Building Resilience with the Use of Digital Twins

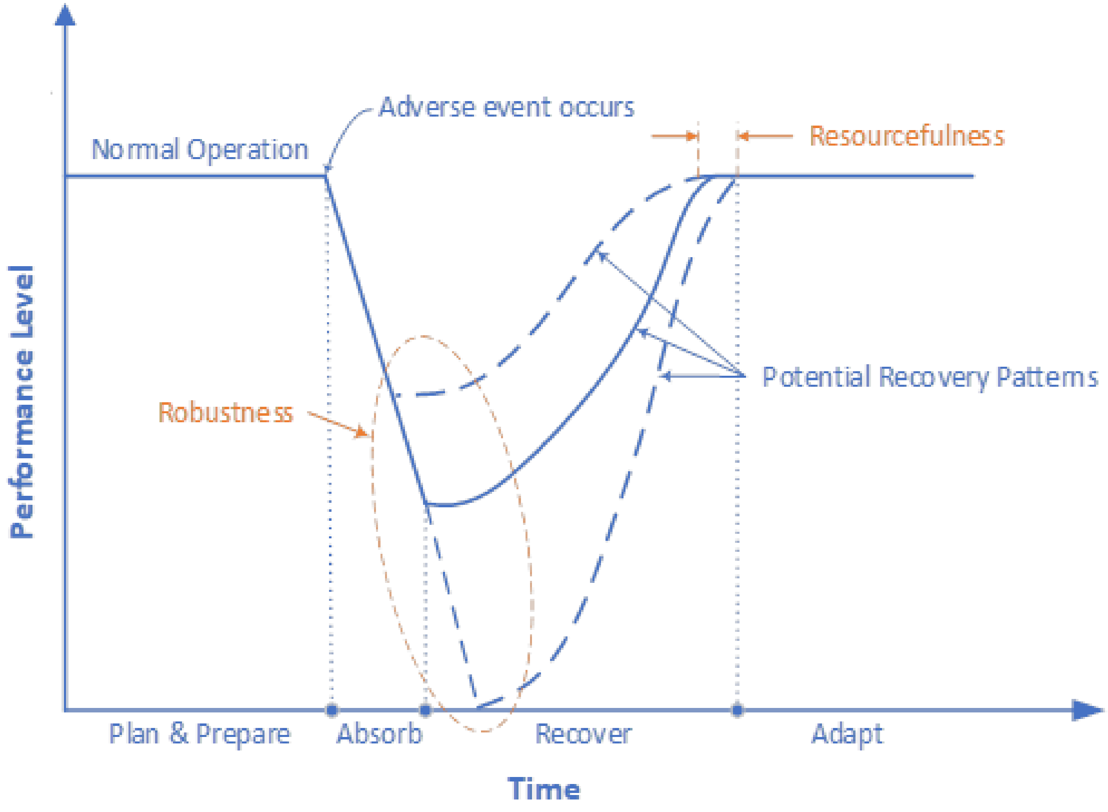
Modeling Extreme Environmental Events

Rob Choromokos
Senior Principal Team Leader
rchoromokos@epri.com

IAEA Resiliency Workshop – SS-02
August 26, 2025

Overview

- Environmental threats are impacting plant operations now and will intensify
- Industry is conducting short- and long-term assessments
- Forward looking advancements in cooling, materials, and forecasting are warranted



What can we do to Plan, Prepare and Absorb these impacts?

Information Required to Drive Solutions

Current Knowledge

- Regional forecasts reveal probable future conditions
- OE reveals near-term vulnerabilities in cooling and heat sinks
- Initial reviews show system margin reductions under future stressors

Research in Progress

- Heat transfer performance degradation
- Material degradation under extreme conditions
- Flow blockage from biological or debris buildup

Strategic Questions

- What investments ensure plant margin?
- What solutions are needed and when?
- How can I ensure generation reliability?
- What predictive tools support my strategy?

