitate adding features, measures and/or management actions that add resilience to foreseeable shifts in LHCs over a project's service life.

C–3. Establish Decision Context.

a. This step focuses on understanding project context and the overall decision-making framework. Early in the process, the IIR PDT member should work with the rest of the PDT to understand the following:

(1) Project scope and scale (e.g., size, cost, complexity, risk tolerance).

(2) Project problems, opportunities, objectives, and constraints (POOCs).

(3) Whether the application is for an existing or new project. This is an important distinction because an existing project may have less flexibility to add resilience. Additionally, an existing project's performance history in response to a range of hydrometeorological conditions may be considered.

(4) Measures, actions, and features under consideration, as well as the potential adaptability of the project.

(5) The project's potential performance indicators and definition of nonperformance.

(6) Decision timeframes and the project's planned service life (See Appendix F, section F–4 for more detail).

(7) Potential for system-wide impacts (cumulative impacts on other systems in the project area) and/or impacts to other federal agency missions.

b. Understanding historical hydrometeorological conditions can provide a baseline for recognizing how future changes could impact project POOCs. Practitioners should consider whether any weather-related stressors (e.g., extreme droughts, floods, storms) experienced in the past could cause problems if they became more severe or frequent in the future.

c. Based on the project location and project scale, the IIR PDT member should determine the need for an RSLC analysis and establish whether investing in additional analysis to understand and/or quantify changes in hydrometeorology by pursuing a Tier 2 assessment is warranted.

d. The IIR PDT member should understand resource availability, level of risk tolerance, and the degree of interest in evaluating impacts driven by foreseeable shifts in hydrometeorology over the project service life and adding resilience to counteract these impacts.

C–4. Identifying Relevant Hydrometeorological Factors for Analysis.

a. This step determines which RHFs contribute to the project POOCs. Defining RHFs should characterize and consider existing hydrometeorological conditions, associated weather-related sensitivities, sensitivities to cumulative or compound weather event impacts (i.e., the combined effect of increases in extreme storm events and storm surge) and key hydrologic processes. The PDT should be engaged in identifying RHFs early in the project. RHFs should be revisited and updated throughout the project.

b. The PDT must identify and consider which measurable variables are tied to RHFs and have the potential to exacerbate or ameliorate the identified project problems and opportunities. For example, a project that addresses spring flooding may be concerned about winter and spring temperature and precipitation, especially with respect to snowpack conditions, and the resulting effect on the magnitude and duration of spring flows. However, this PDT may not be as concerned about river conditions during the late summer and would thus not consider the hydrometeorological variables that influence these flows. By contrast, the variables tied to the RHFs that contribute to late summer low flows (i.e., precipitation, temperature, drought) in the same watershed may be of great concern for an ecosystem restoration project.

c. The Tier 1 assessment should clearly state the RHFs and associated hydrometeorological variables and explain how/why they contribute to the problems and opportunities identified for the project. To support USACE's plan formulation process, this should be narratively described when characterizing the future condition. RHFs and associated variables can be identified by considering the following questions.

(1) What hydrometeorological variables are most critical to the project?

(2) Which critical hydrometeorological variables have the potential to be impacted by changing long-term trends in meteorology?

(3) What changes in hydrometeorological conditions (magnitude, directionality, and seasonality, etc.) could adversely or positively affect project performance?

(4) What known and foreseeable interdependencies (i.e., positive and negative feedback mechanisms) between weather and hydrologic response could be impacted by a given change in hydrometeorology?

(5) What impact have historic weather-related stressors like extreme events had on the project area and/or project performance?

d. To identify RHFs and select variables for a Tier 1 assessment, both primary and secondary weather-related impacts to hydrologic processes, as well as the potential for interdependencies, should be considered to the greatest extent possible. Examples of primary and secondary impacts to hydrologic processes are summarized in Table C–1.

e. Concurrent changes in temperature and precipitation patterns are an example of critical interdependencies impacting streamflow response. For instance, in a historically snow-dominated watershed, the combined effect of decreasing snowpack due to increasing winter temperatures and increases in the frequency and intensity of summer storms may result in shifts in the magnitude and seasonality of the annual peak streamflow response. The annual peak streamflow response may shift from occurring in spring to summer.

Table C–1
Example impacts driven by nonstationary hydrometeorology[a,b]

Primary Shift in Weather-Related Impacts	Associated Secondary Impacts to Hydrometeorological Response	Example RHFs	Example Measurable Variables for Analysis
Increases in temperature and/or changes in precipitation patterns	• Changes in seasonality (e.g., timing of snowmelt, growing season length, frost-free season length, freeze-thaw cycle)	• Temperature • Precipitation	• First frost/freeze/hard freeze dates[c]
Increases in temperature and/or changed precipitation patterns	• Increases in the frequency and intensity of extreme rainstorms	• Temperature • Precipitation	• Annual maximum 1-day precipitation
Changes in precipitation	• Changes in streamflow	• Precipitation • Streamflow	• Annual maximum peak streamflow
Wildfire and changes in precipitation	• Changes in erosivity/landslide frequency • Changes in risk of flash floods	• Precipitation • Sedimentation • Streamflow • Wildfire	• Fire risk days[d] • Total suspended solids (TSS) • Annual maximum 1-day precipitation • Annual maximum peak streamflow
Changes in air temperature	• Heat wave • Changes in water temperature	• Temperature	• Days above 95 °F • Annual maximum temperature
Changes in temperature and/or precipitation	• Drought • Wildfire • Changes in snowpack	• Temperature • Wildfire • Drought • Precipitation	• Consecutive dry days • Annual maximum snow water equivalent (SWE) • Fire risk days[d]

NOTES:

[a] Adapted from California Planning for Adaptive Communities (CEMA and CNRA 2012).

[b] Table C–1 is not a comprehensive list of primary and secondary hydrometeorological factors and varies by location and application. For instance, an increase in precipitation does not necessarily directly translate to an increase in streamflow in a project area with a concurrent increase in temperature-driven infiltration and/or evapotranspiration, etc.

[c] The NOAA National Weather Service (NWS n.d.) first frost date is based on the first occurrence of 36 °F, first freeze is based on the first occurrence of 32 °F, and first hard freeze is based on the first occurrence of 28 °F.

[d] This is the average annual number of days in which extreme weather conditions favor the ignition and spread of wildfires because both fine and coarse fuels have dried out (USACE 2017).

C–5. Literature Review: Observed and Future Trends.

a. The literature review describes published patterns in observed and future hydrometeorological changes. At minimum, it should summarize observed and future trends in temperature, precipitation, and the hydrologic response (e.g., streamflow) most relevant to the project RHFs. The literature review should describe existing hydrometeorological conditions as well as characterize changes already observed and potential future changes in the RHFs for the project area. The number of references reviewed and length of the literature review summary should be scaled to the overall project.

(1) Tier 1 assessments that support smaller scale projects should be concise and can rely on already synthesized information from the U.S. National Climate Assessments (NCAs) (i.e., Melillo, Richmond, and Yohe 2014 [NCA3]; Crimmins et al. 2023 [NCA5]), NOAA state climate summaries (NOAA 2022), and 2015 regional climate syntheses published by USACE (USACE n.d.).

(2) A literature review that supports a large-scale project should be comprehensive and include authoritative findings from regionally relevant, recently published, peer-reviewed journal articles and technical reports generated by academia, reputable science institutions and organizations, and government agencies.

b. If the review uses regionally specific research (e.g., reports published by local universities, state water resources agencies), IIR CoP leadership can be consulted to verify applicability.

c. Information from multiple references should be aggregated to evaluate the degree of consensus within the literature in terms of the directionality and magnitude of observed and future trends in the RHFs being assessed.

C–6. Statistical Nonstationarity Analysis: Observed Hydrometeorology.

a. To support efficiency and confirm that analyses are technically defensible, consistent, and reproducible, statistical analysis to test for nonstationarity should use the approach detailed in Appendix D and the USACE TST. The TST is a web-based tool that supports consistent, repeatable data preprocessing, EDA, and evaluation for statistical evidence of nonstationarity. The TST is available via the IIR CoP's application portal.

b. The TST evaluates for monotonic trends, breakpoints, and change points in hydrologic time series variables (e.g., streamflow, precipitation, temperature). Tool outputs should identify strong nonstationarities based on the criteria of consensus, robustness, and magnitude of change (See Appendix D for more detail in terms of what constitutes strong evidence of nonstationarity).

(1) For USACE applications, change point tests compare statistical properties in different subsets of the data. In comparison, breakpoint tests iteratively add data and recommend breaks when regression model errors fall outside of expected variance bounds (See Appendix D, section D–6, for more detail).

(2) To detect nonstationarities, many statistical tests should be applied at the same time, as each test has unique tradeoffs. More detail related to the recommended statistical tests and their required input parameters is in the TST User Guide.

(3) IIR leadership approval is required to use a statistical method not currently in the TST.

c. The TST enables analysis on either user-uploaded time series data or preloaded data from USGS. The preloaded data includes annual peak and monthly mean streamflows and stage gage data.

d. Functionality of the TST relevant to conducting nonstationarity analysis is in the tool's Explore Data, Trend Analysis, and Nonstationarity Detection modules.

(1) Explore Data allows users to select their own data or preloaded USGS streamflow datasets to visualize that data and explore the dataset's statistical characteristics. This portion of the tool also contains a range of data preprocessing features.

(2) Trend Analysis includes different statistical methods to detect trends. Outputs include the directionality and slope of the trend, as well as hypothesis test results for trend significance (i.e., p-values).

(3) Nonstationarity Detection uses different statistical methods to detect both abrupt and smooth nonstationarities in the period of record. This module supports both change point analysis and breakpoint analysis (see Appendix D and the TST User Guide for more detail).

e. Observed hydrometeorological time series tied to the project's RHFs should be analyzed for evidence of nonstationarity. Variables should be aggregated annually and analyzed on a yearly, monthly and/or seasonal basis (e.g., annual maximum 3-day precipitation, annual average flow occurring during a given month, annual maximum summer temperature). The TST should not determine trends and nonstationarities in sub-annual time series, as such data cannot be assumed to be independent and identically distributed. Further guidance on which hydrometeorological time series can be appropriately evaluated using the methods in the TST is provided in Appendix D.

f. The number of sites and data types selected for analysis should be based on the RHFs identified, the spatial extents of the project, and the overall project scope and level of risk tolerance.

C–7. Evaluating Future Hydrometeorology.

a. The USACE CHAT allows USACE staff easy access to CMIP-model-based simulated future hydrometeorological data products. Automating the analyses eases the computational burden of evaluating future-simulated hydrometeorology. For more detailed information about the tool, please refer to the CHAT User Guide.

b. CHAT visualizes outputs derived from simulations of daily unregulated streamflow, temperature, and precipitation-based variables over a historical period (e.g., 1951–2005 for CMIP5), as well as future period (e.g., 2006–2099 for CMIP5). CHAT uses statistically downscaled outputs from CMIP models to visualize hydrometeorological variables. Future hydrometeorology uses scenarios representing pathways to various radiative forcings by the end of the century. The tool facilitates trend analysis and boxplot visualizations of future, epoch-based shifts in annual and monthly variables. CHAT provides repeatable, efficient and reliable analytical analyses.

(1) Using CHAT begins with choosing the eight-digit hydrologic unit code (HUC) watershed and/or stream segment relevant to the project in the tool's study location selector, as seen in Figure C–1.

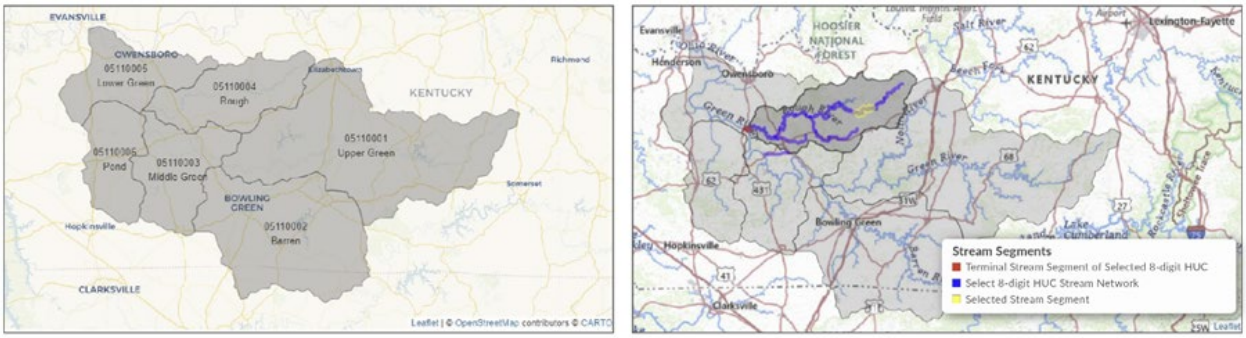

Figure C–1. Example of a HUC-8 (left) and stream segment (right) in the study location selector

(2) CHAT provides simulated meteorological (precipitation and temperature) outputs aggregated to each eight-digit HUC basin in the CONUS and routed, unregulated streamflow generated using a hydrologic modeling framework displaying output corresponding to a selected stream segment. CHAT variables are listed in Table C–2.

Table C–2
CHAT variables

Precipitation	Temperature	Streamflow
• Annual maximum one-day • Annual maximum three-day • Annual accumulated precipitation (total volume) • Maximum number of consecutive dry days (drought indicator)	• Annual mean one-day • Annual maximum one-day • Annual minimum one-day	• Annual streamflow volume (total volume) • Annual mean one-day (average flow conditions) • Annual maximum of mean monthly (high flow conditions)

(3) For each hydrometeorological variable, CHAT displays analytical output through a user interface consisting of the following four tabs:

(a) The Modeled Time Series Explorer tab provides a printable graphic displaying the inter-model range and mean for a given hydrometeorological variable in the selected eight-digit HUC (or stream segment) across the simulated historical and future periods.

1. The inter-model range indicates the cumulative uncertainty associated with each step of the modeling chain and should be discussed qualitatively, in brief, as part of Tier 1 assessment documentation to provide context to CHAT outputs.

2. Robustness metrics overlay the annual time series plots to assess inter-model agreement on the directionality of the change signal and the significance of the future trend relative to the variability of simulated historical outputs. Robustness metrics should be displayed by checking the Show Robustness Metrics box.

(b) The Modeled-Time Series Trend Analysis tab provides a printable graphic of trendlines fit to the mean of the historical simulations and the mean of the future simulations of selected hydrometeorological variables. Trend line slope, as well as an evaluation of statistical significance (i.e., p-value < 0.05) is provided.

(c) The Monthly Box Plots: Epoch-Based Changes tab provides a printable graphic that compares differences in the CMIP model ensemble mean of a monthly hydrometeorological variable between a base epoch (e.g., 1976–2005) versus the mean computed for two future epochs: mid-century (e.g., 2035–2065) and late century (e.g., 2070–2090). This information can be applied to understand potential future changes in seasonality.

(d) The Annual Box Plots: Epoch-Based Changes tab provides a printable graphic that compares differences in the CMIP model ensemble mean of a hydrometeorological variable between a base epoch versus the mean computed for two future epochs (e.g., 2035–2065 and 2070–2090).

(4) For both the historical and future periods, hydrometeorological outputs are generated using simulated CMIP-model outputs. CMIP-model-based historical period outputs displayed in CHAT cannot be directly compared to observed time series, especially in places where observed time series represent regulated conditions. The CMIP-model-based streamflow results displayed in CHAT do not account for regulation. Additionally, CMIP models simulate long-term averages, trends, and variability in weather patterns, rather than historical weather. They use initial atmosphere, ocean, and land surface conditions to start simulations; however, the chaotic nature of the atmosphere quickly (on the order of days) leads to large differences from actual weather as the model steps forward in time.

c. Although this output does not support numerical analysis, it does provide insight into the degree and direction of relative change. Relative change can be evaluated by comparing the simulated historical and future period outputs. CHAT outputs cannot be applied as numerical inputs to design or alternative evaluation. CHAT outputs can be applied to characterize DWR risk and inform risk-based decision making by illustrating potential changes in future hydrometeorology. Relative epoch-based changes indicated by the box plots and trend line slope can infer the directionality of change (increasing or decreasing) and define the magnitude of change over relatively long time-time horizons (e.g., greater than 30-year periods).

d. Degree of relative change should be considered in conjunction with associated robustness metrics. Change is robust if trends are statistically significant (i.e., p-value < 0.05), robustness criteria indicate agreement in the direction of change between CMIP models, and the change signal is significant relative to the variability of the historical period outputs.

e. The potential for future changes in sea level and compound coastal flood/precipitation frequency are not currently captured by the models that derive CHAT streamflow outputs.

C–8. Applying the Civil Works Vulnerability Assessment Tool.

a. CWVAT assesses vulnerability at varying watershed scales to support USACE missions, operations, programs, and projects. CWVAT evaluates the vulnerability of USACE assets, project features, and management plans to present and future extreme, weather-related hazards. By conducting a vulnerability assessment and using other tools and resources developed by the IIR CoP, USACE staff can make risk-informed decisions to achieve long-term resilience. Detailed information about the tool is available in the CWVAT User Manual.

b. For the CWVAT, vulnerability is comprised of the project or project area's exposure to present and future extreme weather-related hazards, sensitivity to the impacts of the hazards, and adaptive capacity to reduce the negative impacts of the hazards. Exposure to weather-related hazards can be driven by changes in temperature (e.g., is it getting warmer in the project area?), precipitation (e.g., is storm intensity increasing?), and hydrologic response (e.g., is increased flooding anticipated?). Sensitivity to hazard exposure includes negative impacts to long-term project performance, as well as the severity of those impacts. Adaptive capacity includes the ability to design or modify a project to strengthen resilience against future hazard-driven impacts.

c. CWVAT provides important information about the components of a project area's vulnerability to weather-related hazards; however, fully capturing vulnerability must be achieved by implementing this ECB, which thoroughly assesses hydrometeorological conditions through time and engages the entire PDT and public throughout the planning and design process.

d. CWVAT aggregates information spatially using watershed boundaries and temporally by epochs for baseline and future periods. It computes vulnerability scores across broad categories using indicators based on actionable information from CMIP models and authoritative data sources produced by federal agencies and academia.

e. Indicators provide valuable information to identify trends in key hydrometeorological variables. Indicators are grouped into categories such as weather-related hazards (e.g., drought, extreme temperature, and wildfire) and business lines (e.g., flood risk management, aquatic ecosystem restoration, and navigation) to represent vulnerability and its components: exposure, sensitivity, and adaptive capacity. Figure C–2 illustrates an example of the indicators that inform the extreme temperature hazard. Subsequent sections use this example to illustrate how to use this information as part of a vulnerability assessment.

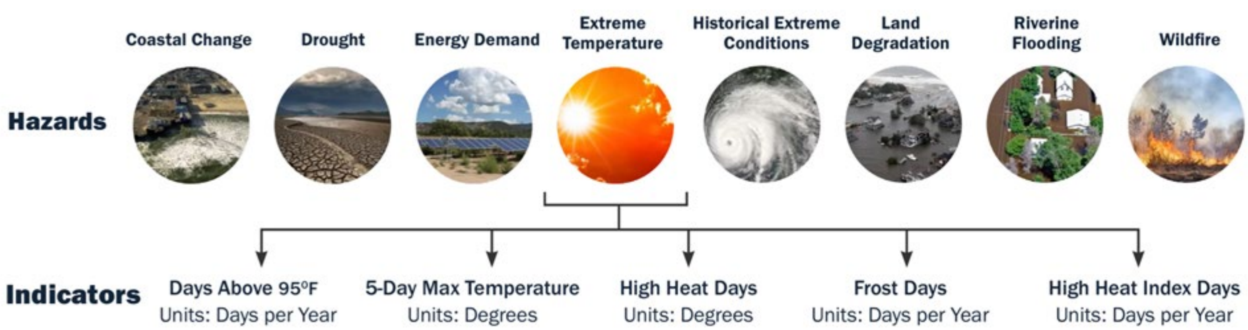

Figure C–2. Potential indicators tied to the extreme temperature hazard

f. Depending on the data source of each indicator, indicators can be constant through time, a function of time, or a function of time and scenario.

(1) Indicators that are constant do not account for changes in physical, socioeconomic, or future hydrometeorological conditions; therefore, the indicator value does not change for future epochs or scenarios.

(2) Indicators that are a function of time represent future conditions (e.g., changes in land use) but do not represent changes in hydrometeorological conditions.

(3) Indicators that are a function of time and scenario are based on a range of future hydrometeorological conditions. Vulnerability scores and the raw indicator values that compute vulnerability scores are computed for future time periods and scenarios. CWVAT defines two 30-year epochs, or time periods, centered around 2050 and 2085. CWVAT defines scenarios based on the RCP 4.5 and 8.5 scenarios of the CMIP5 hydrometeorology products, representing pathways to a given change in radiative forcing by the end of the century. By providing results for a different epoch-scenario combinations, CWVAT reveals some of the uncertainty associated with evaluating model-based future conditions.

g. CWVAT performs vulnerability assessments for two use cases: large-scale comparative vulnerability assessments and small-scale project area vulnerability assessments.

(1) Large-scale comparative assessments generally compare vulnerability to changing hydrometeorological conditions between a portfolio of sites for a broader category (e.g., weather-related hazard or business line). Using the example in Figure C–2, the extreme temperature hazard vulnerability score could be useful if senior leadership were making investment decisions across a national portfolio of aquatic ecosystem restoration projects with sensitivities to extreme temperature increases. Leadership could use CWVAT results to prioritize investment on sites with higher vulnerability to extreme temperature.

(2) Small-scale project area assessments comparatively illustrate vulnerability within the project area as compared to other watersheds across the U.S. At the project level, evaluating changes in specific indicator values can also support screening level decisions. For instance, the 5-day maximum temperature indicator trends between historical and future epochs provides insight into the project's vulnerability to extreme temperature change.

h. CWVAT is designed for screening-level assessments by comparing indexed vulnerability scores between watersheds or sites and interpreting trends in relevant hydrometeorological factors. CWVAT cannot quantitatively inform formulation or design.

C–9. Risk Assessment.

a. Systematically assessing DWR risk to project performance supports characterizing future conditions, decision-making, and semi-quantitatively describing residual DWR risk. The DWR risk assessment must identify opportunities to add resilience and/or adaptive capacity to the recommended plan.

b. The DWR risk assessment consists of the following steps (see Appendix B, Figure B–2): (1) identifying the source of risk by characterizing potential triggers and hazards, (2) identifying potential harms and consequences of the hazard, (3) assessing the likelihood of the hazard and harm materializing, (4) assessing the impact or consequence of the hazard and harm, (5) recommending resilience to DWR risk via monitoring and/or a risk management/mitigation action or element as appropriate, and (6) qualitatively describing the uncertainty associated with the DWR risk assessment. This methodology is covered in detail in Appendix E.

C–10. Consider Resilience and Dynamic Adaptation. The PDT should approach projects with a resilience mindset by evaluating the DWR risk that hydrometeorological change presents to future project performance. This evaluation should inform decision-making and identify opportunities to enhance resilience (Hilleary et al. 2024). Outputs from the LHC assessment can justify adding resilience features to the project. Appendix F provides an overview of how to consider resilience and dynamic adaptation strategies as part of a project.

C–11. Documenting Results.

a. The Tier 1 assessment should discuss RHFs, the associated measurable hydrometeorological variables selected to support analysis, and how changes in RHFs contribute to the project's problems and opportunities. Findings based on the literature review, statistical nonstationarity detection (NSD) analysis (through TST), evaluating modeled future hydrometeorology (through CHAT), and assessing vulnerability (through the CWVAT) should be documented in an appendix and summarized in the main report to define DWR risk.

b. When documenting NSD results, figures and output from the TST should support EDA and nonstationarity analysis. Documentation should reference the principles of consensus, robustness, and magnitude of change (see Appendix D for more detail) when identifying strong evidence of nonstationarity. For the time series analyzed, the data source, period of record, drainage area (streamflow only), degree of regulation (streamflow only), and potential known sources of nonstationarity in the data should be documented.

c. Visuals that illustrate simulated future hydrometeorological outputs should be presented in comparison to analogous, simulated historical period output. Figures for studies limited to a Tier 1 assessment should be extracted from CHAT. The robustness, directionality and statistical significance of trends in CHAT outputs should be summarized. Both annual and/or monthly epoch-based changes should be presented and described where applicable. The assessment should, at minimum, include a brief qualitative discussion of uncertainty associated with future, CMIP-model-based hydrometeorology as illustrated by the range (spread) of CMIP-based outputs presented in CHAT.

d. The analysis should use tables and figures to present CWVAT assessment results. Discussion should state that CWVAT supports screening-level analysis. Changes in indicator values relevant to the project purpose should be presented for the historical period relative to a future period of interest. Vulnerability scores and relevant, relative comparisons should be documented for USACE business lines or weather-related hazards of interest.

e. Narrative and tables should document the DWR risk evaluation and its inherent uncertainties (see Appendix E for more detail). Project documentation must include a DWR risk table that characterizes residual risk. Resilience and/or adaptability to changing conditions and associated impacts should be fully documented (see Appendix E and Appendix F for more detail).

f. To support USACE's plan formulation process, characterizing future conditions must include a brief overview of how changing LHCs may impact the project area if no action is taken.

g. Templates for small-scale Tier 1 assessments are available on the IIR CoP KMP site, and examples of completed LHC assessments for applications of varying scope and scale are available via the web-based IIR CoP RAL.

C–12. Appendix C References

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Appendix D
Statistical Nonstationarity Analysis

List of Figures

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List of Tables

D–1. Background.

a. Adverse impacts relevant to USACE operations, changing LHCs, and modifications to watersheds undermine the fundamental design assumption of stationarity (the assumption that the statistical characteristics of hydrometeorological time series data are constant through time). The stationarity assumption enables the use of well-accepted statistical methods in water resources planning and design.

b. Analyses using observed data are critical to understanding hydrologic response. Considerable uncertainty is associated with simulating future meteorological variables and understanding the influence of changes in weather patterns on LHCs (Harrigan et al. 2017). Analyses based on observed data can identify where hydrometeorological conditions are changing. Understanding LHCs is critical to effectively manage and minimize DWR risk in both engineered and/or nature-based solutions (Slater et al. 2021).

c. Given the importance of the stationarity assumption, as well as growing scientific debate over the ongoing validity of this assumption (Lins and Cohn 2011; Milly et al. 2008), USACE has a vested interest in establishing and applying methods to understand where and how hydrometeorological conditions may be changing.

D–2. Overview.

a. Nonstationarity refers to changes to the statistical characteristics (e.g., mean, median, scale-variance, interquartile range) of datasets through time (Faulkner et al. 2021; Maraun, Rust, and Timmer 2004; Rea et al. 2009; Rougé, Ge, and Cai 2013; Slater et al. 2021; Villarini et al. 2009). Changes in hydrometeorological processes can occur either abruptly or gradually depending on the characteristics of the factors affecting physical processes (Chandler and Scott 2011; McCuen 2003). For example, constructing a dam could abruptly change downstream streamflow patterns, while ongoing watershed development could gradually alter the shape of the resulting flood hydrograph (EM 1110-2-1415). Statistical methods detect both abrupt and gradual change.

b. Although the exercise of evaluating time series data for evidence of nonstationarity is important and critical to understanding the potential for changing conditions, it is also difficult. Notably, differentiating between evidence of a permanent, long-term change versus short-term variability or long-term persistence is challenging (Fleming and Weber 2012; Slater et al. 2021). Making these differentiations is especially difficult when the time series being analyzed are short (Khaliq et al. 2008). Due consideration must be given to the inherent uncertainty (Slater et al. 2021) and underlying assumptions associated with the statistical methods being applied (Serinaldi, Kilsby, and Lombardo 2018).

c. This appendix provides technical guidance on evaluating for evidence of nonstationarity in observed hydrometeorological records. Analysis should be scaled appropriately by considering how the analysis is applied and the project complexity.

d. Examining hydrometeorological records for evidence of statistical change involves several steps. The first is to select the critical hydrometeorological variable(s) to evaluate and to identify observed time series of adequate length to use in the analysis. After identifying each variable of interest, four additional tasks support nonstationarity analysis: EDA, data preparation, applying adequate test statistics, and interpreting the results (Kundzewicz and Robson 2004).

D–3. Variable Selection.

a. The time series to analyze should be selected based on project scale, data availability, and the practitioner's understanding of the potential effect of LHCs on hydrological processes that are key to the project objectives (e.g., project feature design, watershed management decisions).

b. Potential variables include annual maximum flow measurements, moderate and low flow variables, river stage, lake/reservoir pool elevation, precipitation time series, temperature time series, and computed indices. In general, these hydrometeorological time series can be evaluated effectively when aggregated annually and analyzed on an annual (e.g., annual, maximum streamflow), monthly (e.g., annual, cumulative March precipitation), or seasonal basis (e.g., annual, mean winter temperature). However, the variable selected may need more preprocessing or nuanced interpretation. Additionally, working with long time series (i.e., greater than 50 years) is important.

c. The variable selected should maximize the power of the statistical tests being applied and provide meaningful results. The power of statistical tests is a measure of their effectiveness in determining trends, change points, etc.

(1) Statistical power is increased by reducing the potential for serial correlation, zero inflation (i.e., frequent zero-valued observations), overdispersion (i.e., high variability), and time series with a limited number of unique values. Overdispersion and having a limited number of unique sample values are not typically an issue for observed hydrometeorological time series but can be an issue for some count datasets (Campbell 2021).[7]

(2) For instance, when considering the impacts of changing conditions on lakes and reservoirs, computed reservoir inflows should be evaluated rather than the directly observed pool elevations or outflows. Both pool elevations and outflows frequently exhibit a degree of year-to-year serial correlation and are heavily impacted by water management practices.

(3) Caution should be taken when applying statistical methods to evaluate low flow variables (including those to characterize drought) and count datasets. Low flow measurements frequently exhibit data quality issues relative to moderate flow measurements (Mallakpour and Villarini 2016). Low flow and count datasets frequently do not meet the underlying assumptions required by many statistical tests that evaluate stationarity.

(4) Because sub-annual datasets exhibit considerable periodicity and noise, the methods in this guidance generally do not apply to sub-annual data, as these time series are often not independent and identically distributed.

(5) Preprocessing techniques and approaches to analyzing nonstationarity in coastal time series like tide levels are complex and outside the scope of this guidance.

d. To evaluate time series that do not meet the underlying assumptions of the statistical test in the TST, the PDT should consult the IIR CoP leadership for further technical guidance.

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[7] Count datasets are typically the number of times a hydrometeorological event occurs each year or season. Frequently, these datasets focus on extreme events and counts are based on a threshold (e.g., number of days above a given temperature, annually).

D–4. Exploratory Data Analysis.

a. EDA is a critical step to performing a nonstationarity analysis and understanding changes in observed records (Slater et al. 2021). EDA informs data analysis methods and identifies potential data quality concerns. Additionally, EDA can identify potential drivers of nonstationarity.

b. EDA includes surveying what is known about the time series and project area. This part of EDA includes consulting time series' metadata like the USGS streamflow gage water year summaries; reviewing relevant hydrometeorological studies, reports, and products (e.g., land use datasets, historical reports, water management manuals, paleoflood studies as covered by ETL 1100-2-4); and gathering institutional knowledge by consulting with local experts.

c. Key aspects to consider are (1) the quality of the data, (2) historic changes in data collection (e.g., station equipment, gage placement), (3) natural phenomena that impact data reliability (e.g., backwater conditions, frozen apparatus), (4) the presence of gaps and missing data, as well as how data was derived (e.g., combining observed and modeled data) and (5) prior knowledge of drivers of nonstationarity in the project area (Faulkner et al. 2021; Slater et al. 2021; Zarenistanak, Dhorde, and Kripalani 2014). EDA should also indicate whether the underlying assumptions critical to the statistical methods are being met.

d. EDA consists of basic data exploration, which includes plotting and reviewing the raw data for analysis. Raw data varies considerably in its format and timescales (Harrigan et al. 2017; Slater et al. 2021). In addition to plotting the data chronologically (e.g., hyetographs and hydrographs), other graphics and statistical methods should be applied (e.g., screening-level change point tests, distribution fitting to identify outliers, tests for normality, serial correlation). Features of the USACE TST support EDA.

e. NSD methods typically assume that the time series is not autocorrelated. Autocorrelation occurs when values in a time series are strongly influenced by the preceding values. In time series data, autocorrelation is also known as serial correlation (Helsel et al. 2020). Autocorrelation affects the statistical significance of the test results because when autocorrelated, the effective sample size is smaller than the number of observations.

(1) When a time series is positively autocorrelated, high values tend to follow high values and low values tend to follow low values. When a dataset is negatively autocorrelated, low values tend to follow high values and vice versa (Kurunç, Yürekli, and Çevik 2005). When present in hydrometeorological time series datasets, autocorrelation is typically positive (Lund et al. 2023).

(2) Hydrometeorological datasets can be autocorrelated due to short- and long-term persistent trends in hydrology, meteorology, groundwater influence (e.g., high baseflow persisting over a multi-year period), and water management practices (Faulkner et al. 2021; Ryberg, Stone, and Baker 2020; Serinaldi, Kilsby, and Lombardo 2018).

(3) Autocorrelation can be explored using the USACE TST. The Explore Data tab provides summary statistics, including the autoregressive lag-one correlation coefficient (AR(1) Coeff.) and the autocorrelation function (ACF). The ACF is visualized using a correlogram, displaying autocorrelation at various lags with 95 percent confidence limits. Data points exceeding these limits indicate statistically significant autocorrelation at the 5 percent level.

(4) "Positive serial correlation among the observations would increase the chance of a significant answer even in the absence of a trend." (Cox and Stuart 1955) If significant serial correlation is found, the temporal dependence could represent the process of interest, or an artifact due to the presence of gradual/abrupt change. Consequently, providing guidelines on dealing with this issue is difficult because any recommendations should be made case-by-case.

f. Parametric tests applied to evaluate for evidence of nonstationarity require that the data meet their distributional assumptions (such as being normally distributed). When this assumption is not met, parametric tests lose their sensitivity (statistical power) to detect trends or change points. For this reason, EDA should determine whether a known statistical distribution can adequately model the time series. The TST automatically applies the Anderson-Darling test to evaluate for normality in conjunction with parametric change point testing. To visualize whether a dataset fits a normal distribution, a quantile-quantile plot, where the data and the normal theoretical quantiles plot on the 45-degree reference line (1-to-1 line), can also demonstrate that data can reasonably be assumed to be normal (Ford 2020).

D–5. Data Preparation.

a. Following EDA, some data preparation steps are frequently required, unless a curated dataset like the USGS annual peak streamflow dataset is being analyzed. As part of data preparation, erroneous datapoints including spurious outliers and data gaps should be identified and corrected prior to nonstationarity analysis. The amount of pre-processing and additional analysis depends on the variable of interest, data availability, and project scale. For smaller scale applications, it may be more appropriate to exclude a given test result or time series from analysis or to select an alternate variable to evaluate, rather than conduct extended preprocessing or evaluation (e.g., imputation, applying transforms, modified tests).

b. Sub-annual time series should be aggregated by year (or water year) prior to nonstationarity analysis. Data can be aggregated to represent an annual, monthly, or seasonal total, minimum, maximum, average, index, or count values. Different aggregation techniques can support analysis of RHFs tied to project objectives and foreseeable future impacts.

c. Data aggregation helps statistical tests to meet their underlying assumptions. This can be accomplished by refining variable selection (e.g., selecting an alternate index or threshold applied for count data analysis) or by limiting the period of the year over which data is aggregated (e.g., minimizing the incidence of zero flow values due to frozen conditions by excluding winter flows from annual low flow analysis).

d. When a significant fraction of the aggregated data (e.g., by water year) is missing, this can be addressed by excluding the time series from the overall analysis, limiting the date range to exclude times periods with missing data, or using imputation methods to fill in the time series (Oelsner et al. 2017). Excluding time series with missing data or limiting the range of time being examined can be advantageous and offers a quick solution but can limit the statistical power because of the shorter record length available for analysis (Hamzah et al. 2020).

e. To detect nonstationarities in hydrometeorological records, the dataset being assessed should be relatively long and continuous (Slater et al. 2021). Evaluated datasets should consist of 50 years or more of record (Faulkner et al. 2021). Datasets between 30 and 49 years in length can be analyzed, but caution should be applied when interpreting results. Datasets with fewer than 30 years of record should not be evaluated for evidence of statistical nonstationarity using the methods in the TST (England et al. 2019; Harrigan et al. 2017).

f. Annually aggregated datasets should not have more than 3 years of consecutive missing data or more than 5 percent of the annual datapoints missing overall. Missing annual flow data can be approximated using equi-percentile methods (Hughes and Smakhtin 1996) or maintenance of variance extension (MOVE) type three (MOVE.3) (Vogel and Stedinger 1985).

g. Daily hydrometeorological time series being aggregated annually for nonstationarity analysis should be missing no more than 5 percent of the data and no more than 10 consecutive observations. If the dataset does not meet this criterion, imputation methods such as taking the average of neighboring values, linear interpolation, or MOVE methods can be applied (Hirsch 1982; Vogel and Stedinger 1985). When imputation methods cannot be applied, eliminating a site or removing the yearly data point from analysis should be considered.

(1) When daily temperature and streamflow datasets are missing one day of data, the missing value can be estimated using the average of its neighboring values. Linear interpolation can be applied to estimate streamflow and temperature data gaps of fewer than 7 days. However, in smaller/flashier watersheds, concurrent flows recorded at nearby hydrologically similar watersheds should be reviewed to confirm that linear interpolation does not omit a significant event. When missing more than 7 days of data, daily flows can be estimated using equi-percentile methods or the MOVE relationships (Vogel and Stedinger 1985).

(2) When precipitation datasets are missing fewer than 7 days of data, the gaps can be filled in with data collected at a neighboring station in a meteorologically similar (i.e., similar long-term weather patterns) location of similar orographic makeup. Precipitation and temperature records can be filled in using inverse distance weighting (IDW) methods when more than 7 days of consecutive measurements are missing.

h. When the underlying assumptions of the statistical tests being applied are not met (e.g., serial correlation, non-normal distributions), pre-processing can improve the data and identified data characteristics can be considered when making methodological choices (e.g., exclude test results where the assumptions of the statistical test are not met). As an overall statement, working on the original record is preferable to avoid the potential pitfalls associated with filtering (e.g., pre-whitening) or applying transformation techniques without understanding their strengths and weaknesses.

(1) A transform can reduce the influence of outliers and improve distribution fitting. For most applications, a Box-Cox transform is recommended (Box and Cox 1964), while for count data a square root transform is frequently applied.

(2) Different techniques have been proposed to accommodate potential serial correlation, such as pre-whitening and trend-free pre-whitening (Militino, Moradi, and Ugarte 2020; von Storch 1995; Yue et al. 2002).

(a) Pre-whitening usually assumes that the temporal dependence can be modeled by an autoregressive model of order one (AR(1) Model) (see, e.g., Vandaele 1983). Examining the presence of changes in the residual series after accounting for the autocorrelation structure is then possible. However, the validity of the assumption that temporal dependence can be described by an AR(1) Model is unclear, as are the repercussions of model misspecification in assessing the significance of the change point, breakpoint, or trend test.

(b) The presence of serial correlation only affects interpreting the hypothesis testing of results that show statistical significance. Accounting for autocorrelation is not needed if the results are not statistically significant, because with autocorrelation removed, the results are even less statistically significant

(3) When pre-processing, results derived with and without data adjustment should be evaluated to see if transforming the dataset or adjusting for serial correlation (e.g., pre-whitening, trend-free pre-whitening, variance correction, bias corrected pre-whitening) generates conflicting results. Applying a transform or adjusting for serial correlation can reduce the power of a statistical test. In some cases, an analysis may require that more advanced pre-processing and/or statistical methods be applied than is covered within the scope of this guidance.

D–6. Statistical Analysis: Change Point, Breakpoint, and Monotonic Trend Detection Methods.

a. All recommended statistical methods (i.e., change point analysis, breakpoint analysis, and monotonic trend analysis) for testing for evidence of nonstationarity are in the USACE TST. The TST can apply recommended statistical methods to USGS river stage and streamflow records preloaded in the tool or to user-uploaded time series.

b. Because each statistical test has strengths and weaknesses, multiple methods are recommended to establish evidence of nonstationarity in a dataset. IIR CoP leadership consultation, review, and approval are required to apply a statistical method not in the TST.

c. For all the statistical methods recommended, the null hypothesis means no evidence of statistical change or of a trend in the data (Zhou et al. 2019). The applied statistical test seeks to reject the null hypothesis (i.e., the time series is stationary). A Type I error rejects the null hypothesis when the null hypothesis is true (false positive). In the case of trend tests, a Type I error indicates a statistically significant trend in the sample when one does not exist in the population. When evaluating statistical methods for detecting nonstationarities in hydrometeorological time series, tests that identify false positives are preferable to false negatives (i.e., results that fail to detect evidence of change when it does exist).

d. Detecting evidence of nonstationarity involves two primary types of tests: parametric and nonparametric. In general, most scientific literature and the World Meteorological Organization recommend applying more flexible nonparametric methods for evaluating the stationarity of hydrometeorological time series.

(1) Parametric tests assume an underlying statistical distribution, with the Gaussian (normal) distribution being most common. Distribution fitting graphics, along with the Anderson-Darling test, can be applied during EDA to assess whether a given dataset conforms to a normal distribution. Hydrometeorological datasets do not often fit a normal distribution, because these data types typically have skewed distributions (Helsel 2020; Ryberg et al. 2020). Certain parametric tests are still frequently applied to characterize hydrometeorological data, like the student t-test and ordinary least squares (OLS) linear regression. These methods are advantageous because end-users are familiar with their application and results are easily communicated (Slater et al. 2021).

(2) Nonparametric tests do not make distributional assumptions (Conover 1999; Mallakpour and Villarini 2016). A disadvantage of a nonparametric test is that they can be overly

sensitive, yielding more Type I errors than parametric tests. Where this loss of power is minimal, nonparametric tests do have the large advantage of having less restrictive assumptions (Kottegoda and Rosso 2008; McCuen 2003). Additional information about nonparametric tests is in Conover (1999), among others.

e. The first category of tests in the TST are abrupt change point tests. Change points (or step changes) are abrupt changes in the structural patterns of a dataset (Lund et al. 2007; Ryberg et al. 2020; Zhou et al. 2019), such that a dataset can be divided into two subsets where the statistical properties (e.g., mean, median, scale [variance]) of the two distributions are different (Ryberg et al. 2020).

(1) Abrupt change point methods look for single or multiple change points in the time series. Change point detection methods are superior if they can detect multiple change points, though change point methods that detect multiple change points also have higher false positive rates (e.g., more change points detected than may exist) (Ryberg, Hodgkins, and Dudley 2020).

(2) Change point detection is easiest when time series have small variances, large differences in mean/variance values between subsets of data prior to and after change points, and greater overall skew (Xie et al. 2019). If the change signal is less pronounced (Zhou et al. 2019) the methods lose statistical power. Another potential issue is that the presence of a trend in the dataset can influence change point detection results (Lund et al. 2023). Serial correlation, outliers, and back-to-back extremes or low variance can also undermine the statistical power of change point methods (Ryberg et al. 2020).

(3) Within the scientific literature, change point tests are most frequently applied to detect shifts in the mean (first moment) as compared to tests that identify shifts in the scale (variance, second moment) of the distribution. This is in part because change point tests for scale/variance lose power with a concurrent shift in mean (Quessy et al. 2011). Even though changes in higher moments (e.g., skew) may have even more dramatic effects on extremes, their detection is complicated by the limited sample size of hydrometeorological records.

(4) The following is a list of abrupt change point methods that can be applied in concert to detect strong statistical evidence of change within a hydrometeorological time series. For more detail related to applying each test, please see the TST User Guide.

(a) The Pettitt (1979) test detects a single abrupt change in the mean of the distribution. Among nonparametric change point tests, the Pettitt test is one of the most widely used in the hydrometeorological literature. The Pettitt test can detect multiple change points using binary segmentation (Edwards and Cavalli-Sforza 1965).

(b) The change point model (cpm) framework includes the following nonparametric two-sample hypothesis tests: Mann-Whitney, Mood, LePage, Kolmogorov-Smirnov, or Cramer-von-Mises statistics (Hawkins and Zamba 2005; Hawkins, Qiu, and Kang 2003; Ross 2015).

1. The Mann-Whitney test evaluates whether the mean from one subset of data differs from the mean in another subset. Similarly, the Mood test identifies changes in the scale between data subsets.

2. The LePage, Kolmogorov-Smirnov, and Cramer-von-Mises tests identify distributional changes between data subsets. The main difference among the tests for

distributional changes is that the Kolmogorov-Smirnov test tends to focus more on the central part of the distribution, while the Cramer-von-Mises test is more sensitive within the distribution's tails (Kottegoda and Rosso 2008).

(c) The energy-based divisive change point (ecp) method is a nonparametric test to detect multiple change points in the distribution of the variable of interest (Matteson and James 2014). The ecp method makes as few assumptions as possible to detect multiple change points and can detect any type of distributional changes. To apply ecp, a minimum number of datapoints between change points must be identified up front. This limits its ability to detect multiple change points and favors change points near the center of the time series.

(d) The Sequential Mann-Kendall (SQ-MK) test (WMO 1990) is a popular modified version of the Mann-Kendall (MK) test applied to identify change points in time series data (Gupta and Mishra 2022; Mphale et al. 2018; Suhaila and Yusop 2018; Zarenistanak, Dhorde, and Kripalani 2014). The SQ-MK test resembles the MK rank test for monotonic trends but differs by sequentially adding data points to identify change points and calculating a new test statistic (Kendall's tau).

f. The TST also includes the Lombard Smooth change point detection tests. The Lombard model (1987), like the other change point tests described in this appendix, identifies breaks in the mean and/or scale (variance) of the distribution of the time series. Unlike the abrupt change point tests, the Lombard model does not assume that the transition from one state to the next occurs discretely (i.e., from one year to the next). Instead, the transition is allowed to happen either smoothly over a certain number of years or abruptly.

(1) Because formulations of the Lombard tests can detect both abrupt and gradual shifts in the statistical properties of the datasets being analyzed, they are considered more general methods than the abrupt change point tests (Delisle and Assani 2021).

(2) The Lombard Wilcoxon test can detect both abrupt and smooth changes in the mean of a distribution, while the Lombard Mood test can detect both abrupt and smooth transitions in the scale of a distribution. Generally, both the abrupt and smooth realizations of the test are applied concurrently.

(3) The Lombard test can detect multiple change points using binary segmentation (Edwards and Cavalli-Sforza 1965), in which the presence of change points is tested for in each sub-series until no more statistically significant step changes are detected.

g. Detecting a change point by a smooth or abrupt method does not definitively differentiate between the type of nonstationarity being detected (smooth versus abrupt). "For instance, an abrupt method may identify the center of a gradual linear trend as a change point. Similarly, a gradual method may identify a trend when the data series exhibits a change point." (Ryberg et al. 2020)

h. Most of the change point tests take a frequentist approach to evaluating for evidence of statistical change. Bayesian approaches can characterize the probability of a change point at each data point in the series being assessed in terms of a probability distribution. The TST includes the Bayesian change point (bcp) method to identify statistically significant changes in sample mean (Barry and Hartigan 1993; Erdman and Emerson 2007). Although the bcp method should be considered for analysis, it is a parametric approach that assumes normality.

Hydrometeorological datasets rarely fit a Gaussian (normal) distribution, and thus in most instances this method is inappropriate.

i. In addition to helping detect change points, the TST also supports breakpoint evaluation. Breakpoints are detected when the character of the dataset is no longer behaving as anticipated given the behavior of the earlier part of the data. Breakpoint analysis is characterized by fitting models (i.e., linear regression) and comparing the error of fit. Unlike change point analysis, breakpoint analysis does not divide the data series into segments to test the difference in the statistics of those segments but iteratively adds data points to the series and identifies breakpoints based on an assessment of deviations in the OLS linear regression model.

(1) Breakpoints are identified when regression model errors fall outside of expected variance bounds (Faybishenko et al. 2023; Giang et al. 2022). These expected variance bounds are known as empirical fluctuation processes (EFPs). The null hypothesis is generally no structural change and should be rejected when the EFPs become too large (Zeileis et al. 2002). These detected changes (known as breakpoints) in the regression errors can segment the data into chunks that can be modeled and analyzed individually for trends.

(2) Compared to changepoint tests like the Pettitt test, breakpoint analysis exhibits lower sensitivity in detecting small magnitude changes (Militino, Moradi, and Ugarte 2020).