Extreme Conditions Include (But Are Not Limited to)

- Direct Sunlight
  - Heat
  - UV degradation
- Ambient/Extreme Temperatures
- Wind-Driven Abrasives
- Heavy Snowfall
- Elevated Heat Sink Temperatures
- Changing Salinity
- Flora and Fauna / Biodiversity Changes
  - Challenges related to rising temperatures
  - Changes in the physical and chemical composition of water bodies (e.g., warmer temperatures, environmental runoff)

Extreme Environmental Conditions Impact

- Material Degradation
  - Metals (Corrosion/Erosion)
  - Polymers
  - Concrete
- Heat Transfer
  - Increased heat duty
  - Heat sink challenges
- Critical to identify areas where climate conditions may compromise equipment, systems, performance, and safety

Climate Vulnerability assessments identified key issues requiring mitigation plans to ensure resilience

Components and Systems of Interest

- Safety-Related Heat Exchangers
- Open Water Cooling Piping
- HVAC Systems and Ventilation
- Diesel Generators
- Cooling Towers
- Production Heat Exchangers: Feedwater Heaters, Moisture Separator Reheaters (MSRs), Condensers
- Spent Fuel Pool

Project Goals and Objectives

Modeling plants using data reconciliation as digital twins

- Models would be used to conduct “what-if” studies based on
  - Real time or historical plant performance data
  - Component characteristics (e.g. heat transfer over inlet temperature) based on reconciled values
  - Extreme weather forecast data

The goal is to evaluate two primary performance challenges:

- Fluctuating heat sink temperatures projected through 2050 (with data provided by EPRI)
- Additional heat duty introduced by various uprates, including:
  - MUR (Measurement Uncertainty Recapture)
  - Stretch
  - Extended Power

Modeling Considerations

- Operation mode 1: Normal operation mode - all systems in process during normal operation must be modeled
  - Ideally, two plants would be modeled
    - Open body of cooling water
    - Cooling tower
- Operation mode 2 to X - Emergency operation mode
  - Shutdown from normal operation to subcritical cold state
  - Shutdown in case of LOCA
  - Shutdown under emergency conditions
  - Plant shutdown state
- Two climate conditions modeled
  - Extreme High Temperature
  - Extreme Cold Temperature

Emergency systems which are needed for defined emergency scenarios must be modeled

Model Considerations

Development of models that represent the nuclear auxiliary cooling system, the conventional auxiliary cooling system, and the main cooling water system, and simulation with elevated flow water temperatures and ambient air temperatures

Temperatures in respective subsystems must be checked to determine whether permissible operating values and/or design parameters are exceeded

The following operation modes must be considered for nuclear/conventional auxiliary cooling system, main cooling water system

- Normal operation mode
- Shutdown from normal operation to subcritical cold
- Shutdown in case of LOCA
- Shutdown under emergency conditions plant shutdown state
- Plant shutdown state

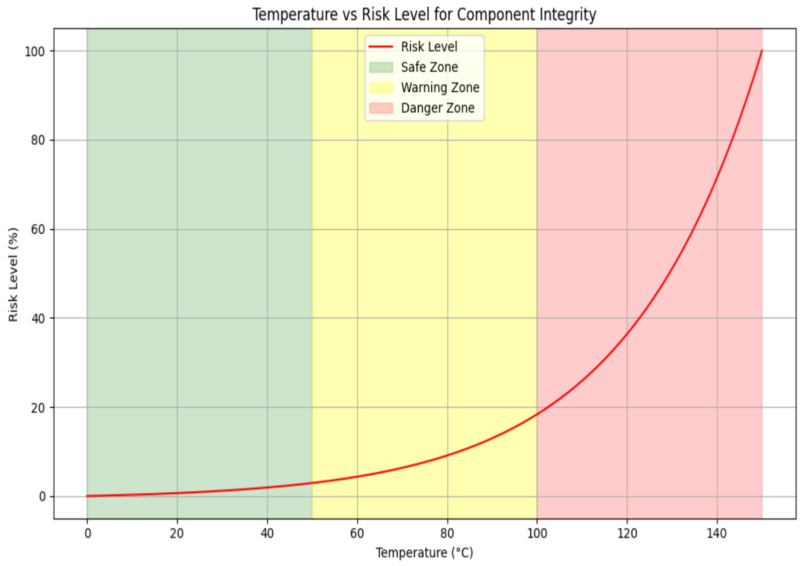
Key Data Outputs Would Include

- Quantitative impact on generation
  - Using weather predictions for data reconciliation model
- Effects on generation components
  - e.g., excess wear or degradation
- Performance changes in safety-related heat exchanger systems
- Discharge temperatures for environmental compliance
- Identification of leading indicators for equipment or production issues
- Identification of component limits during the defined operation modes