(3) Effective breakpoint analysis relies on having an adequate sample size. The TST's breakpoint analysis requires a predefined minimum number of observations between consecutive breakpoints. This required input limits the test's ability to detect breakpoints near the start and end of the record. The user-specified minimum between breakpoints should be as small as possible to increase the power of the test (Militino, Moradi, and Ugarte 2020).

j. Within the literature, the terms "breakpoints," "breakthrough points," and "change points" are often used interchangeably (Faybishenko et al. 2023). For USACE applications, change point tests compare statistical properties in different subsets of the data, while breakpoints iteratively add data and recommend breaks when regression model errors fall outside of expected variance bounds.

k. In addition to change point and breakpoint analysis, the TST facilitates monotonic trend analysis. A dataset has a monotonic trend when the correlation between a dependent variable (e.g., peak streamflow) and an independent variable (e.g., time) is statistically significant. Tests for monotonic patterns indicate whether the statistical properties of the data are relatively constant, increasing, or decreasing. Linear correlation is a special case of monotonic correlation where the relationship between the independent and dependent variable is linear (Helsel et al. 2020).

(1) The MK test, the Spearman rank-order test, and the student's t-test can evaluate whether a dataset has evidence of a statistically significant trend (e.g., $p\text{-value} < 0.05$) over the period being evaluated. Traditional linear OLS regression-based slope and Sen's slope can indicate the magnitude and directionality of change.

(2) The MK and Spearman tests identify monotonic trends (increasing or decreasing patterns) in data, encompassing linear, logarithmic, and exponential relationships. While a statistically significant MK and Spearman test result indicates the presence of a trend, it is not necessarily a linear trend. Consequently, automatically using the OLS regression slope as a

measure of the detected trend's magnitude is inappropriate. The OLS slope is specifically designed for linear relationships and may be misleading when the true relationship is nonlinear.

(3) In the case of OLS regression, the coefficient of determination (R^2) is used to evaluate goodness of fit or the strength of the relationship. R^2 equals the square of the Pearson's coefficient (R). The parametric t-test determines confidence in results, indicating whether the trend is statistically significant (Zhang et al. 2011). The t-test evaluates the null hypothesis that the slope is zero, which implies no trend exists in the data. OLS regression results can be easily plotted, and the magnitude of change can be inferred from the OLS slope (Zhang et al. 2011).

(4) A limitation of using OLS regression to assess trends in hydrometeorological time series data is that it assumes normally distributed error terms. The accuracy of statistical inferences derived from OLS regression relies on these assumptions being reasonably satisfied. However, hydrometeorological data is often skewed, which can lead to non-normally distributed errors. Therefore, more robust linear regression methods, such as the Sen's slope estimator (Sen 1968), are recommended and are also used in the USACE IIR CoP tools (i.e., TST) to more confidently capture the magnitude and directionality of change.

l. Because the results of NSD methods are sensitive to record length and because hydrometeorological conditions can change both abruptly and gradually, time series should be reanalyzed every 5–10 years, depending on the level of risk tolerance associated with the project.

D–7. Interpreting the Results.

a. Evidence of nonstationarity is strong when statistically significant change (e.g., $p\text{-value} < 0.05$) is detected by multiple methods, is characterized by a significant shift in magnitude, and can be considered robust. Multiple statistical tests for nonstationarities should be applied to build confidence in findings and to understand the sensitivity of the results to methodological choice (Getahun, Li, and Pun 2021; Jaiswal, Lohani, and Tiwari 2015; Yaman and Ertuğrul 2020; Zhou et al. 2022). The USACE TST presents results derived from multiple statistical methods to identify strong nonstationarities using the following criteria.

(1) Consensus implies that multiple NSD methods (abrupt change point methods and breakpoint analysis) indicate evidence of change circa a given point in time (within a 5-year period). Decision rules for resolving results are prescribed as follows (Getahun, Li, and Pun 2021; Jaiswal, Lohani, and Tiwari 2015):

(a) If three or more tests detect a change, the series is non-homogenous; if two tests detect a change, the series homogeneity is doubtful; and if one or no tests detect a change, the series is homogenous.

(b) Additionally, detecting a statistically significant trend in the datasets and/or detecting a smooth change point over more than a 5-year period that encompasses the abrupt change point and/or breakpoint should be documented and adds to the level of consensus.

(c) In evaluating for consensus, smooth and abrupt Lombard tests targeting the same test statistic are considered as one line of evidence. Sequential and regular MK results are also treated as one line of evidence. This avoids overinflating the degree of agreement between alternate methods.

(2) An operationally significant change in the magnitude of the record mean and variance before and after the change point indicates a strong nonstationarity. Considering both

the results of statistical tests (e.g., statistical significance) and the magnitude of change that has hydrological significance to the project is important (Helsel et al. 2020; Lins and Cohn 2011). For instance, although a statistically significant trend may be detected in recorded peak streamflows, the magnitude of that change may not have practical significance to the project. Engineering judgment should be applied when interpreting evidence of a shift in a time series' statistical properties.

(3) Confidence in results is described in terms of robustness. This includes communicating the significance level (i.e., p-value) associated with test results, considering the strengths, weaknesses, and underlying assumptions associated with the tests, sensitivity to record length, and field significance. This aspect of the assessment should be scaled to the Tier 1 assessment and the project.

(a) For smaller-scale applications, it is generally sufficient to present robustness by briefly discussing the strengths and weaknesses associated with the tests, evaluating trends in subsets of data prior to and preceding the suspected strong nonstationarity, and reporting significance levels (e.g., p-values) where applicable.

(b) When using the MK test to assess monotonic trends, report Kendall's tau (τ) as an additional measure of the trend's direction and strength. Kendall's tau quantifies the correlation between the ranks of observations in the time series and their corresponding time points, ranging from −1 (perfect decreasing trend) to +1 (perfect increasing trend). While a positive τ suggests an increasing trend and a negative τ a decreasing trend, the magnitude of τ indicates the trend's strength. However, do not interpret τ as proof of a statistically significant trend without confirming it through the MK test itself (typically using a significance level of $p < 0.05$). A large sample size can artificially inflate tau values, potentially leading to misinterpretations (Chen, Ghadami, and Epureanu 2022).

(c) Evaluating multiple locations to establish field significance or assessing the impacts of record length via sensitivity testing is recommended in support of larger-scale applications (see Appendix D, section D–8 for more detail).

b. Null hypothesis testing via change point analysis, trend analysis, etc., cannot unilaterally justify applying nonstationary models. Instead, they should be applied as a preliminary screening tool and a means of judging whether evidence of change in hydrometeorological variables is worth further consideration. Analysis should indicate whether additional investigation targeted at attribution is worthwhile (Serinaldi, Kilsby, and Lombardo 2018).

c. The results of statistical analyses alone should not frame conclusive statements about whether conditions are considered nonstationary. Results should be considered along with evaluating multiple lines of additional evidence, understanding the physical drivers of change (e.g., performing in-depth attribution analysis), and identifying prior knowledge of drivers of nonstationarity (Fleming and Weber 2012; Serinaldi, Kilsby, and Lombardo 2018; Slater et al. 2021).

d. Even with no evidence of statistical change in the observed time series, the project's hydrometeorology could still reflect nonstationary conditions that have not materialized or been detected due to a limited sample size, confounding factors that mask the nonstationarity signal (e.g., changes in land use and water management over time), significant variability in observed records (i.e., small signal-to-noise ratio), and other sources of uncertainty (Kim and Villarini 2024; Serinaldi, Kilsby, and Lombardo 2018; Villarini and Wasko 2021).

D–8. Supplementary Evaluation to Understand Robustness of Results.

a. Change point, breakpoint, and trend detection results are sensitive to record length. Long-term records (more than 50 years) can be evaluated for sensitivity to record length by varying the start and end dates (e.g., by 5–10 years). Substantial variation in results across these record lengths undermines the reliability of the findings; consistent results, however, provide robust support for the identified trends.

b. For all applications, the record should be divided into subsets of data preceding and following points where three or more change point/breakpoint test results indicate a statistically significant change or break in the record.

(1) Monotonic trend tests can be applied to data subsets with a minimum of 25 years of record. However, subset record length should be considered when interpreting results. Applying monotonic trend analysis to a relatively short record introduces larger sampling uncertainties and a smaller chance of rejecting the null hypothesis.

(2) Testing for trends in subsets of data prior to and after points with evidence of nonstationarity gains confidence in the results of monotonic trend analysis. The presence of change points/breakpoints in the dataset can decrease the power of monotonic trend tests. Additionally, testing for monotonic trends in the subsets of data before and after instances of strong evidence of nonstationarity provides insight into whether the trends exhibited within the dataset are likely to persist.

c. Many hypothesis tests, like those that evaluate for trends and change points, use a test statistic and a p-value to dictate whether the null hypothesis (no trend/no change) should be rejected. The smaller the p-value, the less likely that the observed evidence of change or a trend in each dataset is due to chance alone. A p-value of 0.05 is often chosen as adequate evidence of an alternative hypothesis, meaning a 5 percent chance of accepting the alternative hypothesis (e.g., sample means are not the same) when it is not true.

(1) Several challenges emerge in interpreting the nonstationarity test results when p-values are used. The limitations of binary interpretations of p-values (e.g., a strict cut-off in statistical significance based on a single p-value) have been widely discussed in the literature. Notably, p-values in and of themselves cannot assess the strength of the stationarity assumption; they only indicate the probability of obtaining the result (Wasserstein and Lazar 2016). The American Statistical Association, for example, warns that simple decision-rules around a single detection threshold (e.g., 0.05) “can lead to erroneous beliefs and poor decision making.” (Wasserstein and Lazar 2016)

(2) Helsel et al. (2020) indicates that the p-value itself should be reported, rather than simply whether it falls below a selected threshold such as 0.05. To report and interpret p-values, Hirsch, Archfield, and De Cicco (2015) propose a likelihood framework (Table D–1) to qualify the degree of statistical support for a given trend being positive or negative. The third column of Table D–1 provides an illustration of p-value evaluation in the context of USACE nonstationarity analysis.

Table D–1
Definitions for descriptive statements of likelihood of increasing trends*

Range of p-values	Descriptors*	USACE Nonstationarity Evaluation
≥ 0.95 and ≤ 1.0	Highly Unlikely	Insufficient Evidence (None)
≥ 0.90 and < 0.95	Very Unlikely	Insufficient Evidence (None)
≥ 0.66 and < 0.90	Unlikely	Insufficient Evidence (None)
> 0.33 and < 0.66	About as Likely as Not	Insufficient Evidence (None)
> 0.1 and ≤ 0.33	Likely	Weak Evidence
> 0.05 and ≤ 0.1	Very Likely	Moderate Evidence
≥ 0 and ≤ 0.05	Highly Likely	Strong Evidence

* Adapted from Hirsch, Archfield, and DeCicco 2015.

d. For large-scale projects, consider taking extra steps to check how robust the results are. Identifying a significant change point, breakpoint, or trend at one location increases the probability of detecting similar changes at neighboring locations; testing for “field significance” determines the overall consistency and reliability of the change signal across the region to help identify whether the observed changes represent a widespread phenomenon or isolated events.

(1) Field significance testing evaluates detected trends and change points across multiple sites within a hydrometeorologically homogenous region. Field significance is most frequently evaluated by mapping station-based results. Alternatively, field significance can be evaluated by defining test statistics that represent the entire region.

(2) Analyzing trends and evidence of change for a single-measurement station does not consider spatial coherence. Evaluating for nonstationarity across a larger spatial domain and identifying coextensive evidence of change can clarify evidence pointing to nonstationary conditions and increase confidence in results (Fleming and Weber 2012; Mphale et al. 2018; Zhang et al. 2022).

(3) Sub-regions to evaluate field significance should be carefully selected prior to performing the regional analysis. Evaluating too large of a spatial extent may result in misinterpreting results driven by masking/domination, and analyzing too small of a spatial extent may exclude relevant gage sites and/or miss evidence of change points (Khapalova et al. 2018).

(4) To avoid introducing biases, the spatial domain should be based on the underlying physical processes that produce the hydrometeorological response being generated (e.g., glacial, nival-/snow-dominated, fluvial-/rain-dominated, hybrid). Watershed characteristics and regional weather dynamics should be considered (Serinaldi, Kilsby, and Lombardo 2018). Flows should be analyzed “in a region with homogenous hydrologic regimes” (Fleming and Weber 2012). This can present a challenge because even adjacent watersheds can vary substantially due to heterogeneity in the geophysical environment (Farahani and Khalili 2013; Fleming and Weber 2012).

(5) If the distribution of the variable of interest has a regional tendency toward statistically significant changes, it can be reported spatially, or the impact of spatial correlation in these records could be evaluated to establish the field significance (Douglas, Vogel, and Kroll 2000; Hirsch and Ryberg 2012; Livezy and Chen 1983).

(a) Inter-site correlation affects the significance level of the trend tests by reducing the effective sample size. If unaccounted for, the spatial correlation rejects the null hypothesis (no change) more frequently than if no spatial correlation was present. This is only an issue if analyses are at the regional scale, not if results are reported on a site-by-site basis.

(b) Different methods have been proposed to address this issue, such as the Walker's test and false discovery rate (Wilks 2006) or bootstrapping (Douglas, Vogel, and Kroll 2000; Hirsch and Ryberg 2012).

D–9. Identifying Potential Drivers of Nonstationarity.

a. If statistically significant changes are detected, understanding the possible physical mechanisms responsible for these changes is important. An LHC assessment must identify and describe potential drivers in as much detail as possible to give context to results of NSD analysis. The level of effort tied to exploring potential drivers of nonstationarity should be scaled to the complexity of the overall project. Drivers of nonstationarity should be separated into three categories: spurious drivers or false nonstationarity, outliers, and process-based drivers of nonstationarity.

(1) Spurious drivers of nonstationarity should be evaluated for during EDA and should be corrected for during data preparation. Examples of spurious drivers of nonstationarity include issues like a gage relocation, recording errors, shifts in rating curves, combining modeled and observed data, misapplied imputation methods, etc.

(2) Spurious drivers of nonstationarity that cannot be corrected for should be documented. During EDA, statistical methods, including change point detection tests, can be an initial screening tool to aid in identifying spurious drivers of nonstationarity.

b. Extreme values that are outliers in a dataset can be driven by real, observed hydrometeorological conditions, in addition to the erroneous measurements. In streamflow time series, outliers can be observed because of floods or droughts driven by extreme weather caused by hydrometeorological processes distinct from the rest of the time series or due to the inclusion of observations from a different statistical population from the rest of the data, such as a flood peak caused by a dam failure or a short-term shift in management practices.

(1) Outliers can have a large effect on the computed moving-means and variances, which can trigger some methods to identify an abrupt change point in a dataset. For this reason, comparing change points detected by graphically visualizing the record is important. In the case of outliers driven by observed hydrometeorological phenomena, a value should be classified as an outlier rather than a change point (Ryberg et al. 2020).

(2) Where possible (for instance in the case of a dam break or levee failure) the effects of the outlier should be controlled for using modeling techniques, and the data should be reanalyzed for evidence of long-term statistical change.

c. After identifying and accounting for spurious drivers of nonstationarity and identifying potential outliers, the first element to consider when evaluating process-based drivers of nonstationarity is any prior (a priori) knowledge of the existence of possible changes in the watershed of interest (e.g., year of construction of a dam).

(1) When prior knowledge of a change point is available, users should be cautious of test results that do not identify a change point in the expected timeframe. The user can apply

their knowledge of a potential change point to alter the significance parameters associated with each change point test in the TST.

(2) Prior knowledge of drivers of nonstationarity enables the user to attribute evidence of change. Once attributed to a known, easily characterized driver like sudden land use or land cover change (e.g., post clear-cut or wildfire), constructing a water management structure, or change in water management, a time series can be homogenized using hydrologic modeling techniques (e.g., rainfall-runoff modeling, reservoir modeling, or applying an unregulated-regulated transform per existing USACE guidance such as EM 1110-2-1417 and ER 1105-2-101). Once the known nonstationarity is controlled for, the dataset can be reevaluated for further evidence of change.

d. In situations with no prior knowledge of the presence or nature of changes that may have occurred over time, the potential for multiple drivers of nonstationarity makes attribution challenging and/or no straightforward way to homogenize the record exists. In these cases, potential sources of nonstationarity should be documented, and the timescales over which these drivers are likely to result in evidence of change should be specified.

(1) Drivers of nonstationarity can result in abrupt shifts in hydrometeorological conditions that occur within a matter of years (e.g., the effects of a wildfire or water management structure on streamflow response) or more gradually over several decades (e.g., the construction of small, distributed storage structures or land cover changes).

(2) Some drivers of change in hydrometeorological conditions only begin to materialize over much longer periods of time (for instance, long-term persistent trends). Analyzing the historical records for evidence of change helps identify and explain the different processes driving hydrometeorological response (e.g., rainfall versus snowmelt-driven flooding). Understanding these critical drivers through study of historical records helps evaluate how the drivers could potentially change in the future (Kim and Villarini 2024).

e. Table D–2 through Table D–7 include lists of potential drivers of nonstationarity in streamflow response to consider as part of a nonstationarity evaluation. In all cases where evidence of strong nonstationarity is detected, the potential for an unknown driver to cause detected change points, tends and breakpoints should always be acknowledged.

Table D–2
Causal mechanisms for change points, breakpoints and trends in streamflow response, category I: long-term, weather-related causal mechanisms*

Driver	Time Scale	General Description
Extreme precipitation changes	Long term	Change driven by increases in the frequency and/or intensity of extreme (short-term) precipitation events.
Changes in drought characteristics	Long term	Change driven by increases in the frequency, duration., and/or intensity of drought events.
Long-term precipitation changes	Long term	Shifts in long-term multi-month or inter-annual precipitation patterns driven by large-scale storm systems. This includes shifts in antecedent wetness or dryness, long-term persistence, or multi-decadal variability driven by oceanic or atmospheric patterns.

Driver	Time Scale	General Description
Long-term hydrometeorological variability	Long term	Hydrometeorological variability driven by combined temperature and precipitation changes where the primary driver (temperature versus precipitation change) cannot be determined.
Changes in snowpack/snowmelt	Long term	Changes in snowpack development and ice; changes in the frost-free season; changes in snowmelt timing/characteristics driven by seasonal temperature and precipitation changes (e.g., distribution of snow, rain-on-snow, rain).
Changes in air temperature	Long term	Change driven by shifts in air temperature unrelated to snowmelt or drought. Temperature changes can influence the seasonality of the streamflow response, as well as water temperatures, water and power use, and evapotranspiration rates.

*As adapted from Ryberg 2022.

Table D–3
Causal mechanisms for change points, breakpoints and trends in streamflow response, category II: water management structures (river training, impoundments, and diversions)*

Driver	Time Scale	General Description
Large impoundments	Abrupt	Large multipurpose reservoir projects that are big enough to attenuate flood peaks. Change can be driven by construction or changes in water management practices.
Small impoundments	Abrupt/Gradual	Run-of-the-river dams, hydropower dams, changes to the outlets of natural ponds/lakes, stock dams, or other such features that when aggregated over time impact streamflow response (e.g., distributed storage). Change can be driven by construction or changes in water management practices.
Wastewater discharges	Abrupt/Gradual	Discharges from systems that collect, treat, and dispose of domestic and industrial wastewater. Treated wastewater treatment plant effluent is often discharged to rivers and streams.
Cooling water discharges	Abrupt/Gradual	Discharges from thermal power plants (coal, nuclear, natural gas) that rely on water as a heat sink (ANL 2007).
Water supply discharges	Abrupt/Gradual	Discharges from systems that withdraw water from surface or groundwater systems for a variety of uses including municipal water supply, industrial water use, and agricultural irrigation. In some cases (e.g., return flows from irrigation, stormwater runoff) water is released back into lakes, rivers, streams, or groundwater.
Groundwater withdrawals	Abrupt/Gradual	Groundwater withdrawals to support irrigation, municipal water supply, power plant cooling water, or other.
Surface-water withdrawals	Abrupt/Gradual	Surface-water withdrawals to support irrigation, municipal water supply, power plant cooling water, or other.
Inter-basin water transfer and Intra-basin diversions	Abrupt	Change can be driven by construction or changes in water management practices.
Drainage	Abrupt/Gradual	Includes agricultural drainage practices like ditching and drain tile, as wetland drainage for agriculture and urban development, or other.

*As adapted from Ryberg 2022, unless otherwise noted on the table.

Table D–4
Causal mechanisms for change points, breakpoints and trends in streamflow response, category III: land-use and land-cover changes*

Driver	Time Scale	General Description
Agriculture	Abrupt/Gradual	Shifts from native vegetation to cropland, changes in crop cover; for instance, shifting from perennial to annual vegetation or row crops to small grains, changes in rangeland grazing activities, or other changes to land-use/land-cover in support of agricultural activity.
Land cover shifts	Gradual/Long term	For instance, shifts from forest to wet meadow or marsh or intrusion of invasive species for instance invasive woody species in a riparian habitat.
Deforestation	Abrupt/Gradual	Large-scale changes in forest cover can affect peak streamflows. In addition to potential effects on infiltration, reduced forest canopy can decrease interception and transpiration, increasing total flood volumes as well as the peak (Kang et al. 2025).
Urbanization	Abrupt/Gradual	Urban land cover that impacts runoff response by increasing impervious surfaces and via stormwater management/interior drainage infrastructure.
Wildfire	Abrupt/Long term	Measurable increases in peak streamflows, relative to those in an unburned watershed, can result from increased water velocities caused by a reduction in vegetative ground cover and decreased infiltration caused by changes in the soil profile that result in hydrophobic soils, air entrapment, and soil pore sealing.

*As adapted from Ryberg 2022, unless otherwise noted on the table.

Table D–5
Causal mechanisms for change points, breakpoints and trends in streamflow response, category IV: geomorphological changes*

Driver	Time Scale	General Description
Channel geomorphology	Abrupt/Gradual/ Long term	Changes in discharge patterns and/or changes in erosion and sedimentation driven by terrestrial watershed changes or changes in hydrometeorology that alter channel geomorphology, which can impact streamflow response and affect floodplain and longitudinal connectivity. This includes coastal erosion impacting river mouth dynamics, near-shore hydrodynamics (including wave formation) and lower reaches of coastal rivers, including river deltas and estuaries.
Seismic activity	Abrupt	Vibrations in the earth (typically caused by earthquakes) that generate ground shaking that can destabilize land and infrastructure. This shaking can liquefy soils, weaken slopes, and alter water systems. Impacts can include changes in channel geomorphology, sedimentation rates, and changes in groundwater flow (Earthquake Hazards Program n.d.).

Driver	Time Scale	General Description
Volcanic activity	Abrupt/Long term	Activity that results as pressure forces gas, molten rock, and volcanic ash through the earth's surface (FEMA n.d.). Volcanic activity can block and change channel systems, increase sedimentation and sediment supply, change land cover, alter channel hydraulics and increase secondary flood hazards (Lee 1996). Volcanic eruptions can alter global precipitation and streamflow patterns for multiple years after an eruption (Iles and Hegerl 2015).
Subsidence	Long term	Gradual sinking or settling of land over a large area that decreases land elevation relative to sea level. This phenomenon can be caused by natural geological processes or human activities such as the extraction of groundwater or soil compaction (National Ocean Service n.d.).
Permafrost	Long term	Ground that remains frozen (temperature less than 0 °C) for at least two consecutive years), which is vulnerable to thawing due to both natural processes and human activities. Permafrost thaw can result in alteration of surface and groundwater drainage, slope failure, and land subsidence (Osterkamp and Jorgenson 2009).
Glaciation	Long term	A temperature- and precipitation-driven process by which glaciers form and evolve. Over decades, accumulated snow compresses and transforms into glacier ice. Glaciers are valuable indicators of shifting hydrometeorological conditions because of their sensitivity to changes in temperature and precipitation (USGS n.d.). Changes in glacier volume can alter the quantity and timing of streamflow (Curran et al. 2025).

*As adapted from Ryberg 2022, unless otherwise noted on the table.

Table D–6
Causal mechanisms for change points, breakpoints and trends in streamflow response, category V: coastal processes*

Driver	Time Scale	General Description
Sea level change	Long term	Gradual increase in base water levels affecting coastal streamflow/circulation patterns, potentially causing groundwater impacts (i.e., salination), coastal upwelling (i.e., changes in temperature and nutrient patterns), backwater effects, and altering tidal ranges, discharge rates, and sedimentation patterns in coastal rivers.
Tropical cyclones, typhoons, and storm surge, hurricanes	Abrupt/Long term	Extreme precipitation and storm surge causing rapid short-term increases in streamflow and potential long-term changes in flow regimes if frequency or intensity of events changes.
El Niño southern oscillation (ENSO) or other large-scale weather patterns	Abrupt/Long term	Periodic changes in precipitation patterns and sea surface temperatures affecting streamflow variability, particularly in coastal and near-coastal watersheds.

*As adapted from Ryberg 2022.

Table D–7
Causal mechanisms for change points, breakpoints and trends in streamflow response, category VI: unknown*

Driver	Time Scale	General Description
Unknown causes	Variable	Cases that have no known mechanism for a detected trend, breakpoint or change point. This includes the potential for false positives.

*As adapted from Ryberg 2022.

D–10. Documentation

a. Nonstationarity analysis must be documented through a narrative discussion in the LHC assessment appendix. The main report should include a concise summary of nonstationarity assessment results. The detailed narrative in the appendix should focus on evaluating hydrometeorological time series tied to RHFs.

b. The IIR CoP has several available resources that demonstrate how to appropriately document the results of a nonstationarity analysis. Templates for small-scale LHC assessments are available on the IIR CoP KMP site, and examples of completed assessments for applications of varying scope and scale are available via the web-based IIR CoP RAL.

c. The appendix describing LHCs should thoroughly document EDA and data preparation. For each time series evaluated for evidence of nonstationarity, discussion should include a time series plot, time series metadata (including record length), relevant project/watershed context, any prior knowledge of drivers of nonstationarity (e.g., regulation upstream, irrigation withdrawals), identified data quality issues (e.g., spurious outliers, missing data), and how any data quality concerns were resolved.

d. Documentation should discuss whether the time series includes outliers, fits a known statistical distribution, and/or exhibits evidence of serial correlation and how these factors were evaluated using the TST. Data preprocessing steps such as record homogenization, imputation, applying a transform, and/or selecting methods to account for serial correlation should be described.

e. The full time series should be evaluated for evidence of statistical change using the TST to test for smooth/abrupt change points, breakpoints, and monotonic trends. Where statistical change in the time series is suspected, the writeup should discuss the lines of evidence that identify strong evidence of change. The principles of consensus, magnitude, and robustness as defined by this guidance must be used when characterizing a record as exhibiting strong evidence of nonstationarity. The magnitude and directionality of change should be discussed in terms of operational significance. Where appropriate, graphics should support the narrative.

f. Additional evaluation to gain confidence in results (robustness) should be scaled to mirror the scope and scale of the hydrological analysis that supports the project. The strengths and weaknesses associated with the NSD analysis applied should be communicated.

(1) To establish the degree of robustness, at minimum, the statistical significance of test results should be reported both numerically and as likelihood statements (where appropriate).

(2) Subsets of data prior to and after strong nonstationarities should be analyzed for monotonic trends.

g. To help interpret NSD results, the assessment must identify and discuss potential drivers of nonstationarity using Table D–2 through Table D–7 as a resource. This discussion represents an initial assessment of what may be driving nonstationarity and must always be accompanied with an acknowledgment that multiple drivers could be contributing to the detected change and that some causes may be unknown.

h. When hydrometeorological records collected in the project area have evidence of strong nonstationarity, either conducting or recommending subsequent more in-depth attribution analysis and/or continued monitoring may be necessary.

(1) In cases with no clear, prior knowledge of what may be causing nonstationarity, further attribution analysis is necessary to fully evaluate changes in hydrometeorological response and to fully understand how those drivers impact future hydrometeorology.

(2) Without a prior knowledge of what is driving observed change and/or more in-depth attribution analysis, detecting changes in the historical record only offers a way to understand what happened in the past but does not support definitive inference of what to anticipate in the future.

(3) Procedures for conducting in-depth attribution analysis are outside the scope of this guidance but can be pursued with advisement from IIR CoP leadership.

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Appendix E
Dynamic Weather-Related Risk Assessment

List of Figures

List of Tables

E–1. Introduction.

a. Risk driven by nonstationary (changed) hydrometeorological conditions must be considered throughout every USACE effort having long-term impacts. Evaluating risk related to potential impacts driven by nonstationary hydrometeorological conditions is required and must be one of the criteria used in USACE decision-making and in support of describing future conditions (FWOP and future with project conditions).

b. Nonstationary hydrometeorological conditions can present a new risk to existing and/or proposed project features, measures, and management actions[8] or can increase an already existing risk. Risk is tied to changes in primary and secondary hydrometeorological impacts such as increases or decreases in extreme temperature, changes in rainfall and drought frequency/intensity, shifts in seasonality, and changes in streamflow (see Appendix C, Table C–1 for more examples).

E–2. Overview.

a. An LHC assessment applies the standard USACE risk framework (Yoe and Harper 2017) to evaluate how DWR risks to project performance might change with time. An LHC assessment supports risk-informed decision-making (RIDM) (Hilleary et al. 2024) by identifying, communicating, and managing project risks driven by changing hydrometeorological conditions. The DWR risk assessment should consider potential changes in hydrometeorology that could either elevate or alleviate risks to project performance in the future. DWR risks must be considered in conjunction with other risks to identify opportunities to add resilience in support of long-term project performance.

b. An LHC assessment allows proposed project deliverables (e.g., alternatives, measures, and management changes) to be formulated and evaluated for performance under a range of future extreme weather conditions. The assessment considers multiple lines of evidence to identify weather-related triggers, hazards, and harms (i.e., negative social, economic, and environmental consequences). Appendix B, Figure B–2 illustrates the DWR risk assessment workflow.

c. Characterizing DWR risk integrates the findings of each step of the LHC assessment (Tier 1, Tier 2 and RSLC evaluations) to define the likelihood of weather-related THHs occurring over a project's service life. In the context of an LHC assessment, triggers are changes to hydrometeorological conditions with the potential to impact project performance. Triggers should reflect either primary or secondary RHFs (see Appendix C, Table C–1). Hazards are the potential sources of harm driven by a given trigger. Harms capture the impacts and consequences associated with failing to achieve project objectives across the following four categories: life safety, economic development, the environment, and communities (social effects). Likelihood represents the probability of a hazard materializing and resulting in a harm.

d. Lines of evidence considered as part of an LHC assessment include a literature review, statistical nonstationarity analysis, assessment of simulated future hydrometeorology, and vulnerability assessment. Defining and characterizing long-term weather-related risks to

[8] The DWR risk assessment applies to all USACE activities including, but not limited to, projects, studies, and management plans. For simplicity, "project" describes all USACE activities.

project performance must be documented narratively and supported with a DWR risk assessment table.

e. Weather-related THHs must be integrated throughout the plan formulation process to define future conditions, make risk-informed decisions, and determine residual risk. Residual risk is risk that remains after the project has been implemented. Characterizing the risk driven by nonstationary conditions early in the planning process lets practitioners identify and justify alternatives composed of features, management actions, and/or measures that effectively increase resilience (FHWA 2017).

f. For projects that do not conclude in a recommended plan (e.g., watershed studies) the DWR risk assessment focuses on the risk that changing hydrometeorological conditions presents to USACE business line(s) of interest (e.g., flood risk management, navigation, aquatic ecosystem restoration, water supply, emergency management).

g. When evaluating existing structures or management plans (e.g., water control manuals and portfolio assessments), DWR risk assessments reflect risk to current features/directives and consider how the existing design or management plan might already offer a degree of resilience.

h. For dam safety studies, the DWR risk assessment focuses on PFMs and their susceptibility to hydrometeorological changes.

E–3. Role in Plan Formulation.

a. Considering DWR risk at the onset of and throughout a project's service life is critical to making sound decisions and to identify features, measures, and/or management objectives that may not perform as intended or fail under the plausible range of future conditions. Features, measures, and management actions are the building blocks of alternatives to formulate and evaluate as part of USACE's plan formulation process.

b. Even in the early stages of plan formulation, criteria to formulate (pre-AMM) and evaluate (post-AMM) the final array of alternatives should consider DWR risk and identify opportunities to add resilience to future impacts over a project's intended service life.

c. The objectives of a DWR risk assessment are to identify new or increased risk(s) due to nonstationary hydrometeorological conditions and options to increase project resilience. Options to increase project resilience include robust design, proactive monitoring, and dynamic adaptation to reduce future residual risk. The risk assessment required by this guidance (1) provides an understanding of how RHFs impact the future condition and the performance of identified alternatives, (2) considers resilience to change as alternatives are formulated and evaluated (3) characterizes and communicates residual risk driven by changing hydrometeorology tied to the TSP/LPP/recommended plan and (4) identifies whether to add resilience to the TSP/LPP/recommended plan if residual risk is too high.

d. Alternative evaluation between the AMM and TSP milestones must consider future weather-related risks tied to a project's features, measures, and/or management actions. The DWR risk evaluation should consider potential hydrometeorological change within the project area over the project's service life, as well as how nonstationary hydrometeorology might impact the long-term performance of each alternative being considered. Elements of an alternative can be evaluated separately or in combination.

(1) Evaluating each element of an alternative individually (e.g., evaluating armoring design separately from the levee structure) makes it possible to identify which elements associated with a given alternative are most sensitive to changes in hydrometeorological conditions and have the potential to undermine overall plan performance in the future.

(2) The evaluation should also consider how the elements of an alternative interact holistically to support performance under future conditions.

e. Although not required, it may be advantageous to use the DWR risk table format to evaluate the features, measures, and management actions being considered. The risk table directly compares the DWR risk associated with each element and alternative in terms of economic, environmental, and/or social consequences (impacts) prevented. This content can justify resilience features under a comprehensive benefits-based approach (see Appendix F for more detail).

f. The DWR risk table format must present DWR risk evaluations associated with measures and/or management actions reflected in the TSP, LPP (if applicable), and recommended plan. In most cases the table only needs to include and evaluate major features, meaning that features need not be broken down into their components (e.g., a flood gate should be evaluated in its totality versus breaking it down by lifting arm, hydraulics, sill, seal, frame, gate panels, etc.). When a plan implements similar features, measures, and management actions throughout the project area, a single entry to the risk table can represent each widely applied element.

g. The LHC assessment process should be iterative as the PDT modifies alternatives under consideration, identifies the TSP (and LPP), and defines the recommended plan. The DWR risk table should be iteratively adjusted to reflect a recommended plan that reduces DWR residual risk to a tolerable level prior to the CVM. Appendix B, Figure B–3 aligns the components of a DWR risk assessment with the three major feasibility study milestones (AMM, TSP, and CVM).

E–4. USACE Risk Assessments: Approach and Key Concepts.

a. Consistent with existing guidance (DPM CW 2018-05, ER 1105-2-101, and ER 1105-2-103), a risk framework includes risk assessment, risk management, and risk communication. Effective planning identifies and manages risks through comprehensive analysis and stakeholder engagement (Hilleary et al. 2024). Risk is defined in terms of the product of the probability and severity of undesirable consequences (ER 1110-2-1156). Uncertainty is inherent to assessing risks. USACE's risk framework supports decision-making while addressing and communicating uncertainties.

b. USACE risk-informed planning addresses risks in the project area (e.g., flooding, invasive species, economic setbacks), risks during the planning process (e.g., project delays, cost overruns), and outcome risks (e.g., uncertainty in future conditions or project performance). Characterizing potential risks due to changing hydrometeorological conditions helps evaluate these risks and identify residual risks (Yoe and Harper 2017).

c. Evaluating and documenting DWR risk supports USACE's risk-informed planning process, since many project risks can be impacted by changing conditions. For instance, environmental parameters such as streamflow and temperature are critical to formulating measures and alternatives for an aquatic ecosystem restoration study. For flood risk management projects and inland navigation, extended flood and drought conditions could negatively impact inland waterways and force restrictions to navigation.

d. One objective of a risk assessment is to identify unacceptable levels of risk.

(1) Risk is broadly acceptable if the probability of undesirable consequences occurring is sufficiently low and/or the odds of the consequences materializing are insignificant in terms of public safety or economic, environmental, and socioeconomic impacts. Further effort to reduce risk is not required in these cases.

(2) A tolerable risk is risk reduced to a manageable level; people and society are prepared to accept this level of risk to secure benefits at an acceptable cost (ER 1110-2-1156). Tolerable risk levels are determined in close coordination with team members, including project partners and stakeholders.

(3) Unacceptable risk is risk that does not meet tolerable levels, and therefore, action must be taken to reduce risk to human life, ecosystems, property, etc.

e. Consistent and continuous risk communication within and among the USACE vertical team can help identify risk tolerance levels (Hilleary et al. 2024).

f. Some examples of USACE policies that include thresholds that can define unacceptable risk are:

(1) ER 1110-2-1156 explains tolerable risk thresholds and references USACE Tolerable Risk Guidelines, including Annual Probability of Failure, life safety risk, economic risk, environmental and other non-monetary risks, and an overall risk summary for the project.

(2) ECB 2022-7 describes the PDT's role in establishing project-specific tolerable risk thresholds during the planning phase.

(3) EM 5-1-11, Project Delivery Business Process, dictates the need to develop initial risk profiles outlining risk tolerances at project acceptance that are further refined and documented throughout the project's service life, preferably in a risk register or similar tool.

g. Unacceptable risks driven by potential shifts in hydrometeorology can be addressed through various approaches or combinations of approaches to increase project resilience. Unacceptable risk can be addressed by avoiding, controlling, or burning down risk (OUSD(R&E) 2023). See Appendix F for more detail.

(1) USACE risk avoidance methods include adopting conservative design standards and adhering strict operational protocols to prevent conditions from leading to loss of performance or failure.

(2) Risk can be controlled by actively reducing it to an acceptable level. Examples of controlling risk include levee hardening and infrastructure modification (e.g., increased drainage system capacity).

(3) Risk burn-down consists of the incremental actions to address and reduce risk over time using an approach like dynamic adaptation (also referenced as adaptive management).

h. Risk communication involves the two-way exchange of information, both internally (among PDT members) and externally (with partners and stakeholders), to support risk-informed decision-making. The Natural Hazards Center's Principles of Risk Communication Guidebook outlines specific ways to effectively communicate risk (Hilleary et al. 2024). Successful risk communication comprehensively characterizes hazards and consequences. Effectively communicating the high degree of uncertainty associated with characterizing future conditions is a critical component of the DWR risk assessment.

E–5. DWR Risk Assessment Methods.

a. DWR risk assessments should be systematic, with the end goal of semi-quantitatively describing risk due to a wide range of LHCs. The DWR risk assessment consists of the following six steps:

(1) Identify RHFs tied to the project purpose and characterize associated triggers and hazards. Identify the potential harms and consequences tied to the hazard should it occur.

(2) Assess the likelihood of the THHs materializing.

(3) Define impact(s) associated with THHs tied to consequence categories.

(4) Evaluate DWR risk by considering the combined likelihood and impacts of the THHs for each project feature, measure, and/or management action being evaluated. Compare risk to tolerable risk levels.

(5) If required, perform iterative management of risk to an acceptable level by recommending that resilience be added through monitoring and/or a risk management/mitigation action or element.

(6) Communicate DWR risk and qualitatively describe the uncertainty associated with the risk assessment.

b. To support USACE’s plan formulation process, steps (1) and (2) help characterize the future condition and develop the screened array of alternatives needed before the AMM milestone. Steps (1) through (4) support alternative evaluation, helping identify and characterize the TSP and any LPP. These steps also help determine the recommended plan prior to the CVM milestone. Steps (5) and (6) must be considered as part of any TSP, LPP (as applicable), and recommended plan. Appendix B, Figure B–3 outlines how the DWR risk assessment aligns with USACE’s planning process.

c. When a sequence of events contributes to the likelihood of a given harm, this should be narratively described as part of the risk assessment. The narrative should also generally qualitatively convey uncertainties associated with how risk is characterized.

d. Table E–1 describes the information to evaluate and communicate in a DWR risk assessment, along with key considerations to apply when characterizing resulting risk for each feature, measure, and/or management action being considered in support of plan formulation.

e. In general, the element of an alternative, recommended plan, project component, or system component with the maximum risk score is equivalent to the overall risk to the alternative, recommended plan, project, or system. A possible exception is where a proposed alternative, recommended plan, project, or system contains elements that either amplify risk or, more typically, offer redundancy or increased resilience when combined. Such cases should collectively evaluate the risk associated with elements acting together to offset or amplify the risk driven by changing hydrometeorological conditions.

Table E–1
DWR risk assessment components

Risk Assessment Components	Description	Key Considerations
Project Feature/Measure/ Management Action	The decision, management plan, project feature, or USACE business line being evaluated.[a,b] Examples include erosion protection, floodwall, pump system, and dam embankment.	• What project alternatives, measures, and/or management strategies are critical to meeting project objectives? • Could the proposed project be impacted positively or negatively by changing hydrometeorology?
Hydrometeorological Trigger	The RHF (tied to primary or secondary hydrometeorological impacts) that drives the risk. Examples include increases in discharge, water surface elevations, and/or extreme precipitation.	• What changes in hydrometeorology (e.g., changes in temperature, precipitation, seasonality, wildfire, drought, streamflow) could directly or indirectly impact the project (built, natural, or human system) being evaluated?
Hazard	Shift in hydrometeorological conditions (trigger) impacting performance/effective management. Examples include future increases in flood frequencies, reservoir inflows, stormwater volumes, or durations of high water	• How would changes in hydrometeorological conditions impact the built, natural, or human system being evaluated? • Is the potential change in hydrometeorology going to make conditions worse or better?
Harm	Negative impacts driven by changed project output/performance and/or basin conditions. Examples include increased erosion, dam overtopping, or increased seepage around a reservoir outlet causing damages.	• How is the project exposed to the weather-related hazard, and how would it be negatively impacted? • Does the hazard represent a new stress to the project, or does it amplify an existing stress?
Hazard Likelihood Rating (Table E–2 and Table E–3)	Semi-quantitative likelihood of a trigger and hazard occurring, defined through multiple lines of evidence.	• How likely is the trigger to occur, resulting in the specified hazard? • What lines of evidence point to that likelihood (e.g., strong evidence of nonstationarity in observed record)?
Overall Likelihood of Harm Rating (Table E–2 and Table E–3)	Adjusted hazard likelihood rating considering the degree of resilience provided by the feature/management action.	• If the project is implemented, how likely are the trigger and hazard to occur and result in a harm? • Is resilience already built into the project?
Impact Rating (Table E–4)	Rated consequence of THHs for each project feature and/or management action being considered.	• How sensitive is the project to a shift in hydrometeorology, and/or how significant is the resulting harm? • How severe are the potential consequences driven by the THHs?

Risk Assessment Components	Description	Key Considerations
Risk Score (see Figure E–1)	Semi-quantitative score combining likelihood and consequences (impacts) to determine residual risk to performance and/or the project area.	• How significant is the risk? • Is the risk tolerable for all consequence categories (life safety, economic, environmental, and social effects)?
Residual Risk	Maximum risk remaining after risk management actions have been implemented. Risk is impossible to eliminate; therefore, some level of residual risk is expected.	• If risk score is moderate or high, further discussion by the PDT is required to assess whether residual risk is acceptable or if resilience should be added to the design/management strategy.
Risk Evaluation and Reduction Recommendations	Identifying risks and suggested actions to reduce risks. Project performance should be monitored throughout its service life and the need to add resilience revisited as conditions change.	• Is the residual risk acceptable? • What actions could be taken to reduce risk (e.g., resilience features, dynamic adaptation)? • How should the risk be managed (e.g., acceptance, avoidance, transfer, control, adaptation)? • Are these actions within USACE's authority?
Communicating Risk and Associated Uncertainty	A critical part of risk communication is describing uncertainty. This discussion should include, at a minimum, a brief qualitative discussion of uncertainties associated with the multiple lines of evidence used to characterize the likelihood and impacts of THHs.	• How much uncertainty is associated with each line of evidence to establish THHs? • How does this contribute to overall characterization of risk (e.g., degree of consensus within the literature; discussing strength of nonstationarities in observed records; discussing CHAT robustness metrics and spread in future scenarios of hydrometeorology)? • What further analysis could reduce uncertainty (e.g., conducting a Tier 2 analysis; evaluating alternatives using all three sea level change [SLC] curves)?

NOTES:

[a] Efforts not targeted at evaluating a specific feature or decision should evaluate risk in the context of the business line under consideration.

[b] The DWR risk table for a dam safety study should include the features susceptible to PFMs sensitive to weather-driven hazards.

E–6. Likelihood Determination: Triggers, Hazards and Harms.

a. The first step in determining risk due to changing hydrometeorology is to determine the THHs. Triggers are primary or secondary RHFs that present a problem or opportunity for the project, while a hazard is a condition that creates the harm. The harm is the consequence of the hazard occurring. For example, increasing rainfall intensity (trigger) could create flash floods (hazard) that could endanger lives in the flooded area (harm) (Table E–1).

b. The defined THHs should characterize future hydrometeorological conditions. The likelihood of THHs materializing in the future is characterized using a semi-quantitative likelihood rating. The likelihood of a THH can be rare (1), unlikely (2), possible (3), likely (4), or highly likely (5). To help contextualize likelihood ratings, they can be considered as analogous to the quantitative probabilities of occurrence in Table E–2. Likelihood scores should be assigned to each feature, measure, and/or management action being evaluated. As noted in Appendix E, paragraph E–5.b, combinations of elements can be evaluated, as well, if applicable.

c. Likelihood ratings can represent the probability of a weather-related trigger materializing for the first time or an existing trigger becoming more frequent or amplified (e.g., longer in duration, greater in intensity and/or magnitude) at any point in a project's service life. The goal of this analysis is to understand the overall likelihood of a hazard occurring and resulting in an impact. Examples include both a single extreme event like a flood, resulting in catastrophic failure, or long-term increases in drought frequency, resulting in economic impacts to commercial navigation over time.

d. The IIR CoP tools and resources provide the basis for determining the likelihood of a trigger and resulting hazard (hazard likelihood rating) occurring in the future. This likelihood rating is adjusted to consider existing or added resilience acting to increase performance reliability and reduce the likelihood of the identified harm materializing (overall likelihood of harm rating). Additionally, the associated uncertainties with the trigger mechanisms and likelihood evaluation are considered.

Table E–2
Evaluating semi-quantitative likelihood

Likelihood Rating	Likelihood Score	Interpretation: Analogous Probability of Occurrence
Rare	1	0%–20%
Unlikely	2	20%–40%
Possible	3	40%–60%
Likely	4	60%–80%
Highly Likely	5	80%–100%

e. Likelihood ratings can be generated using a tabulated rubric for each individual project feature, measure and/or management action being considered. Table E–3 includes an example rubric. As noted in paragraph E–5.b, combinations of elements can also be evaluated, if applicable. Table E–3 should be archived as part of the LHC assessment and is an optional part of the report documentation. Fields to tailor to each individual assessment are in italicized text.

f. The rubric results in a numeric score, representing a semi-quantitative likelihood rating, along with a brief narrative justification for the score and rating. The likelihood justification describes the likelihood associated with the trigger and hazard as well as the adjustment of the likelihood of harm occurring based on the inherent resilience of the feature or resilience added through plan formulation by the PDT.

g. The likelihood of a hazard occurring because of changing hydrometeorology should be defined by evaluating multiple lines of evidence generated from the components of a Tier 1 assessment as established by this ECB (i.e., literature review, nonstationarity analysis using the TST, evaluating projected hydrometeorological conditions using the CHAT, and assessing vulnerability using the CWVAT). This risk assessment helps determine the semi-quantitative likelihood of a weather-related trigger and its associated hazards and harms materializing over a project's service life. Where applicable, the likelihood rating can incorporate results from additional tools and resources such as RSLC[9] analysis and/or Tier 2 analysis of future hydrometeorology.[10]

h. For the example in Table E–3, each line of evidence is weighted equally when computing the average trigger/hazard likelihood score. However, where confidence is higher in certain lines of evidence (e.g., literature review output, evaluating future hydrometeorology of a specific project area via Tier 2 analysis), a weighted average can define the hazard likelihood score. The assessment narrative should justify any weighting scheme.

i. Regardless of whether a weighting scheme is applied, documentation should include at minimum a broad qualitative discussion of the uncertainty associated with deriving the overall likelihood score. Uncertainty associated with literature review findings, statistical nonstationarity analysis, and how to apply output that relies on modeled-based future simulations of hydrometeorology should be discussed as follows:

(1) The number of literature review entries reviewed and the degree of consensus between findings should be highlighted.

(2) Confidence in statistical NSD results (robustness) should be summarized following the guidelines in Appendix D.

(3) The inherent uncertainty associated with future simulations of hydrometeorology should be illustrated by presenting ensemble-based results demonstrating the range of potential future conditions and how those conditions fluctuate over time. The degree of agreement between ensemble members should be described in in terms of directionality of change. How strong the change signal is relative to historic variability should also be evaluated. For Tier 1 assessments, the CHAT plots and robustness output should provide this content.

j. The initial portion of the likelihood rubric displayed in Table E–3 describes how to define the hazard likelihood. Lines of evidence to evaluate the likelihood rating are specific to each RHF, as well as measures, features, and management actions being evaluated.

k. Some measures, design standards, and management practices offer inherent resilience that supports reliability and prevents harms even as hydrometeorological conditions change. Specific actions can make a project more resilient to impacts driven by changing hydrometeorological extremes.

l. Resilient aspects of each measure, feature, and/or management action should be highlighted. The level to which they reduce the likelihood of a harm materializing should be characterized as complete or partial and used to adjust the likelihood score accordingly. The second part of Table E–3 documents the adjustment to the overall likelihood of harm resulting from resilience features inherent to the element being proposed and/or added through plan formulation. The way each measure, feature, and/or management action offers resilience to the harm resulting from a trigger and hazard is unique to each assessment.

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[9] RSLC analysis supports RSLC-related likelihood ratings. The trigger might be sea level rise resulting in harms like a higher river profile, saltwater intrusion into groundwater, increased erosion/sedimentation, etc.

[10] Tier 2 analysis requires consulting with, and scope approval from, the IIR CoP.

Table E–3
Likelihood of trigger, hazard, and harm rubric example

<table>
<tr><td>Project Feature:</td><td colspan="6">Levee Erosion Protection – Rip Rap</td></tr>
<tr><td>Trigger:</td><td colspan="6">Increased discharge and water surface elevation (WSEL)</td></tr>
<tr><td>Hazard:</td><td colspan="6">Future flood velocities, loading durations, and elevations may be higher than present</td></tr>
<tr><td>Harm:</td><td colspan="6">Higher water/longer loading duration and increases in future flood velocities may displace rip rap, requiring repair</td></tr>
<tr><td>Lines of Evidence
(e.g., resource, tool, analysis)</td><td colspan="3">Variable(s) Analyzed/Evaluation Applied</td><td colspan="2">Result</td><td>Hazard Likelihood Score (1–5)</td></tr>
<tr><td rowspan="4">Literature Review
References: 3rd & 4th NCA, 2015 USACE Literature Synthesis HUC 09, NOAA ND State Climate Summary</td><td colspan="2" rowspan="2">Peak Streamflow (trends and degree of consensus between references)</td><td>Observed</td><td>Increasing Trend</td><td>Low Consensus</td><td rowspan="4">2 – Unlikely: Analogous Probability of Occurrence (20–40%)</td></tr>
<tr><td>Future</td><td>No Trend</td><td>Low Consensus</td></tr>
<tr><td colspan="2" rowspan="2">Extreme Precipitation Trends-Intensity and Frequency (trends and consensus between references)</td><td>Observed</td><td>Mixed Trends</td><td>Low Consensus</td></tr>
<tr><td>Future</td><td>Mixed Trends</td><td>Low Consensus</td></tr>
<tr><td rowspan="5">TST</td><td rowspan="5">Annual Maximum Flow
Performance Threshold: Operationally significant change >5% (500 cfs)</td><td rowspan="2">Monotonic Trend Analysis</td><td>Full Record (1936–2024):</td><td colspan="2">Weak Increasing; > 0.1 and ≤ 0.33</td><td rowspan="5">2 – Unlikely: Analogous Probability of Occurrence (20–40%)</td></tr>
<tr><td>Subset (1952–2024):</td><td colspan="2">None; p-value > 0.33</td></tr>
<tr><td rowspan="3">Change point/ Breakpoint Analysis</td><td>Year with Consensus:</td><td colspan="2">1940</td></tr>
<tr><td>Statistic/Change Magnitude/Exceeds 5% Threshold?</td><td colspan="2">Mean; +1.5k cfs; Above Threshold</td></tr>
<tr><td>Robustness:</td><td colspan="2">Low</td></tr>
<tr><td rowspan="4">CHAT</td><td rowspan="4">Annual-Maximum of Mean Monthly Streamflow</td><td colspan="2">Scenario:</td><td>RCP 4.5</td><td>RCP 8.5</td><td rowspan="4">3 - Possible: Analogous Probability of Occurrence (40%–60%)</td></tr>
<tr><td colspan="2">2050 Robust Change Signal</td><td>No Signal</td><td>Weak Signal, Positive</td></tr>
<tr><td colspan="2">2085 Robust Change Signal</td><td>Weak Signal, Positive</td><td>Weak Signal, Positive</td></tr>
<tr><td colspan="2">Trend Analysis Future Period (2006–2099)</td><td>None; p-value > 0.33</td><td>Strong, Increasing; p-value ≤ 0.05</td></tr>
</table>

<table>
<tr><td>Project Feature:</td><td colspan="6">Levee Erosion Protection – Rip Rap</td></tr>
<tr><td rowspan="2"></td><td>Performance Threshold: Operationally significant change in Annual Median Flow> 15%</td><td>Change exceeds threshold
2085 epoch relative to base epoch</td><td>No, 13%</td><td colspan="2">Yes, 25%</td><td rowspan="2"></td></tr>
<tr><td colspan="2">Is the seasonality of flow changing?
2085 epoch relative to base epoch</td><td>Yes; Increases in winter and spring flow.</td><td colspan="2">Yes; Increases in winter and spring flow.</td></tr>
<tr><td rowspan="11">CWVAT
Hazard: Riverine Flooding</td><td colspan="2">Epoch:</td><td>Base</td><td>2050</td><td>2085</td><td rowspan="11">2 - Unlikely: Analogous Probability of Occurrence (Low Likelihood 20%–40%)</td></tr>
<tr><td rowspan="2">Qualitative Exposure Rating</td><td>Low Scenario</td><td rowspan="2">Medium</td><td>Medium</td><td>Medium</td></tr>
<tr><td>High Scenario</td><td>Medium</td><td>Medium</td></tr>
<tr><td rowspan="2">Overall Hazard Rating (Z-Score)</td><td>Low Scenario</td><td rowspan="2">−0.50</td><td>−0.14</td><td>−0.01</td></tr>
<tr><td>High Scenario</td><td>0.05</td><td>0.48</td></tr>
<tr><td rowspan="4">Flood Magnification Factor (Unitless) Performance Threshold: Operationally significant change when > 15% increase</td><td>Low Scenario</td><td rowspan="2">1</td><td>2.78</td><td>3.65</td></tr>
<tr><td>High Scenario</td><td>3.65</td><td>5.08</td></tr>
<tr><td>% Change High Scenario/ Exceeds 20% Threshold?</td><td rowspan="2">NA</td><td>6%/No</td><td>9%/No</td></tr>
<tr><td>% Change High Scenario/ Exceeds 20% Threshold?</td><td>11%/No</td><td>18%/Yes</td></tr>
</table>

<table>
<tr><td colspan="8">Hazard Likelihood Average Score (1–5):</td><td>3 - Possible</td></tr>
<tr><td rowspan="2">Resilient Characteristics</td><td>✓</td><td>Conservative Design</td><td></td><td>Easily Modified</td><td></td><td>Adaptive</td><td></td><td>IIR Informed Design Criteria</td></tr>
<tr><td></td><td>Other, Describe:</td><td colspan="6"></td></tr>
<tr><td colspan="8">Resulting Reduction of Likelihood of Harm (All/Partial/None):</td><td>Partial</td></tr>
<tr><td colspan="8">Overall Harm Likelihood Score (1–5)</td><td>2 – Unlikely</td></tr>
<tr><td>Justification for Likelihood Assessment</td><td colspan="8">Observed and future streamflow trends show no clear consensus in the literature. An apparent changepoint circa 1940 is likely an artifact of the extreme 2011 flood, which is considered an outlier event. The CWVAT exposure rating for riverine flooding is only medium, and operationally significant flood magnification is only likely if a high scenario is assumed towards the end of the century. Erosion protection is conservatively designed to the event of record, the 2011 event. This event is several orders of magnitude larger than the 0.2% AEP event.</td></tr>
</table>

E–7. Impact Ratings

a. Impact ratings capture the consequences of THHs, as well as the effects of failure or reduced performance of project features, measures and/or management actions being considered. Along with a likelihood rating, an evaluation should characterize potential impacts as insignificant (1), minor (2), moderate (3), major (4), or severe (5).

b. The PDT should define an impact rating for the following four consequence categories: life safety, economic, environmental, and social impacts. The DWR impact assessment includes life safety because of its critical importance to USACE missions. Table E–4 provides an example of consequence criteria to consider for a DWR risk assessment. The PDT can tailor the criteria to fit a given application.

Table E–4
Consequence severity criteria to define impact rating

Impact Rating	Consequence Criteria
1 - Insignificant	Failure or lack of performance of the project feature presents no life safety risk concerns and presents insignificant socioeconomic or ecosystems concerns.
2 - Minor	Failure or lack of performance of the project feature presents no life safety risk concerns but could result in minor economic damages or damage to aquatic ecosystems. Minor impacts to community resilience and cohesiveness, no population displacement, or only very minor public health concerns.
3 - Moderate	Failure or lack of performance of the project feature presents no life safety risk concerns but could result in moderate economic damages or damage to ecosystems. Moderate impacts to community resilience and cohesiveness, population displacement, or public health concerns.
4 - Major	Failure or lack of performance of the project feature could result in a life safety threat, major economic damages, or destruction of ecosystems. Significant impacts to community resilience and cohesiveness, population displacement, or major public health concerns.
5 - Severe	Failure or lack of performance would result in life safety risk, significant economic damages, or destruction of ecosystems beyond recovery. Irreversible impacts to community resilience and cohesiveness, mass population displacement, or significant public health concerns.

E–8. Risk Score. The DWR risk assessment culminates in an aggregate risk score comprised of the likelihood and the impact of the THHs. The risk matrix in Figure E–1 combines the likelihood and impact into a risk score, which falls into one of the following three risk categories: low, moderate, or high. Risk scores are computed by multiplying the likelihood and impact scores.

Risk Matrix		Impact Severity				
		Insignificant (1)	Minor (2)	Moderate (3)	Major (4)	Severe (5)
Likelihood	Highly Likely (5)	5	10	15	20	25
	Likely (4)	4	8	12	16	20
	Possible (3)	3	6	9	12	15
	Unlikely (2)	2	4	6	8	10
	Rare (1)	1	2	3	4	5
				Low	Moderate	High

Figure E–1. Risk matrix

E–9. Risk Evaluation

a. To provide real-world context, a flood risk management example project illustrates the risk evaluation approach required by this guidance (see Figure E–2).

(1) The example project evaluates the performance of an existing dam and flood bypass channel and provides enhanced flood risk management and interior drainage to reduce flood risk to a downstream industrial area. Proposed project features include a levee with rip rap, a flood wall, and a pump station tied into a subsurface stormwater conveyance system.

(2) The primary operating objective of the dam is to reduce flood risk to a downstream community. In addition to the dam, the city center has a flood bypass channel. The community is upstream of a growing industrial area, which has endured frequent and more extensive flooding in the past decade as compared to the 50 years since the dam and bypass were constructed. As a secondary operating objective, the dam supplies water to both the community and the downstream industrial zone.

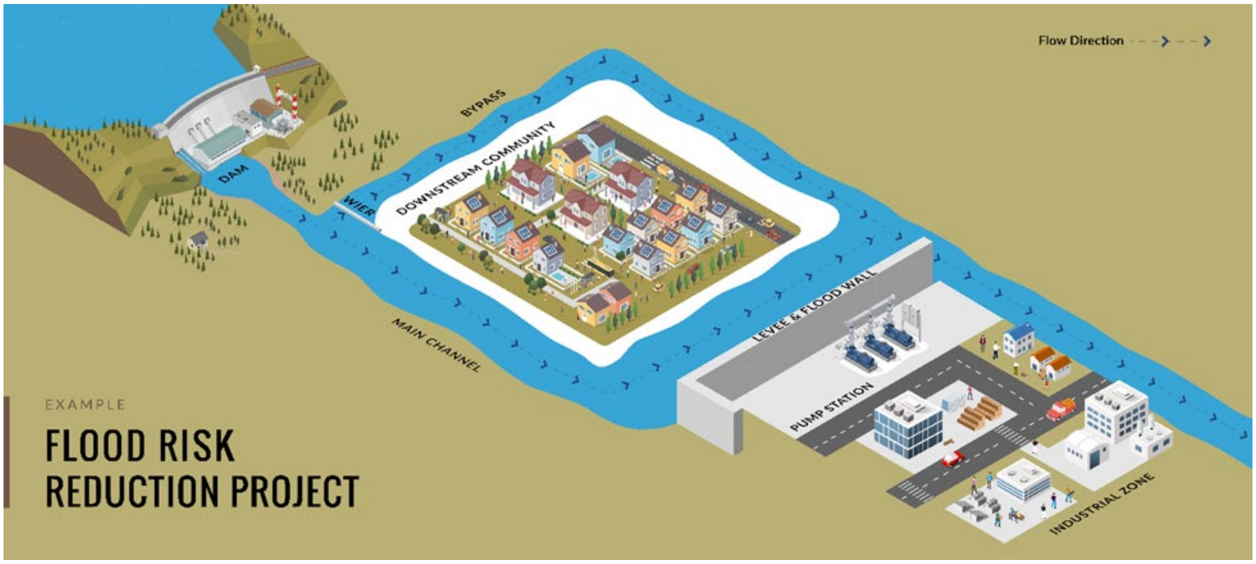

Figure E–2. Example project – flood risk reduction infrastructure

b. The likelihood and impact of the THHs are assessed to calculate categorical risk (life safety, economic, environmental, social) semi-quantitatively for each project feature, measure, and/or management action being evaluated. For the example in Figure E–2, Table E–5 illustrates how to compute risk for each consequence category. Table E–5 is the DWR risk assessment risk rubric; it must be archived as part of the DWR risk assessment and can be part of report documentation. The THHs being evaluated are in the table because a given feature, measure, and/or management action could have multiple THHs. The maximum risk score for each feature in Table E–5 is reported as part of the DWR risk table (see Max. Risk Score in Table E–6).

c. An example DWR risk table is in Table E–6. To support USACE's plan formulation process, this table must be in report documentation and at minimum include rows for each major feature, measure (including nonstructural measures), and/or management objective in the TSP, LPP (if applicable), and recommended plan. For plans where similar features/measures are being recommended at different sites throughout the project area, the PDT should present the duplicative features/measures as a singular table entry.

d. Efforts not evaluating a specific feature or decision should evaluate DWR risk in the context of the business line under consideration. The DWR risk table columns should describe the THHs, a semi-quantitative likelihood assessment, and suggested risk management actions, as well as the residual risk remaining after proposed risk management actions have been implemented (Yoe and Harper 2017).

e. The DWR risk table should report only the maximum score from the four consequence categories (from the risk rubric, Table E–5). However, all moderate to high-risk categorical scores should be discussed narratively, capturing content analogous to what is presented in Table E–5.

f. When a risk is deemed unacceptable, the PDT should reformulate or add resilience to manage the risk. Report documentation must describe this iterative risk management approach. This process is illustrated for the example project (Figure E–2) by evaluating its conveyance system design. The original interior drainage conveyance system design offered an unacceptable high (16) level of risk (see Table E–6). The PDT used the DWR risk evaluation to justify upsizing the stormwater conveyance system design (see Table E–7).

g. Not all changes in hydrometeorology increase risks. In certain situations, changing conditions can improve current or proposed project performance or offset risk. Where a change in hydrometeorology is anticipated to reduce risk and/or improve performance, benefits should be briefly discussed narratively. For example, wetland restoration features in a proposed floodway may benefit from more frequent wetting and larger volumes of water, making these more sustainable in the future.

Table E–5
Example risk rubric (PAR = population at risk; NBS = nature-based solution)

Project Feature	Trigger	Hazard	Harm	Likeli-hood	Life Safety	Economic	Environmental	Social Effects	RISK SCORE
Levee erosion protection – rip rap, industrial zone	Increased discharge and water surface elevation (WSEL)	Future flood velocities and elevations may be higher than present	Higher water/longer loading duration and increases in future flood velocities may displace rip rap. requiring repair (increased OMRR&R)	2	Damage to rip rap alone will not cause life safety risk. Impact: 1 Risk: 2	Reduced levee performance due to erosion causes damage but not total loss Impact: 2 Risk: 4	Large sediment erosion impacts aquatic ecosystem Impact: 3 Risk: 6	The levee system that the rip rap protects is resilient to failure, and increased flow/WSEL would not have significant impacts Impact: 1 Risk: 2	Max. Individual Score 6- Life Safety
Levees and floodwalls, industrial zone	Increased discharge and WSEL	Water volumes and depths may be higher than at present	Overtopping leading to flooding	2	Limited number of inhabitants in protected area; PAR 129; loss of life 0; warning time 3 days Impact: 2 Risk: 4	Overtopping causes damage but not total loss based on interior drainage plan Impact: 2 Risk: 4	Limited impacts to ecosystem Impact: 1 Risk: 2	Periodic overtopping resilient to failure has no significant impacts Impact: 2 Risk: 4	Max. Individual Score 4- Econ. /Social
Interior drainage conveyance design, industrial zone	Increased extreme precipitation	Future stormwater volumes along the mainstem and tributary may be coincidently larger than present	Interior drainage capacity may be overwhelmed, causing interior flooding	4	Limited number of inhabitants in protected area; PAR 12; loss of life 0; warning time 3 days Impact: 2 Risk: 8	Large portion of the industrial area at risk of event-based flooding over time Impact: 4 Risk: 16	Existing ecosystems could be inundated for a short period of time Impact: 3 Risk: 12	Growing industrial area presents a major source of socioeconomic growth Impact: 4 Risk: 16	Max. Individual Score 16- Econ. /Social
Interior drainage pump design- industrial zone	Increased extreme precipitation	Future stormwater volumes along the mainstem and tributary may be coincidently larger than present	Pump station capacity may be overwhelmed, causing interior flooding	1	Limited number of inhabitants in protected area; PAR 129; loss of life 0; warning time 3 days Impact: 2 Risk: 2	Large portion of the industrial area at risk of event-based flooding over time Impact: 4 Risk: 4	Existing ecosystems could be inundated for a short period of time. Impact: 3 Risk: 3	Growing industrial area presents a major source of socioeconomic growth Impact: 4 Risk: 4	Max. Individual Score 4-Econ. /Social
Weir at upstream end of flood bypass channel	Increased precipitation from large, slow-moving storms	Future stormwater volumes may be larger than present and may occur more frequently	Weir may be overtopped more frequently than at present, resulting in more frequent flows and high velocities in the floodway	3	Emergency services temporarily impacted Impact: 3 Risk: 9	Limited economic damages, as the floodway is designed to be flooded Impact: 2 Risk: 6	Bypass designed as an NBS with diverse ecosystem Impact: 3 Risk: 9	Floodway runs through residential area but activation is limited, even with more frequent events Impact: 2 Risk: 6	Max. Individual Score 9- Life Safety/ Env.
Dam embankment and discharge outlet	Increased heavy precipitation events and increased dam inflows	Future dam inflows may be larger than present conditions and floods may occur more frequently	Increased dam inflows result in higher pool elevations and dam embankment loading, leading to more seepage around the outlet (recognized as a PFM)	1	Seepage could threaten stability of the dam embankment, threatening lives in the city downstream Impact: 5 Risk: 5	Significant economic damages in city and industrial area downstream Impact: 5 Risk: 5	Failure damages the diverse ecosystems downstream of structure Impact: 4 Risk: 4	Limited social effects Impact: 4 Risk: 4	Max. Individual Score 5- Life Safety/Econ.

Table E–6
DWR risk table example -interim (initial iteration; double underlined text signifies unacceptable residual risk)

Project Feature	Trigger	Hazard and Hazard Likelihood Rating	Harm	Overall Likelihood of Harm and Resilience Features	Max. Impact Rating (from Risk Rubric)	Max. Risk Score (from Risk Rubric)	Residual Risk	Evaluation	Recommended Actions to Maintain Acceptable Risk Level
Levee erosion protection – rip rap, industrial zone	Increased discharge and WSEL	Future flood velocities, loading durations, and WSEL may be higher than present. **Possible (3)**	Higher water/longer loading duration and increases in future flood velocities may displace rip rap, requiring repair (increased OMRR&R)	**Unlikely (2)** Considerable safety factor in rip rap design.	**Moderate (3)**	**Low (6-Life Safety)**	Vulnerable to extreme flood events (AEP < 0.2%)	Acceptable. DWR risk adequately controlled through design and accepted for extremely rare events (AEP < 0.2%).	Monitor for damage to riprap.
Levees and floodwalls, industrial zone	Increased discharge and WSEL	Water volumes and depths may be higher than at present. **Likely (4)**	Overtopping leading to flooding.	**Unlikely (2)** Measure accounts for H&H uncertainty with the 90% confidence band.	**Minor (2)**	**Low (4-Econ. /Social)**	Limited residual risk; project only susceptible to frequency events greater than the design, which provides 90% assurance for the 0.2% AEP flood event.	Acceptable. DWR risk adequately controlled through design.	Monitor performance under extreme flood events and flood frequency for increases in streamflow statistics.
Interior drainage conveyance design, industrial zone	Increased extreme precipitation	Future stormwater volumes along the mainstem and tributary may be coincidently larger than present. **Likely (4)**	Interior drainage capacity may be overwhelmed causing interior flooding.	**Likely (4)** Storm sewer design sized to a 10-year, 24-hour rainfall event. Future upsizing of the subsurface would be challenging.	**Major (4)**	**High (16-Econ. / Social)**	Project feature vulnerable to future increases in extreme rainfall events and cannot be easily adapted should increase risk materialize.	Unacceptable, significant residual risk. A significant DWR risk to future feature performance exists.	Modifications should be made to design to lessen residual risk.
Interior drainage pump design, industrial zone	Increased extreme precipitation	Future stormwater volumes along the mainstem and tributary may be coincidently larger than present. **Possible (3)**	Pump station capacity may be overwhelmed causing interior flooding.	**Rare (1)** Increased likelihood of this hazard occurs late-century, beyond the project's service life. Design includes a larger pump building capable of housing future, upsized pump retrofit	**Major (4)**	**Minor (4-Econ. /Social)**	Failure to implement the dynamic adaptation approach (considering future pump retrofit) could result in increased residual risk.	Acceptable. Risk controlled through conservative level of design and dynamic adaptation.	Monitor likelihood of increased risk and use a dynamic adaptation approach to determine when larger pump sizes may be needed.
Weir at upstream end of flood bypass channel	Increased precipitation from larger, slower-moving storms	Future stormwater volumes may be larger than present and may occur more frequently. **Possible (3)**	Weir may be overtopped more frequently than at present, resulting in more frequent flows and high velocities in the floodway.	**Possible (3)** Current discharge capacity of the bypass includes overdesign.	**Moderate (3)**	**Moderate (9-Life Safety/ Env.)**	Limited residual risk due to overdesign and performance history.	Acceptable risk based on current overdesign and erosion risk controlled through design and monitoring.	Monitor streamflow characteristics and continue to conduct periodic inspections to confirm the design remains adequate.
Dam embankment and discharge outlet	Increased heavy precipitation events and increased dam inflows	Future dam inflows may be larger than present conditions and floods may occur more frequently. **Unlikely (2)**	Increased dam inflows result in higher pool elevations and loading of the dam embankment leading to more seepage around the outlet. (recognized as a PFM)	**Rare (1)** Design includes cutoff wall to reduce the risk of seepage and erosion around the outlet. Design reduces this PFM to a rare likelihood.	**Major (5)**	**Low (5-Life Safety/Econ.)**	Risk controlled; very limited residual risk due to robust design.	Acceptable. Risk controlled through design.	No action. Continue monitoring during regular inspections and periodic assessments.

Table E–7
DWR risk table example -final realization of interior drainage conveyance design replacing original entry in Table E–6

Project Feature	Trigger	Hazard and Hazard Likelihood Rating	Harm	Overall Likelihood of Harm and Resilience Features	Max. Impact Rating (from Risk Rubric)	Max. Risk Score (from Risk Rubric)	Residual Risk	Evaluation	Recommended Actions to Maintain Acceptable Risk Level
Interior drainage conveyance design, industrial zone	Increased extreme precipitation	Future stormwater volumes along the mainstem and tributary may be coincidently larger than present. **Likely (4)**	Interior drainage capacity may be overwhelmed causing interior flooding.	**Possible (3)** Design includes a substantial factor of safety (sized to the 50-year, 24-hour rainfall event, versus the typically adopted 10-year event).	**Major (4)**	**Moderate (12- Econ. /Social)**	Limited residual risk due to upsizing the conveyance system to be robust to future increases in extreme precipitation.	Acceptable. Risk adequately controlled through design.	No action; continue to monitor performance.

E–10. Application

a. The PDT should carefully consider risks associated with individual consequence categories to determine if the risk is tolerable. If a risk is moderate or high for a given category, the PDT (along with the vertical team, as necessary) should determine whether the residual risk associated with the TSP or recommended plan is acceptable. Based on this discussion, the PDT must either make modifications to manage for or reduce that risk or describe and justify why no action is taken. Appendix F provides additional detail related to strategies to mitigate DWR risk.

b. The DWR risk assessment process in this appendix lays the groundwork to identify opportunities and justify adding resilience by comprehensively assessing economic, social, and environmental effects. If evaluating DWR risk leads to modifying the design or proposing a management action, the updated and/or added feature(s) should be reevaluated within the DWR risk assessment.

E–11. Documentation.

a. The PDT documents the process of considering and addressing DWR risk through a narrative discussion and a DWR risk table (Table E–6) in the report section or appendix that summarizes the LHC evaluation. The narrative discussion should describe the THHs, likelihood ratings, impacts (e.g., life safety, economic, environmental, and social), risk scores, and associated qualitative uncertainty for each line of evidence that contributed to the risk determination.

b. Report documentation must cover how changes in hydrometeorological conditions impact the future condition and how DWR risk factored into formulating and evaluating alternatives.

c. The DWR risk table (see Table E–6) must present residual risk for, at minimum, the features, measures, and/or management actions reflected in the TSP, LPP (if applicable) and recommended plan.

d. Both the likelihood rubric (Table E–3) and risk rubric (Table E–5) tables can be optional supplementary material in an appendix or maintained with project files for future reference. The likelihood rubric helps illustrate how the likelihood ratings were derived. The risk rubric presents results across all consequence categories and helps explain how the risk rating was derived.

e. In addition to the full LHC assessment in an appendix, the main report should include a brief discussion (at minimum) of DWR risk and residual risk. The main report narrative should focus on the risks to the performance of features, measures, and/or management actions that are sensitive to changes in hydrometeorology and are part of the TSP, LPP (if applicable), and recommended plan.

f. Risks driven by nonstationary hydrometeorological conditions are nearly impossible to eliminate, because uncertainty is inherent to characterizing future conditions and the frequently interrelated effects of changes to RHFs. Therefore, the report narrative, DWR risk table, and the project risk registry, as appropriate, should record the associated risks, including residual risks, actions taken to increase resilience, and a qualitative discussion of uncertainties associated with the risk assessment.

(1) The project risk register (DPM 2020-04) documents the likelihood of each identified risk occurring and the degree of impact to the project (e.g., feasibility, cost, schedule) if the risk is realized. The register manages and documents risk over the course of study and beyond. The risk register is a living document, updated as project conditions change and new potential risks are identified. It captures study risk (e.g., potential for delays, cost increases, poor planning), implementation risk (schedule and cost), and the risks tied to project outcomes (hazard risks and risks to project performance).

(2) An LHC assessment could result in study risks like increased cost and schedule due to a previously unanticipated need to add resilience to the design or for more in-depth analysis of how conditions may change in the future (e.g., Tier 2 assessment). Importantly, the DWR risk assessment identifies residual risk to project performance driven by the potential for changing hydrometeorological conditions.

g. Clearly presenting the findings of the DWR risk assessment helps inform discussions with sponsors, stakeholders, and others; however, documentation alone does not fully convey the highly technical nature of risk assessment results. Open dialogue is required to confirm a sufficient and common understanding of the risk assessment and risk reduction options leading to selecting the most appropriate actions.

E–12. Appendix E References

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Appendix F
Resilience and Dynamic Adaptation

List of Figures

List of Tables

F–1. Purpose.

a. This appendix details how to incorporate considering resilience to DWR threats and hazards into the overall planning process to equip the PDT with a resilience mindset so they formulate and design a project that performs as intended for its service life. See EP 1100-1-5 for additional examples of how USACE practices resilience. This appendix suggests how outputs from an LHC assessment might justify adding resilience to offset DWR risks to project performance.

b. The appendix has the following components:

(1) Section F–2 provides background on USACE policy and guidance related to resilience and covers the principle of resilience as applied to prevent impacts driven by hydrometeorological change.

(2) Section F–3 focuses on how to consider and incorporate resilience into the USACE planning process.

(3) Section F–4 outlines the decision-making criteria to apply when proposing, evaluating designing, and implementing resilience strategies/features.

(4) Sections F–5 to F–7 introduce potential avenues to justify adding resilience as part of USACE projects.

(5) Sections F–8 and F–9 are examples of how resilience can be added to minimize DWR risk.

F–2. Background.

a. USACE projects must be designed, constructed, and maintained to withstand hydrometeorological stressors throughout their service lives (typically 50–100 years). USACE infrastructure can remain in place well beyond the 50-year economic period of analysis; with regular OMRR&R, it may be in place indefinitely (EP 1100-2-1).

b. Historically, USACE project design was based on the range of hydrometeorological conditions experienced in the past. However, recent scientific evidence shows that in some geographic locations, hydrometeorological conditions are changing (nonstationary), and consequently, risk to USACE infrastructure cannot be represented solely by past environmental conditions.

c. The PDT must integrate resilience into established and emerging approaches to accomplish their missions and deliver project benefits. Resilience is the ability to anticipate, prepare for, and adapt to changing conditions and withstand and recover from disruptions. Addressing potential adverse impacts from emerging, weather-related hazards requires close collaboration among multiple PDT disciplines and with the IIR CoP. Furthermore, USACE must collaborate with project partners and their NFSs to maintain project resilience and, when necessary, develop effective resilient solutions to challenges posed by DWR risk.

d. Both USACE guidance and policy, as well as national policy directives and statutes, establish the need for USACE to take action to support resilience. EP 1100-1-2, U.S Army Corps of Engineers Resilience Initiative Roadmap, presents key resilience-related strategies and actions. EP 1100-1-5, USACE Guide to Resilience Practices, more specifically describes resilience practices across CW programs and initiatives.

e. USACE is dedicated to taking specific and measurable actions to provide resilience to the communities with which we partner. Additionally, the assets we operate and maintain must be resilient to a wide range of hydrometeorological conditions. USACE's framework for resilience includes four principles: prepare, absorb, recover, and adapt (PARA). When applied together, PARA establishes a comprehensive, resilience approach to effectively address both acute and chronic hazards.

f. To support the Prepare principle, an LHC assessment defines how changes in long-term weather patterns may affect future conditions (FWOP and future with project conditions). Assessing LHCs provides information that considers resilience to DWR risk as part of decision making. This helps formulate projects that can Absorb and/or Recover from a wide range of hydrometeorological conditions with minimal damages, loss of functionality, or downtime. USACE uses the Adapt principle to identify modifications to project components or systems that maintain or improve performance over time (EP 1100-1-5).

g. USACE recognizes three levels of resilience: project, system, and community resilience. Project resilience is the resilience of an individual project, independent of other projects in the vicinity. System resilience considers the overall resilience of a collection of interdependent projects, such as dams and levees along a river system. Community resilience is the resilience of the built, natural, and social systems that make up the community. Community resilience confirms that projects and systems can absorb and recover from natural and man-made disasters through planning, design, and adaptation. These three levels of resilience are interdependent, and actions taken at any level ultimately affect the other levels (EP 1100-1-5).

h. Cumulative impacts, system-wide impacts, and impacts to other federal agency missions should be identified and considered as part of the "establishing decision context" and "identifying RHFs" phases (Appendix C) of the LHC assessment, so that this information can be incorporated when evaluating a proposed resilience or adaptation strategy. Cumulative impacts refer to the additive effects of several RHFs, such as flooding caused by both storm surge and heavy precipitation. System-wide impacts reflect the cumulative impacts on other systems in the project area due to the adverse effects of RHFs on the performance of a USACE project. In some cases, it may not make sense to add resilience to a project when overall system constraints are considered.

(1) Asset-based resilience measures should consider the bigger picture to avoid creating adaptation islands (FHWA 2017). An example of an adaptation island is a pump station and conveyance system sized to an extreme design storm that feeds into an extensive storm sewer system with a small capacity and without the capability to adapt that capacity later. In this example, the increased size of the pump station and its conveyance system is constrained by the downstream system's limited capacity.

(2) Ideally, actions taken to reduce risk in one region of a system should not shift the risk burden to another portion of the system. Actions taken to reduce risk should not result in a new or increased risk (ER 1105-2-101). An example that illustrates the potential for both risk transfer and transformation is constructing or raising a levee in advance of a foreseeable increase in flood risk. Raising a levee to reduce local flood risk can increase flow downstream. A levee also has the potential to transform gradual and observable flood risk that allows emergency action into sudden and catastrophic flood risk in the case of levee failure (ER 1105-2-101).

i. Resilience applies to built (human-made) and natural environments as well as social systems. USACE helps communities develop resilience through project delivery and a wide range of mission activities. Ecosystems are resilient when they can maintain their structure and function under external stress, including changing hydrometeorological conditions.

j. USACE has a long tradition of supporting community, ecosystem, and infrastructure resilience against environmental threats like flooding, sea level change, extreme precipitation and temperature, and drought. USACE must consider future changes to these environmental threats and the subsequent impacts of these threats to project and system performance.

F–3. Incorporating Resilience into Planning and Design.

a. Applying a resilience mindset and formulating resilient features and measures to address DWR risk is the responsibility of the entire PDT. PDTs are required to identify and account for foreseeable changes in hydrometeorology in all stages of the USACE planning process to help incorporate resilience and adaptation into alternatives. Resilience should be considered to develop effective plans that perform throughout the project service life.

b. The PDT's goal, where possible, is to increase resilience against weather-related hazards that threaten project performance. Items like resource constraints, a project's capacity for resilience (see paragraph F–3.e), and USACE's authority or project authorization may limit the anticipatory approaches a PDT can take to address foreseeable DWR risk. When immediate action to reduce DWR risk to an acceptable level is not possible, residual DWR risk must be characterized and communicated in the report documentation, as described in Appendix E. In most cases, changes in LHCs amplify the impacts of hazards already being considered.

c. Incorporating resilience to changes in weather-related hazards must begin when initiating a project, during plan formulation. During the early stages of project formulation (prior to the AMM), assessing LHC is crucial to help the PDT brainstorm how to address weather-related triggers and hazards. Prior to the AMM, the PDT should determine the scale of assessment (including considering a Tier 2 analysis) required to fully evaluate DWR risks.

d. By considering potential impacts early, the PDT can effectively characterize the future condition and proactively identify an initial array of alternatives that considers resilience up front. This helps avoid formulating less effective and efficient alternatives during the early stages of the project. The earlier in a project that a team can brainstorm ways to incorporate resilience, the more likely it can be accomplished without drastically altering the project cost or schedule (Hilleary et al. 2024).

e. Between the AMM and the TSP milestones, the IIR PDT member should use the LHC assessment to identify residual DWR risks to the performance of the TSP (and any LPP being considered) that could materialize because of nonstationary conditions. The DWR risk assessment process described in Appendix E enables PDTs to identify unacceptable levels of future, weather-related risk, pointing to the need to incorporate additional resilience into the TSP.

f. The level of analysis (i.e., Tier 1 or Tier 2) to design, prescribe, and/or justify a resilient strategy varies depending on course of action being proposed. If a project team is seeking to incrementally justify adding resilience features and/or measures at a significant cost, a Tier 2 analysis may be warranted. Residual DWR risk associated with the final recommended plan must be part of the CVM documentation (see Appendix B, Figure B–3).

g. Many resilience features are amplified forms of measures currently formulated or installed to manage risks associated with today's environmental conditions. USACE provides resilience through one of the following three categories: structural, nonstructural, and nature-based approaches. These approaches can be standalone features or used in tandem to further enhance resilience (FHWA 2017).

(1) Risk can be managed structurally by constructing or modifying infrastructure, like levees, floodgates, and floodwalls. In the case of a flood risk management project, for example, structural solutions reduce the frequency of a weather-related harm occurring (e.g., reduced probability of overtopping in the case of a levee). Structural approaches provide resilience through more conservative design (e.g., increased level of project performance) to increase or validate performance against weather-related hazards.

(2) Nonstructural approaches reduce potential damages but do not reduce the probability of a hazard materializing in the future. Nonstructural approaches reduce damages by removing assets from the hazard area rather than removing the hazard from the asset. Resilience to weather-related hazards can be augmented via nonstructural approaches by elevating structures, relocation, flood warning systems, and floodproofing.

(3) Nature-based approaches reduce damages by using landscape elements to mimic natural features or processes. These approaches, also known as nature-based solutions (NBSs), may provide similar risk reduction with broader project benefits (e.g., wetland restoration).

h. Resilience features can be integrated into the initial phases of project design, iteratively added based on the DWR risk assessment (Appendix E), or incorporated after construction through a phased dynamic adaptation strategy depending on how hydrometeorological conditions are expected to evolve through the life of the project.

i. To justify resilience features, the PDT can perform a cost benefit analysis, life cycle cost analysis, and/or justify adding resilience incrementally by applying a comprehensive benefits approach. The PDT should coordinate closely with the vertical team and national experts (e.g., IIR CoP, centers of expertise, regional technical specialists) to justify features that add resilience to shifts in hydrometeorology.

j. Because future changes in weather-related hazards are likely to materialize later in a project's service life, justifying them frequently requires a nonstandard approach. By consulting with the vertical team and national experts, PDT can confirm that solutions are technically acceptable and can be effectively incorporated via policy exceptions when applicable.

F–4. Key Project Decision-Making Criteria.

a. Several factors should be considered when proposing, evaluating, designing, and implementing resilience features. Key considerations include defining project nonperformance and the project service life. Additionally, identifying and characterizing all existing and proposed features within the project area is important to consider, as well as the feasibility of adding resilience features to a project given a myriad of factors, including sensitivities to hydrometeorological change and socioeconomic constraints.

b. Determining what qualifies as nonperformance based on the project purpose and objectives is important to consider when identifying and justifying the inclusion of resilient features. Even when effective OMRR&R strategies are applied, project performance often degrades over time, and the impacts of increases in the frequency, intensity, and/or duration of weather-related extremes have the potential to accelerate the progression to nonperformance. The project should perform at an acceptable minimum level given the range of potential future changes in hydrological condition and known weather-related stressors throughout its entire project service life.

(1) In applications where nonperformance equates to the potential for life safety risk (e.g., loss of life due to dam or levee failure), nonperformance focuses on preventing failure. For other applications, nonperformance can be defined by consequences, like excessive maintenance requirements, increasingly frequent damages (e.g., flood damages, spillway damage), loss of essential habitat, reduction in provided services (e.g., draft restrictions) and/or an unacceptable level of uncertainty regarding project performance and costs.

(2) If a project has a high risk of not performing at an acceptable minimum level over its project service life, resilience features and strategies must be considered. Resilience strategies could include dynamic adaptation to support rehabilitation to the original level of project performance and/or modernization (increased performance) in the face of changing conditions (see section F–9 for more information on dynamic adaptation strategies).

c. When formulating measures to increase resilience to weather-related hazards, considering the project's service life and understanding when a risk might materialize are crucial. Hydrometeorological conditions must be considered from the anticipated start of construction through the end of a project's service life. If conditions are likely to be nonstationary, impacts can be considered continuously or may be broken into discrete time periods for analysis. Commonly used time horizons include (1) current and near term (impacts currently occurring and best informed by evaluating observations collected in the recent past; i.e., up to present day and 20 years into the future); (2) midterm (a 30-year epoch centered around 2050; i.e., 2035–2064); and long term (a: 30-year epoch centered around 2085; i.e., 2070–2099) (CEMA and CNRA 2012).

d. Understanding how risk may change across these timeframes, as well as project service life, informs long-term strategic decision-making. It helps in planning and prioritizing resilience measures that align with the project's service life and the expected timing of potential weather-related challenges. It avoids investing in resilience features designed for conditions that the project may never experience. By carefully aligning the project service life with the anticipated timeline of impacts, dynamic adaptation strategies can be implemented gradually over time. This approach spreads out the additional expenses associated with these features.

e. A project may already have a degree of resilience in the design or management approach. This should be accounted for when considering what further action should be taken. Some examples of resilience features already embedded in the traditional approach to design could include:

(1) A conservative riprap size.

(2) Flexibility in operations (i.e., the ability to readily modify operations to manage for a wide range of water levels).

(3) Selection of an alternative that supports dynamic adaptation (e.g., the levee design footprint and foundation support a cost-effective, future retrofit offering a higher level of protection).

(4) Controlled and reinforced levee overtopping to minimize damages and support swift post-event recovery.

(5) A diverse planting scheme that thrives under a wide range of potential water level conditions, temperatures, etc.

(6) Robust design, meaning the project can continue to operate correctly across a wide range of operational conditions with minimal damage, alteration, or loss of functionality, and it fails gracefully outside of that range.

f. A project's and project area's capacity for resilience is a function of project purpose, physical characteristics, topography, socioeconomic constraints, community resilience and preparedness, and sensitivity to weather-related hazards, as well as the flexibility of the system to respond and adapt. Considerations include things like existing regulations and laws that might limit future response, limitations on local stakeholder actions and local interests, geomorphology, habitat type, adaptive capacity, and retreat space.

F–5. Cost-Benefit Analysis Considering Nonstationary Hydrometeorology.

a. If applied appropriately, CMIP-model-based simulations of future hydrometeorology can generate cost-benefit analysis (CBA) reflecting nonstationary conditions. CBA methods that incorporate future hydrometeorological conditions are project specific and must follow the guidelines presented for conducting a Tier 2 assessment. In general, USACE suggests a scenario-based approach to determine an alternative's ability to perform and its level of resilience under variable future conditions. Methodological choices applied to generate a nonstationary CBA require USACE IIR CoP leadership review and approval.

b. Many statistical techniques to define the probabilistic relationships of historical data also apply to future scenarios. Working with future simulations of hydrometeorology is challenging due to the wide range of future scenarios derived from different assumptions and models. This spread reflects the considerable cumulative uncertainty generated by each step of the hydrometeorological modeling chain.

(1) As a result of this considerable uncertainty, simulations of future hydrometeorology cannot represent an absolute probability that a given event will happen at a fixed time in the future.

(2) Each simulated scenario should be interpreted as an equally likely realization of future hydrometeorology.

(3) Model-based future realizations of hydrometeorological conditions are conditioned on assumptions involved in generating a given scenario. Statistical relationships should be independently generated for each scenario being considered.

c. For additional guidance on interpreting and applying CMIP-model-based information, see the resources available to support Tier 2 analysis on the IIR KMP site and consult the USACE IIR CoP leadership.

F–6. Life Cycle Cost Analysis Considering Nonstationary Hydrometeorology.

a. CMIP-model-based simulations of future of hydrometeorology can also generate life cycle design analysis for a range of future conditions. Proposing a method to conduct life cycle cost analysis that reflects nonstationary hydrometeorology must follow the guidelines for conducting a Tier 2 assessment and requires USACE IIR CoP leadership review and approval.

b. Comparing the life cycle costs of different project alternatives can justify adding resilience. Per ECB 2020-6, teams can include resilient features if they save on life cycle costs, including repair costs. Life cycle costs include the initial investment along with long-term management costs. Long-term management costs include the cost savings associated with avoiding future damages or downtime.

c. An option with a low initial cost to construct may not have the lowest long-term OMRR&R costs. OMRR&R costs may become significant if considerable maintenance and repair are necessary to maintain a minimum acceptable level of project performance in response to increases in hydrometeorological extremes throughout a project's service life.

F–7. Comprehensive Benefits of Resilience Features.

a. USACE's method to compute costs/benefits and lifecycle costs includes a discount rate, which presents a significant barrier to using these approaches to justify incorporating resilient features in project designs. Including resilient features adds up-front costs, while impacts driven by long-term shifts in hydrometeorology typically only begin later in a project's life cycle. Thus, benefits of features designed to be resilient to these impacts are significantly discounted when performing both CBA and life cycle cost analyses.

b. ER 1105-2-103, Policy for Conducting Civil Works Planning Studies, recognizes project benefits, including those associated with resilience features, that extend beyond maximizing net economic benefits. Additionally, a policy directive from the Assistant Secretary of the Army for Civil Works (ASA(CW) 2021) requires a more comprehensive approach to documenting project benefits. This directive supplements existing guidance by considering economic, environmental, and social benefits equally in project decision-making.

c. A comprehensive benefits-based approach allows the PDT to incrementally justify additional project features or alternatives by comprehensively evaluating benefits in terms of economic development (national and regional), environmental quality (EQ) (national and regional), and other social effects (OSEs). The objective is to connect the analysis to tangible, real-world impacts. Accounting for the social benefits of community resilience is specifically required by ER 1105-2-103.

d. Benefits can be characterized quantitatively, qualitatively, or by applying multiple method approaches (Hilleary and McCain 2024). The Institute for Water Resources (IWR) report, Analysis of Tradeoffs Approaches Applicable to USACE Civil Works Planning, offers guidelines for applying these methods. USACE project teams can use these multi-criterion collaborative approaches to analyze comprehensive benefits to inform decision making and select a recommended alternative (Hilleary and McCain 2024).

e. Approaches to qualitatively and quantitatively account for the benefits of resilience are evolving rapidly within USACE, among collaborating resource agencies, and within the civilian community. Specifying a methodology to characterize (either monetarily or otherwise) the comprehensive benefits and impacts associated with resilient features is outside the scope of this guidance. Developing such an approach should be led by the project economist in collaboration with the project manager, the IIR team member, and the rest of the PDT. Some general guidelines for preparing a comprehensive benefits analysis to incrementally justify resilient features are:

(1) Analysis should fully demonstrate why one alternative offers more resilience than another alternative.

(2) Analysis should lay out, in as much detail as is possible, how the project and any resilient features improve economic, environmental, and social benefits (e.g., community awareness, EQ, and economic development).

(3) Analysis should translate into constructive scales or metrics that can support alternative evaluation.

(4) As detailed in Appendix E, results of an LHC assessment characterize DWR risk. Unacceptable levels of DWR risk over a project's service life to the environment and/or communities can justify incrementally adding resilience features that may not be economically justifiable based on CBA or life cycle cost analysis alone.

(5) The relative cost of a feature or measure being added to increase resilience to future weather-related hazards and its effect on overall project costs should be considered. For instance, choosing to upsize a project feature (e.g., culvert size, rip rap rock size) may represent a relatively small incremental cost or change in the overall CBA while supporting project performance over its full service life under a wider range of future conditions. Improving project performance offers a higher degree of long-term community resilience and can be a significant OSE benefit.

(6) If the cost increase is substantial, a Tier 2 assessment may be required to justify added resilience more quantitatively and to directly support feature/measure design. A Tier 2 assessment requires USACE IIR CoP leadership review and approval.

(7) The overall benefits of a feature that improves resilience to nonstationary weather-related hazards in the long term can be increased by recognizing near-term additional benefits.

(a) For example, an NBS like applying woody debris can reduce erosivity caused by changes in extreme precipitation in the long term, while also offering immediate EQ and OSE benefits in the near term.

(b) Another example is a levee system with a robust foundation that accommodates near-term emergency management actions (e.g., temporary levee raises) and supports long-term resilient features (e.g., permanent levee lifts).

F–8. Resilience Feature/Measures: Options for Inland Applications.

a. The DWR risk assessment framework (defined in Appendix E) involves evaluating risk associated with the impacts of environmental triggers and formulating measures and features that provide resilience against the harms associated with changing hydrometeorology.

b. The PDT has the option of controlling, accepting/monitoring, avoiding, transferring, and/or burning down (OUSD(R&E) 2023) risks deemed unacceptable. The project purpose should be considered, as well as the level of development in the project area. For some projects, taking future action via dynamic adaptation as changes are observed is most appropriate. In areas where impacts are already being experienced, or cumulative or system impacts to an area have the potential to be large and catastrophic, a more anticipatory approach for at least the most vulnerable portions of the system should be considered.

c. Examples of actions that can control, avoid and burn down (OUSD(R&E) 2023) risk are presented in Table F–1, Table F–2, and Table F–3. These approaches can be independent, concurrent, or sequential to reduce the potential for future weather-related impacts.

(1) Controlling DWR risk involves minimizing potential impacts by reducing the likelihood and/or consequence of the risk to the lowest practical level (OUSD(R&E) 2023).

(2) At times, the PDT recognizes weather-related triggers that may materialize but chooses to accept the risks due to several factors, such as level of uncertainty in characterizing future changes in an environmental trigger or minimal impacts to project or system performance. Regardless, the PDT still needs to understand and document weather-related triggers, hazards, harms, and DWR risk and develop a monitoring plan to track shifts in weather-related risk in the future. Depending on USACE's authority, either USACE and/or the NFS monitors the risk to inform future needs for reevaluation.

(3) The most effective resilience measure, in many cases, may be to manage risk by avoiding a current or future harm. In practice, USACE avoids risks by adopting conservative design standards to avoid current and future risk and adhering to strict operational protocols to prevent conditions from leading to loss of performance or failure. For an aquatic ecosystem restoration project, this may involve transitioning from preserving current ecosystem composition to directing change to an alternate, but more sustainable state (Lynch et al. 2021).

(4) Transferring risk reassigns risk to other entities for future consideration and management. Transferring risk could entail the transfer of a project to an NFS while communicating residual risk and committing to inspections of completed works by USACE to support the NFS's continued operation and maintenance of the project. Risks that are transferred should already be managed to an acceptable level. Residual risk should be fully documented, along with any potential environmental triggers to monitor for evidence of change over time. Documentation should include recommended actions if those triggers materialize in the future.

(5) Risk burn-down (OUSD(R&E) 2023) consists of developing a phased prescriptive plan to manage moderate and high risks, especially hazards that may not materialize until well into the life of the project. Dynamic adaptation (also referenced as adaptive management), a specific risk burn-down approach, manages risks driven by nonstationary processes in support of resilience. A dynamic adaptation plan recognizes future risk tied to specific environmental thresholds that can be monitored for and can trigger a pre-planned adaptation measure. This plan should recognize lead times for the planned project adaptations. Dynamic adaptation is discussed in more depth in section F–9.

d. EP 1100-2-1 includes additional options that can add resilience, as well as steps to define dynamic adaptation strategies (i.e., EP 1100-2-1 Chapter 3). Although the EP was developed for coastal environments, its resilience and adaptation approaches are relevant to both coastal and inland applications.

Table F–1
Example of resilience features and measures for inland applications, category I: controlling risk

Approach	Examples
Modify infrastructure – increased project performance	• Upgrade and strengthen existing structures • Floodwall/levee raise • More robust/heightened forms of surface hardening (e.g., higher top of rip rap elevation and/or larger rip rap size) • Add capacity to existing dam • Raise structures to increase clearance
Modify infrastructure – increased capacity	• Upgrade drainage systems • Increase stormwater pump and conveyance capacity
Design redundancy (avoids single failure points)	• Include secondary structures • Add water savings basin (e.g., navigational lock design)
Apply natural and NBS (i.e., leverage natural processes)	• Wetland restoration • Constructing earth berms or woody debris dams • Diverse planting schemes that offer both erosion control and are resilient to a wide range of environmental conditions.
Design Infrastructure to rapidly recovery from weather-related stressors	• Wet and dry floodproofing to offer added resilience to extreme events
Harden embankments and streambanks	• Armoring and retaining walls
Watershed restoration and repair	• Stream restoration and floodplain enhancement (e.g., creating a multipurpose detention pond and low floodplain bench areas for flood distribution)
Weather-related hazard preparedness	• Hazard mapping • Emergency management plans • Drought contingency plans • Evacuation plans • Early warning systems
Water resources management	• Modifying the water control manual • Systemwide dispersed streamflow controls and debris controls • Management actions to maintain existing/historic ecosystem structures • Increase maintenance and dredging • Sediment management

Table F–2
Example of resilience features and measures for inland applications, category II: avoiding risk

Approach	Examples
Relocation/floodplain policy and management	• Nonstructural relocation to improve life safety and reduce damages • Relocating infrastructure outside of the floodplain or coastal impact area • Modifying building codes • Building setbacks

Approach	Examples
Future-informed site selection	• Placement at an elevation/location outside of future floodplain
Managed retreat/accept transformation	• Allow channel migration • Allow land cover transformation • Allow habitat/ecosystem conversion • Changes to vessel design (material, weight, etc.)
Direct transformation	• Ecosystem restoration plantings (e.g., flood/heat tolerant plants) to support a future, desired vegetative community (Lynch et al. 2021) • Facilitate habitat/ecosystem conversion

Table F–3
Example of resilience features and measures for inland applications, category III: risk burn-down (OUSD (R&E) 2023)

Approach	Examples
Adaptation	• Purchasing additional real estate to facilitate future levee base expansion • Building a more robust flood wall or levee foundation to support future raises • Sizing a pump house and associated equipment to enable a future increase to pump size and capacity

F–9. Dynamic Adaptation to Changing Conditions

a. If adding resilient features or measures during plan formulation is not necessary or justifiable, changing conditions, improved simulations of future conditions, and advancements in engineering may justify adding resilience measures in the future (FHWA 2017). An effective long-term resilience strategy incorporates periodic reassessment, enabling adaptive actions in response to changes in hydrometeorological conditions. Effective strategies include a post-construction monitoring plan that tracks long-term project performance alongside observed hydrometeorological trends. Monitoring helps identify adaptations needed to maintain long-term project and system performance.

b. Dynamic adaptation (also referenced as adaptive management) to changing conditions is a systematic, iterative process for continually improving management policies and practices by learning from the outcomes of previously implemented strategies. This approach can effectively manage uncertainty and reduce the risk of overspending. Dynamic adaptation allows flexibility in decision-making, enabling water resource managers to adjust actions based on new information or changing conditions over time.

c. Identifying and evaluating measures that offer resilience to DWR risk and developing a dynamic adaptation strategy to implement these measures should be initiated during alternative development and continue through the project delivery process.

d. Dynamic adaptation reduces uncertainty over time by systematically testing hypotheses, monitoring outcomes, and using the results to inform future actions, enhancing the resilience and effectiveness of projects. Any of the strategies in section F–8 may include an adaptive element, meaning they may be implemented stepwise over time (FHWA 2017).

e. As illustrated in Figure F–1, a dynamic adaptation plan should include a monitoring plan. The monitoring plan establishes the data to collect (e.g., water levels, flows) and the locations and time intervals (e.g., during high flows, daily, monthly) to collect it. The dynamic adaptation plan should indicate thresholds or tipping points corresponding to decision points (triggers) where preemptive intervention is needed to prevent project nonperformance. Variables tied to RHFs and project performance should be monitored throughout a project's service life, and the need to adapt the project should be revisited as conditions change.

f. A threshold or a tipping point refers to a critical point when stability and/or performance begins to decline rapidly and impacts increase dramatically. Action should be taken at a trigger point with enough lead time before exceeding the threshold/tipping point to enable a shift in management practice and/or planning, design, and construction (see Figure F–1). By carefully selecting thresholds/tipping points, triggers, and lead times, a dynamic adaptation plan avoids a situation where inaction results in the inability to perform effectively or lost opportunities to prevent unmanageable/irreversible risk in the future (Lynch et al. 2021).

g. When developing an adaptation strategy for a USACE CW project, collaboration with the NFS and regional resource agencies is imperative, because after construction, the project is likely to be turned over to the NFS for operation and maintenance. In many cases, fully implementing an adaptation plan across a project's service life is beyond USACE's responsibility and authority. In such cases, the NFS implements these plans.

h. Where within USACE authority, the PDT should monitor project performance and establish decision points to trigger reevaluation. Reevaluation can be accomplished through limited or general reevaluation studies.

(1) A monitoring plan is required for all USACE-operated and -maintained infrastructure where nonperformance has the potential to increase life safety risk (e.g., loss of life), property damage, and ecosystem degradation or destruction. For such USACE projects, the required OMRR&R Plan should monitor for increases in DWR risk.

(2) For ecosystem restoration projects, the required monitoring and adaptive management plan should monitor for changing hydrometeorological conditions. For these projects, USACE is authorized to monitor project performance for a limited period of the project service life.

i. Different points in a project's planning horizon should be considered throughout project evaluation to help identify the degree of urgency associated with potential future actions, as well as the expected resilience or robustness of selected alternatives. EP 1100-2-1 recommends evaluating impacts and adaptation strategies for periods of 20 years (current and near term) (CEMA and CNRA 2012), 50 years (midterm, centered around 2050) and 100 years (long term, centered around 2085) from completion of initial construction. This is consistent with the epochs suggested in section F–4.

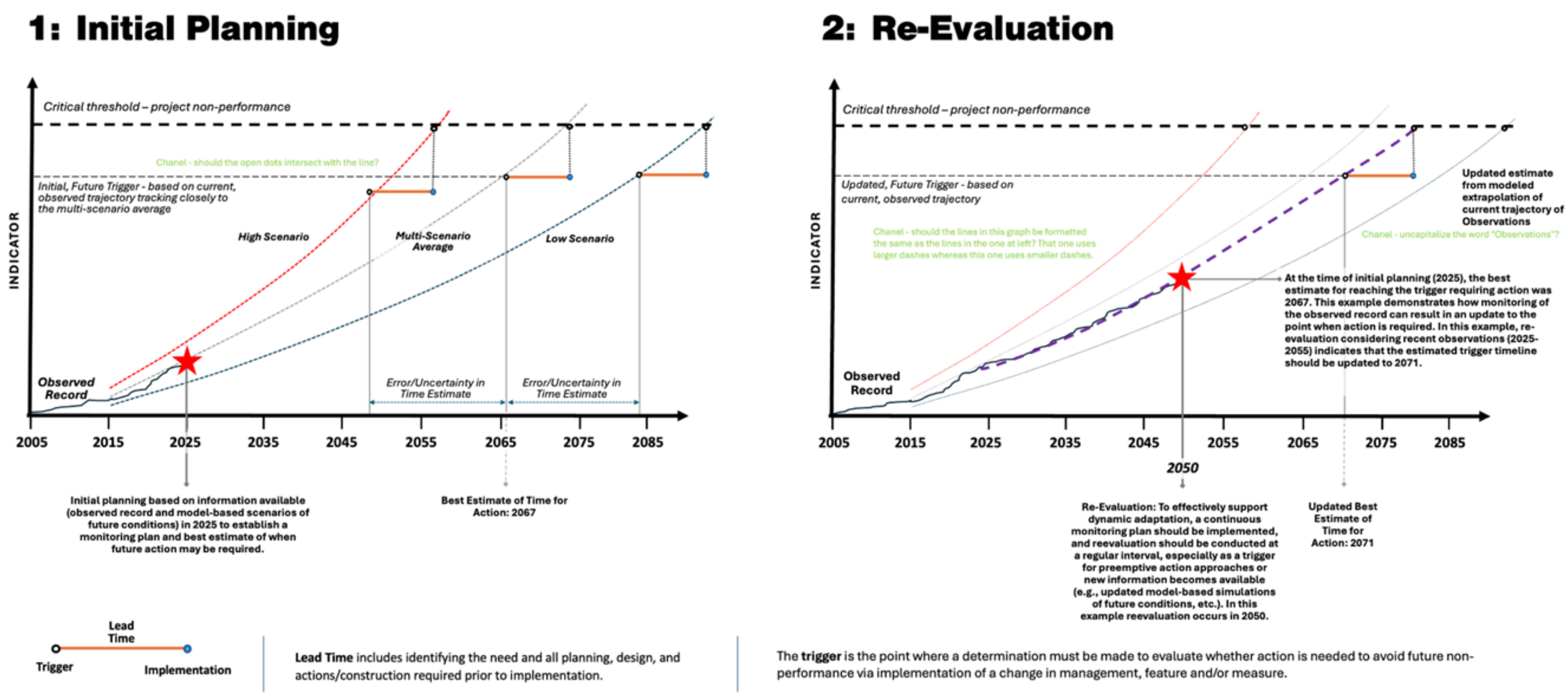

Figure F–1. Components of a dynamic adaptation strategy

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Appendix G
Tier 2 Assessment Scoping and IIR CoP Approval Process

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G–1. Purpose. This appendix provides an overview of the steps required to scope a Tier 2 analysis and receive IIR CoP approval to use an approach to modeling future, model-based scenarios of hydrometeorology generated, evaluated, and/or fine-tuned for a defined area/region and/or a specific application. See Figure G–1 for a visual representation of the process.

G–2. Confirm Resource Availability.

a. The first step verifies that the scale of the project supports an in-depth Tier 2 analysis. This verification includes confirming resource availability (including schedule, expertise, funds, etc.) required for an in-depth analysis and the associated required review (e.g., DQC and ATR).

b. USACE management staff, project managers, planners, and stakeholders/external partners associated with the project should verify support for an analysis using future, model-based simulations of hydrometeorology specific to the project area and purpose. The Tier 2 scope should document the availability of resources and the support of the district(s), PDT leadership, and stakeholders/project partners (if applicable).

G–3. Define the Assessment Context. The second step determines project performance objectives and the sensitivity of watershed components, project features, and measures to changing hydrometeorological conditions. Based on critical project elements (e.g., wetland habitat), this step identifies project-specific hydrometeorological variables (e.g., high-water duration, peak flow, 3-day maximum precipitation) to assess vulnerabilities to weather-related hazards. This step establishes the context to consider nonstationary hydrometeorological conditions, which are summarized in the Tier 2 scope.

G–4. Define the Scope of Work.

a. Prior to dedicating substantial resources to executing a Tier 2, in-depth analysis, the PDT must generate a technical scope of work detailing the objectives of the analysis, how to conduct it, and how to apply the results. The scope of work requires consultation, review, and approval from the IIR CoP leadership prior to starting analysis. The project review plan should document the Tier 2 scope review. The PDT is strongly recommended to consult with IIR CoP leadership throughout the scoping process. The scope of work should describe the resources available and assessment context as outlined in sections G–1 and G–2.

b. The tools and resources to complete a Tier 1 LHC assessment should sufficiently inform the Tier 2 scoping process (see Appendix C). Using the IIR tools and resources, a semi-quantitative, preliminary DWR risk assessment must be completed within the scope to demonstrate the impacts of foreseeable future shifts in weather-related hazards on the project performance objectives.

c. An in-depth analysis is only performed if changing hydrometeorological conditions present a significant risk to the resilience or performance of the project. The results of an in-depth analysis must reduce vulnerabilities or enhance the resilience of the project to future weather-related threats and impacts, and these decision criteria must be described in the scope.

d. The scope must include an inventory of and briefly describe relevant data and model products that are available to support analysis. The inventory may include observed, historic hydrometeorological time-series data, CMIP-model-based downscaled meteorology, simulations of future streamflow response, and available hydrologic models configured to support long-term simulations of runoff response.

e. Based on the inventory of relevant data and model products, the scope must describe the workflow for assessing scenarios that represent future hydrometeorology. Proposed tools, models, and datasets must be fit-for-purpose, meaning the modeling tools and methods proposed align with the project purpose and decision(s) being made. The scope must include assessing the reliability of downscaled modeled hydrometeorology derived from coarser resolution CMIP models for a specific application.

f. The scope must outline how analysis results are evaluated and how to incorporate the conclusions into the decision-making process. The scope must include how to interpret the analysis endpoints and apply them to address project objectives.

G–5. IIR CoP Scope Approval and Vertical Team Alignment. The PDT works with the vertical team to receive concurrence to proceed with the additional analysis required by a Tier 2 evaluation, considering impacts to overall project schedule and budget. The PDT submits the scope to the USACE IIR CoP, and the CoP leadership reviews the submission and indicates whether a project-area-specific in-depth analysis can and should be performed using simulations of future hydrometeorology. Once the scope has been reviewed by the USACE IIR CoP and the coordination and approval are documented, the proposed analysis can support planning and engineering decisions. A sample signoff form is available on the IIR CoP's KMP site.

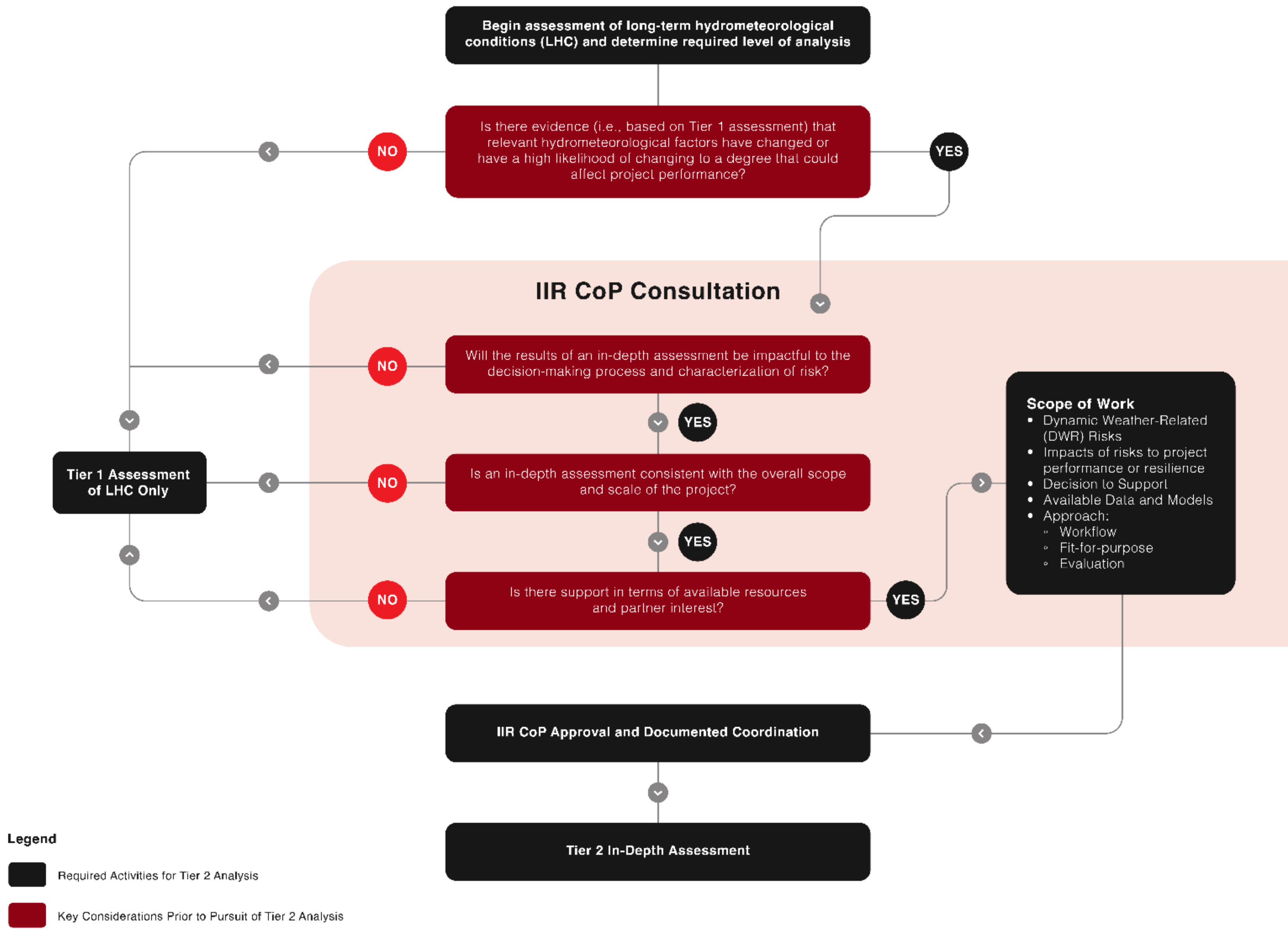

Figure G–1. Stepwise description of scoping and approval process

Glossary of Terms

Abbreviations

ACCCNRS	Advisory Committee on Climate Change and Natural. Resource Science
ACF	Autocorrelation Function
AEP	Annual Exceedance Probability
AMM	Alternative Milestone Meeting
AR(1) Coeff.	Lag 1 Autoregressive Correlation Coefficient
AR(1) Model	Autoregressive Model Order One
ASA	Assistant Secretary of the Army
ASA(CW)	Office of the Assistant Secretary of the Army for Civil Works
ATR	Agency Technical Review
bcp	Bayesian Change Point
CBA	Cost Benefit Analysis
CEMA	California Emergency Management Agency
CERCAP	U.S. Army Corps of Engineers Reviewer Certification and Access Program
cfs	Cubic Feet per Second
CHAT	Comprehensive Hydrology Assessment Tool
CMIP	Coupled Model Intercomparison Project
CMIP5	Coupled Model Intercomparison Project Phase 5
CMIP6	Coupled Model Intercomparison Project Phase 6
CNRA	California Natural Resources Agency
CONUS	Continental United States
CoP	Community of Practice
cpm	Change Point Model
CVM	Command Validation Milestone
CW	Civil Works
CWVAT	Civil Works Vulnerability Assessment Tool
DQC	District Quality Control
DWR	Dynamic Weather-Related
ECB	Engineering and Construction Bulletin
ecp	Energy-Based Divisive Change Point
EDA	Exploratory Data Analysis

EFP	Empirical Fluctuation Process
EM	Engineer Manual
ENSO	El Niño Southern Oscillation
EP	Engineer Pamphlet
EQ	Environmental Quality
ER	Engineer Regulation
ETL	Engineer Technical Letter
FCSA	Feasibility Cost Sharing Agreement
FHWA	Federal Highway Administration
FWOP	Future Without Project
H&H	Hydrologic and Hydraulic
HH&C	Hydrology, Hydraulics, and Coastal
HUC	Hydrologic Unit Code
IDW	Inverse Distance Weighting
IIR	Infrastructure and Installation Resilience
IWR	Institute for Water Resources
KMP	Knowledge Management Portal
LHC	Long-Term Hydrometeorological Condition
LPP	Locally Preferred Plan
MK	Mann-Kendall
MOVE	Maintenance of Variance Extension
MSC	Major Subordinate Command
NASEM	National Academies of Science, Engineering, and Medicine
NAVD88	North American Vertical Datum of 1988
NBS	Nature-Based Solution
NCA	National Climate Assessment
NEPA	National Environmental Policy Act
NFS	Nonfederal Sponsor
NOAA	National Oceanic and Atmospheric Administration
NSD	Nonstationarity Detection
NWS	National Weather Service
OCONUS	Outside the Continental United States
ODASD	Office of the Deputy Assistant Secretary of Defense

OLS	Ordinary Least Squares
OMRR&R	Operation, Maintenance, Repair, Rehabilitation, and Replacement
OSE	Other Social Effects
OUSD(R&E)	Office of the Under Secretary of Defense for Research and Engineering
OWP	Office of Water Prediction
PAR	Population at Risk
PARA	Prepare, Absorb, Recover, and Adapt
PDT	Project Delivery Team
PED	Pre-Construction Engineering and Design
PFM	Potential Failure Mode
P.L.	Public Law
P&LC	Policy and Legal Compliance
PMP	Probable Maximum Precipitation
POOC	Problems, Opportunities, Objectives, and Constraints
RAL	Library of Resilience Assessments
RCP	Representative Concentration Pathway
RHF	Relevant Hydrometeorological Factor
RIDM	Risk-Informed Decision Making
RSLC	Relative Sea Level Change
SLC	Sea Level Change
SMART	Specific, Measurable, Attainable, Risk-Informed, Timely
SQ-MK	Sequential Mann-Kendall
SSP	Shared Socioeconomic Pathway
SWE	Snow Water Equivalent
THH	Trigger, Hazard, and Harm
TSP	Tentatively Selected Plan
TSS	Total Suspended Solids
TST	Time Series Toolbox
USACE	U.S. Army Corps of Engineers
USGS	United States Geological Survey
VTAM	Vertical Team Alignment Memorandum
WGCM	Working Group on Coupled Modelling
W/m^2	Watts per Square Meter

WRRDA	Water Resources Reform Development Act
WSEL	Water Surface Elevation

Terms

Abrupt Statistical Change
A change at a single point in the record that separates the period of record into two subsets of data that have different means, variances, and/or parent distributions. A record can have multiple abrupt changes separating it into several subsets of data.

Absorb
To receive a stress or endure change with minimal damage and without loss of normal functionality or project performance.

Actionable Science
Science that provides data, analyses, or tools that can support decisions regarding risk management. It is ideally co-produced by scientists and decision-makers and creates rigorous and accessible products to meet the needs of stakeholders (ACCCNRS 2015).

Adapt/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 a natural hazard. Capacity may include financial, institutional, educational, cultural, or any other structure that affects an entity's ability to act.

Adaptive Management
See Dynamic Adaptation

Aleatory Uncertainty
Natural variability that results from inherent variability in the physical world. It arises from factors such as random processes and natural unpredictable variation.

Attribution
Ascribing a change in a hydrometeorological record to a specific cause (e.g., regulation, significant irrigation, or land use change upstream of a stream gage).

Autocorrelation
See Serial Correction.

Bayesian Change Point (bcp)
A parametric change point model developed by Barry and Hartigan (1993) that assumes unknown partitions within a sequence of values that break the dataset into groupings of values with a relatively constant mean. In contrast to frequentist procedures for conducting change point analysis that output the specific locations of change points, this method characterizes the probability of a change point at each data point in the series in terms of a probability distribution.

Bayesian Statistics
An approach that expresses results in terms of probability distributions, in contrast to a frequentist approach presenting conclusions as frequencies. Bayesian statistics is based on the Bayesian interpretation of probability, where probability expresses a degree of belief rather than a frequency of occurrence.

Bias-Correction
Adjusting hydrometeorological model outputs to account for systematic errors.

Binary Segmentation
Repeatedly dividing a dataset into two sub-series of data until the desired result is achieved. In this specific context, this consists of dividing the period of record until stationary subsets were identified.

Binary Tree
Data structure where a node has at most two branches/children.

Boundary Condition
A time series of data that describes the behavior of important model variables at the model extents. Mathematically, these specify the loading for a particular solution to a set of partial differential equations.

Box-Cox Transform
A family of transforms that can transform non-normal datasets into a normal shape. This transform depends on an exponent, lambda (λ), which varies from -5 to 5. Lambda is optimized to best approximate a normal distribution. A power log transformation is applied for nonzero values of λ; the function converges to a log transformation when λ equals zero.

Breakpoint
A point identified when regression model errors fall outside of expected variance bounds.

Breakpoint Analysis
Analysis that determines structural breaks or breakpoints by assessing deviations in an OLS linear regression model.

Business Line
In this context, USACE activities related to the authorized purposes of a project or operations. In relation to the CWVAT, these include flood risk management, coastal storm risk management, navigation, aquatic ecosystem restoration, hydropower, recreation, water supply, regulatory, and emergency management.

Change Point Model (cpm)
A model based on a framework to detect statistically significant changes in the overall distributional properties, mean or variance within a univariate series. Applying the CPM requires choosing one of the following nonparametric, two-sample hypothesis tests: Mann-Whitney, Mood, LePage, Kolmogorov-Smirnov, or Cramer-von-Mises statistics.

Change Point Test/Model
A statistical test to determine the presence of a statistically significant change in the data's mean, variance/scale, or distribution.

Community Resilience

20. **The manifestation of the resilience of the built, natural, and social systems that make up the community. A community is a unified group of people who share goals, values, or purposes. It generally functions under the authority of a specific governance structure and seeks to strengthen their resilience by working together with numerous partners. A community is made up of many systems, which can be interconnected or independent, that could be leveraged to increase community resilience.**

Comprehensive Benefits
Benefits measured in various units, typically using a multi-method approach with both qualitative and quantitative techniques in a collaborative environment. USACE PDTs are required to "analyze benefits in total and equally across a full array of benefits categories" (ASA(CW) 2021) to inform decision-making and select a recommended plan. Benefit categories include economic (national and regional), environmental (national and regional), and other social considerations that are valued by the Federal Government, nonfederal sponsor, public, and interested stakeholders. Teams analyze and select a plan to maximize net comprehensive benefits.

Confidence Limits
Computed values on both sides of an estimate of a parameter or quantile that show for a specified probability the range in which the true value of the parameter or quantile lies (England et al. 2019).

Consequence
The harm that results from a single occurrence of a hazard. Consequences are measured in terms of metrics such as economic damage, acreage of habitat lost, value of crops damaged, and lives lost.

Coupled Model Intercomparison Project (CMIP)
A collaborative framework that improves knowledge of changing hydrometeorological conditions by developing and reviewing earth system models. The CMIP initiative was started in 1995 by the Working Group on Coupled Modelling. The project is being carried out in phases and encourages model improvements and assessments of future hydrometeorology by making multi-model output publicly available in an accessible format.

Cramer-von-Mises Change Point Test
A nonparametric statistical test of whether two samples can be assumed to have been drawn from the same statistical distribution based on the difference between the integrals of their cumulative distribution functions (CDFs). It can detect abrupt changes in the overall statistical properties of a dataset (detects distributional changes).

Critical Threshold (also Tipping Point)
For infrastructure, the structural or operational limit beyond which function and/or project performance is impaired or lost. For example, the height of a levee intended to provide flood risk management is a critical threshold. The term can apply 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. Downscaling can be either statistical or dynamical (regional model).

Dry Floodproofing
Placing permanent, deployable, and/or temporary mitigation measures to prevent intrusion of flood waters into a structure.

Dynamic Adaptation (also Adaptive Management)
An approach to resource management that emphasizes learning from past management decisions where knowledge was incomplete, and when, despite inherent uncertainty, managers and policymakers had to act and must act again. Unlike a traditional trial-and-error approach, dynamic adaptation has explicit structure. This structure defines objectives, identifies alternative management measures and/or hypotheses of causation, monitors outcomes, and the identifies the procedures for evaluating these outcomes. Dynamic adaptation is iterative and reduces uncertainty, builds knowledge, and improves management over time in a goal-oriented and structured process.

Ecosystem Resilience
The ability of an ecosystem to maintain its structure and function under external stress, including changing hydrometeorological conditions.

Energy-Based Divisive Change Point (ecp) Method
A framework to detect change points in hydrometeorological data. This method makes as few assumptions as possible to detect multiple change points and any type of distributional changes. The test performs nonparametric change point analysis of both univariate and multivariate time series.

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

Epistemic Uncertainty (also Knowledge Uncertainty)
A state when some information could theoretically exist but is unknown at present for any given reason. It arises from situations such as an incomplete understanding of a system, an incomplete theory, modeling limitations, or data limitations.

Epoch
A period of time.

Equi-Percentile Method
A method to estimate flow where a more complete flow record collected at one location fills in or extends the record at a target location with data gaps or a shorter record. Flow gaps are approximated by calculating the flow percentile relationships (i.e., monthly flow-duration curves) at the two locations and using the percentile associated with a given flow at the more complete record location to estimate the equivalent percentile flow at the target site.

Exposure
The nature and degree to which a system is impacted by significant variations or changes in hydrometeorological extremes.

Extreme Event
Occurrences of unusually severe episodic or long-term average weather conditions that can cause devastating impacts to communities and agricultural and natural ecosystems. Episodic weather-related extreme events are often short-lived and include heat waves, freezes, heavy downpours, tornadoes, tropical cyclones, and floods. In addition to episodic events, extreme events can persist for longer periods or emerge from the accumulation of weather that persists over a longer period. 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.

Field Significance
The simultaneous evaluation of statistical tests for multiple time series collected at different locations to establish spatial correlation. Identifying coextensive change points is often useful in evaluating for evidence of change to determine whether results exhibit spatial and temporal consistency. The geographic regions to evaluate for coextensive evidence of nonstationarity should be carefully selected.

Future Without Project (FWOP) Conditions
Project scenario that establishes baseline future conditions in the absence of federal action that provides the benchmark against which alternative plans are formulated and impacts are assessed.

Gaussian (Normal) Distribution
A commonly used, symmetric distribution characterized by a unimodal, bell-shaped density curve. The sample mean (μ, first moment) defines where the peak of the density curve occurs, the standard deviation (σ, second moment) defines the width of the bell-shaped curve.

Harm
See Consequence.

Hazard
A potential source of harm; a thing or action that can cause adverse effects to a valued asset. This is not limited to the notion of a natural hazard; anything that is a potential source of harm to a valued asset (human, animal, natural, economic, social, environmental).

Homogeneity
In this context, coming from the same statistical population.

Impact
The positive or negative effect on the natural or built environments caused by exposure to a hazard (such as flooding). Weather-related hazards can have multiple impacts on people and communities, infrastructure, and the services it provides, as well as on ecosystems and natural resources. Impact combines exposure and sensitivity (see definitions).

Imputation Technique
A process that can be applied to estimate missing data.

Inland Hydrologic Process
A process that drives and impacts terrestrial runoff, including overland precipitation and lacustrine and riverine hydrologic responses.

Inverse Distance Weighting
An interpolation method that is frequently applied to estimate missing meteorological data. It weights observations made at nearby sites by distance from the location where missing data is approximated. Gages closer to the location of interest are given more weight.

Kolmogorov-Smirnov Change Point Test
A nonparametric statistical test that detects abrupt changes in the overall statistical properties of a dataset (distributional changes).

LePage Change Point Test
A nonparametric statistical test that detects abrupt changes in the overall statistical properties of a dataset (detects distributional changes).

Life Cycle Costs
The initial project investment and costs for operation, maintenance, repair, rehabilitation, and replacement. Life cycle costs should calculate the present worth based on constant dollar analysis and use an appropriate discount rate for future costs. Life cycle costs are evaluated over the expected project service life.

Life Cycle Design
A design process that selects project elements by evaluating and considering both life cycle costs and the long-term performance of materials, components, and systems. Life cycle design safeguards project integrity throughout the project’s service life.

Locally Preferred Plan (LPP)
Plans requested by the nonfederal sponsor that deviate from the federal plan.

Lombard Model
A nonparametric statistical test that detects change points within a hydrometeorological dataset. The Lombard applies binary segmentation to test for the presence of a change point in each sub-series of data until no more statistically significant step changes are detected.

Long-Term Persistence
The occurrence of similar hydrometeorology (e.g., wet cycles, droughts) in clustered oscillations over a wide range of temporal scales.

Maintenance of Variance Extension (MOVE)
The MOVE techniques (i.e., MOVE.1, MOVE.2, and MOVE.3) extend streamflow records by estimating missing data at one site using data collected at a nearby, hydrologically similar location with high cross-correlation that has a more complete record. The MOVE technique functions similarly to a linear regression equation but produces a nearly unbiased estimate of mean and variance.

Mann-Kendall Trend Test
A nonparametric measure of trend. The test calculates the Kendall rank correlation coefficient, or Kendall's tau, a value between −1 and 1, where values close to −1 suggest monotonically decreasing series and values close to +1 suggest monotonically increasing series.

Mann-Whitney Change Point Test
A nonparametric statistical test that detects abrupt changes in the mean of a dataset.

Mean
The center of mass of a given probability distribution.

Moment
A quantitative measure related to the shape of a function like a probability distribution. The nth moment of a function about a value c is equal to the expected value of the distance between x and c raised to the n power. The first three sample moments are the mean (μ), standard deviation (σ), and skewness coefficient (γ). Mean is a raw moment (i.e., $c = 0$), variance is a central moment (i.e., c = mean), and higher moments like skew and kurtosis are standardized central moments.

Monotonic Trend
A function that always maintains the same order between the independent (e.g., time) and dependent (e.g., peak streamflow) variables. Monotonic trends may be either monotonically non-increasing or monotonically non-decreasing.

Monte Carlo Simulation
A simulation in which random statistical sampling techniques determine estimates for unknown values. A Monte Carlo algorithm is a statistical procedure that determines the occurrence of probabilistic events or values of probabilistic variables for deterministic models (i.e., making a random draw).

Mood Change Point Test
A two-sample nonparametric statistical test that detects changes in the scale of a dataset. When applied within the Lombard framework, the mood change point test can detect both abrupt and smooth changes in sample scale. When applied within the cpm framework, the mood change point test detects abrupt changes in sample scale.

National Climate Assessment
A periodic summary report by the U.S. Global Change Research Program that collects, integrates, and assesses climate-driven 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 hydrometeorological parameters due to nonhuman causes. Natural variability has two types: external and internal. External variability is attributed to forces outside of the earth's system (e.g., solar variability, volcanic eruptions, earth's orbital patterns), which represent longer term variations in average weather patterns (decades to century scale). Internal variability includes interactions of the oceans, land surface, and atmosphere, whose timescales are shorter (monthly, annual, or decadal).

Nature-Based Solutions (NBS)
Actions to protect, sustainably manage, or restore naturally functioning or modified ecosystems to address societal challenges while simultaneously providing benefits for people and the environment. NBSs may include beaches, dunes, wetlands, fluvial floodplains, and oyster reefs, among other solutions. A nature-based feature is a feature created by human design, engineering, and construction that works in concert with natural processes or mimics as closely as possible conditions that would occur absent of human changes to the landscape or hydrology to achieve study objectives.

Nonparametric Statistics
Statistical analysis that minimizes reliance on assumptions about the data's underlying distribution.

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

Normal (Gaussian) Distribution
See Gaussian Distribution.

Null Hypothesis
The hypothesis that the applied test is seeking to reject. For example, in change point analysis, the null hypothesis is that the dataset is statistically homogenous.

Outlier
Extreme values that are exceedingly low or high compared to the distributional properties of most of the data.

Overdispersion
In statistics, the presence of a high degree of variability in the dataset. The variance of the dataset is greater than expected for an assumed statistical distribution.

Parametric Statistics
Statistics that assume that the data being analyzed come from a parent population that can be characterized by a known probability distribution (e.g., normal distribution) and its associated parameters (e.g., mean, standard deviation, skew).

Periodicity
The attribute of patterns repeating at regular intervals throughout the dataset. For instance, in daily precipitation datasets seasonal shift in rainfall patterns represent a periodic signal.

Pettitt Change Point Test
A nonparametric statistical test that detects abrupt changes in the mean of a hydrometeorological dataset. It is based on the Mann-Whitney test, and it tests whether two samples come from the same population.

Population
The entire set of data from which a sample is taken or collected. For example, the total number of past, present, and future floods at a location on a river is the population of floods for that location, even if the floods are not measured or recorded.

Posterior Probability
The end result of a Bayesian statistical simulation representing the likelihood of the event in question given past and current information about its occurrence.

Prepare
To plan, organize, equip, train, and exercise to build, apply, and sustain the capabilities to prevent, protect against, ameliorate the effects of, respond to, and recover from damages to life, health, property, livelihoods, ecosystems, and national security.

Pre-Whitening
A technique to reduce the degree of serial correlation within a dataset.

Project Delivery Team (PDT)
A multidisciplinary group assembled to develop the feasibility study. The group generally includes staff from a district and other USACE offices, as well as the project sponsor’s staff.

Project Performance
A project’s quality and effectiveness in achieving stated objectives (e.g., flood risk reduction, maintenance of navigable waterways, aquatic ecosystem restoration) and delivering value to stakeholders. Performance is typically evaluated based on factors such as reliability, capability, efficiency, and maintainability.

Project Resilience
A feature, operation, or plan built into an individual project (e.g., levee, lock, dam, ecosystem design, hospital, powerplant, bridge) that increases the project's capacity to anticipate, prepare for, adapt, and recover from a hazard; the resilience of an individual project, independent of other projects in the vicinity.

Project Service Life
The length of time a project remains in use providing its intended function. This often exceeds the period used for economic analysis of project benefits and costs. Major CW projects can have an indefinite service life. Several cycles of component rehabilitation or replacement may be required to maintain the project's service life.

Radiative Forcing Scenario or Pathway
The plausible net future changes in the energy balance of the earth-atmosphere system. Modeled future trajectories of radiative forcing are based on projected political, social, demographic, technological, and other changes (called storylines). Typically, storylines range from low radiative forcings (e.g., SSP1, RCP 1.6, 2.6) to high radiative forcings (e.g., SSP5, RCP 8.5).

Recommended Plan
The final alternative selected for implementation. It reflects the result of detailed analysis, stakeholder input, and leadership endorsement. This plan is included in the Chief's Report and forms the basis for seeking Congressional authorization and funding. The TSP is the draft plan proposed for feedback, while the recommended plan is the refined and final proposal that USACE puts forward for approval and implementation.

Recover
To return to the previous state of functionality following a disruption or when conditions have changed.

Relative Sea Level Change (RSLC)
A local change in the level of the ocean relative to the land, which might be due to ocean rise and/or land level subsidence. Sea level is measured by a tide gage with respect to the land on which it is situated.

Relevant Hydrometeorological Factor (RHF)
A hydrometeorological process exacerbating or ameliorating watershed conditions and/or identified problems and opportunities. RHFs are categories of hydrometeorological variables (e.g., temperature, precipitation, streamflow) or processes (e.g., snowmelt, wildfire) that reflect potential changes to hydrology.

Representative Concentration Pathway (RCP)
Trajectories representing different factors in the earth's atmosphere that might occur in the future that can impact radiative forcings. RCPs (originally RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5) are labeled after a possible range of increased radiative forcing values in the year 2100 (2.6, 4.5, 6, and 8.5 watts per square meter [W/m^2], respectively).

Residual Risk
The risk that remains after a project is implemented. Residual risk accounts for the consequences of a trigger, hazard, and harm materializing, as well as considering project performance.

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

Risk
The combination of the magnitude of the potential consequence(s) of impact(s) and the likelihood that the consequence(s) occurs.

Risk Assessment
A systematic approach for describing the nature of the risk, including the likelihood and severity of consequences. Risk assessments can be qualitative, semi-quantitative, or quantitative. Risk assessment includes explicit acknowledgment of the uncertainties in risk.

Risk Burn-Down
A risk mitigation strategy consisting of time-phased activities tied to success criteria that can reduce risk to an acceptable level (OUSD(R&E) 2023).

Risk Communication
A two-way exchange of information between risk assessors and those who use the risk assessment results or are affected by the risks and risk management actions. Open communication helps all parties understand the risks and improves risk assessments and risk management decisions and outcomes.

Risk Framework
A decision-making process that comprises three tasks: risk assessment, risk management, and risk communication.

Risk Management
A decision-making process in which risk reduction actions are identified, evaluated, implemented, and monitored. Risk management takes actions to reduce and manage risks identified in a risk assessment.

Sample
An element, part, or fragment of a population. For example, every hydrologic record is a sample of a much longer record.

Scale (in Statistics)
The amount of dispersion or spread in a dataset. Changes in scale are detected through changes in variance and interquartile range.

Scaled Assessment
An assessment that strategically proportions effort, time, and resources to the scope of the project. For this ECB, the scale involves the amount of Tier 1 (and Tier 2 if applicable) assessment content (e.g., analyses) most appropriate to support the project or activity objectives.

Sea Level Change
A change in the mean level of the ocean. Sea level is measured by a tide gage with respect to the land on which it is situated.

Sen's Slope (also Thiel-Sen's Slope)
A robust method for estimating the trend in a dataset (e.g., maximum annual flow time series), Sen's Slope represents the line of best fit. It is calculated as the median of all slopes between pairs of data points. Values for Sen's slope that are greater than zero correspond to an increasing, positive trend. Values below zero indicate a negative trend.

Sensitivity
The degree to which exposure to hydrometeorological 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.

Serial Correlation (also Autocorrelation)
Serial correlation exists when the data points in a sequence are interdependent. Serial correlation indicates a relationship between a given variable and itself over a given time interval.

Sequential Mann-Kendall
A popular modified version of the Mann-Kendall test to identify change points in time series data.

Shared Socioeconomic Pathway (SSP)
A scenario of projected socioeconomic global change. SSP narratives (storylines) quantify and make assumptions about multiple socioeconomic drivers such as population growth, gross domestic product, and urbanization. SSPs are the basis of scenarios for estimating plausible future radiative forcings.

Significance Level (also p-Value)
The probability of rejecting a hypothesis that is true. A p-value of 5 percent is often chosen as adequate evidence of an alternative hypothesis, meaning a 5 percent chance of rejecting the null hypothesis (sample means are the same) when it is not true.

Skewness (also Coefficient Skew or Skew Coefficient)
A measure or index of the lack of symmetry in a frequency distribution; a function of the third moment of magnitudes about their mean and is a measure of asymmetry.

Smooth Statistical Change
In this context, a gradual change in the mean, variance/standard deviation, and/or distribution of the annual maximum discharge dataset recorded at a USGS site. The only methods in the Time Series Toolbox that can detect smooth changes in the statistical properties of the datasets being analyzed are the smooth Lombard Wilcoxon and smooth Lombard Mood method.

Spearman Trend Test
A nonparametric measure of trend. Spearman's test calculates the Spearman rank correlation coefficient, or Spearman's rho, a value between −1 and +1. Values close to −1 suggest strong negative dependence between the two variables (e.g., time and annual maximum flow) and values close to +1 suggest strong positive dependence between two variables.

Specific, Measurable, Attainable, Risk-Informed, and Timely (SMART) Planning
A USACE planning process emphasizing risk-informed planning that leads to decisions.

Spread
The range in outcomes from a large set of models that indicates the uncertainty driven by modeling assumptions and methods.

Spurious Outliers (also False Outlier)
An extreme value that is exceedingly low or high compared to the distributional properties of most of the data and is commonly caused by measurement error/inconsistency or incorrect data entry.

Standard Deviation
A measure of the dispersion or precision of a series of statistical values such as precipitation or streamflow; the square root of the variance (see Variance).

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

System
An integrated whole comprised of multiple separable parts that can be defined geographically, technically, and/or politically, and for USACE, typically including natural and built environments (EP 1100-1-5).

System Resilience
The ability of a system "to withstand a major disruption within acceptable degradation parameters and to recover within an acceptable time and composite costs and risks" (Haimes, Crowther, and Horowitz 2008).

Tentatively Selected Plan (TSP)
The term USACE uses after plan formulation analysis for the plan that meets planning objectives of the study. The TSP may or may not be the national economic development plan or the national ecosystem restoration plan.

Tentatively Selected Plan Milestone
The second decision milestone in the SMART planning process. The milestone is met when the PDT has concurrence on the TSP and the path forward from the vertical team, representing district, division, and headquarters decision-makers. This milestone triggers public release of the draft feasibility report and draft National Environmental Policy Act (NEPA) documentation for concurrent agency and public reviews.

Total Water Level
A combination of mean sea level with a number of other potential contributing factors, including wave runup, non-tidal residuals, wave setup, and astronomical tide. Timing of tide and surge strongly influence total water level, but the interactions are complex. The processes that govern total water levels are time and place dependent.

Transform
A mathematical function applied to data prior to analysis. Common transforms in hydrologic analysis include Box-Cox (which applies a logarithm transform as a subset) and square root (applicable for count datasets).

Trigger
An indicator or event that initiates a risk. In this context, a trigger is specifically tied to a relevant primary or secondary hydrometeorological factor. A trigger presents a problem or an opportunity.

t-Test
A parametric, statistical hypothesis test that compares the means of the two groups and determines the likelihood of the observed differences occurring by chance.

Type I Error
An error that rejects the null hypothesis when the null hypothesis is true, or a false positive. For example, in change point analysis, a type I error detects a change point when it does not actually exist.

Type II Error
An error that fails to reject the null hypothesis when the null hypothesis is not true, or a false negative. For example, in change point analysis, a type II error would fail to identify a change point when the dataset exhibits nonstationarity.

Uncertainty
The result of imperfect knowledge concerning the present or future state of a system, event, situation, or (sub)population under consideration, leading to a lack of confidence in predictions, inferences, or conclusions. Uncertainty has two types: aleatory and epistemic. Aleatory uncertainty is attributed to inherent variation that is understood as variability over time and/or space. Epistemic uncertainty is attributed to our lack of knowledge about the system (e.g., what value to use for an input to a model or what model to use).

USACE Planning Horizon
A time period encompassing the planning, design, construction, and performance of a project, beginning at the start of the planning study and continuing throughout the project's life.

Variance
A measure of the amount of spread or dispersion of a set of values around their mean, obtained by calculating the mean value of the squares of the deviations from the mean, and hence equal to the square of the standard deviation.

Vertical Team
A team of decision-makers and technical experts from the district, major subordinate command (MSC) and headquarters. The vertical team aligns all echelons on the work, the funding requirements (i.e., budget), an adequate study scope, and a realistic schedule.

Vulnerability
The degree to which built infrastructure or other assets could be exposed to changes in weather-related hazards, 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 changing hydrometeorology and related stressors.

Wet Floodproofing
Permanent or contingent measures applied to a structure or its contents that provide resistance to or prevent damage from flooding while allowing floodwaters to enter the structure or area.

Wilcoxon Change Point Test
A nonparametric statistical test implemented by the Lombard model that detects changes in the mean of a dataset. When applied within the Lombard framework, the Wilcoxon change point test detects both abrupt and smooth changes in the sample mean.

Zero-Inflated
Having many zero-valued observations.