Information would support evaluations of design concepts or techniques to assess improvements

Overall Goal

- Use these results to
  - Develop a method to help assess mitigation strategies and vulnerabilities for reliability and resilience
  - Guide research into design and operational solutions well in advance of the projected climate conditions
- Possible component limits will be identified, and hardware-based activities can be initiated in time
- The results of these evaluations will help determine whether new testing is needed to address technical gaps
  - Metal/concrete corrosion and erosion
  - Polymer degradation
  - Identify gaps in heat sink and heat transfer performance

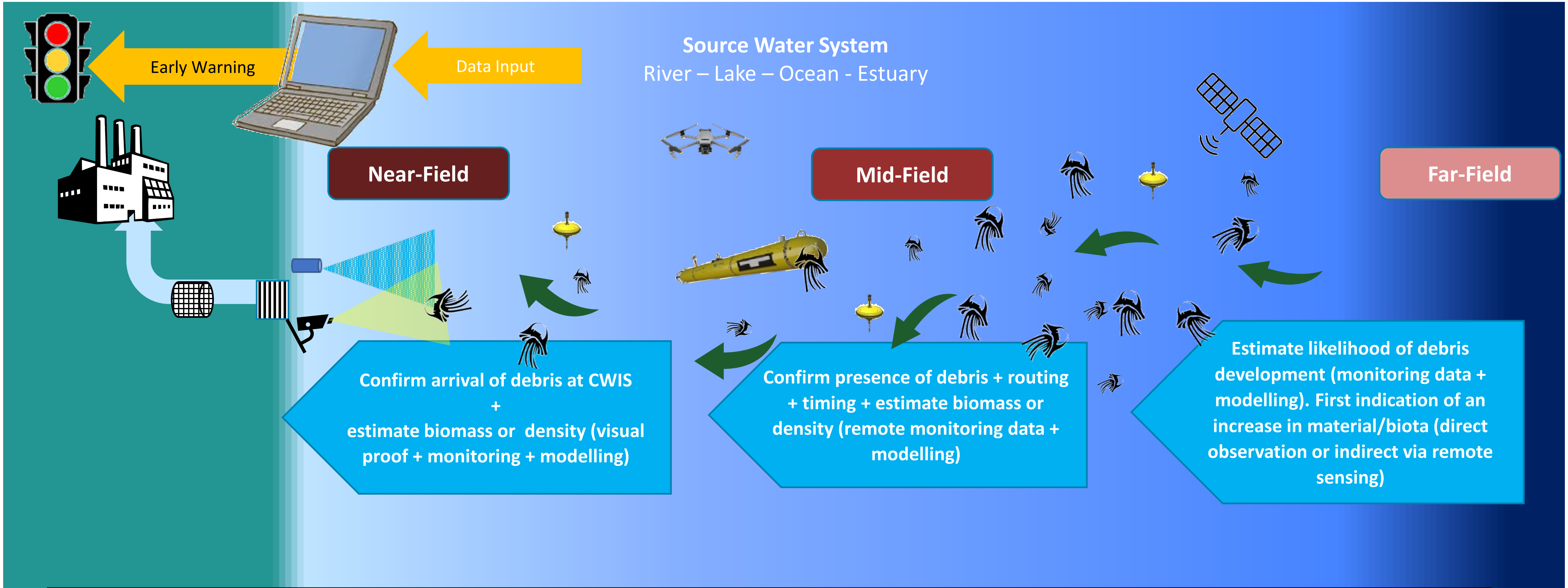


Expand research to cover a broader range of environmental conditions modeled through 2050

EPRI

What's Next?
Predicting and Projecting Intake Threats

Early Warning and Real-time Visualization



Schematic from previous EPRI work:

Reference Manual for Forecasting Debris Events at CWIS (#3002024512)

Intake Resilience through Informed Decisions

- The prior study evaluates the impacts of extreme condition on the heat duty and performance of equipment
- Coincident with performance is the flow of cooling water into the system heat sinks
- Recent increases in bio-diversity and propagation have challenged intake structures
- Jellyfish are notoriously difficult to identify in advance of reaching an intake structure
- A technology for identifying jellyfish movement patterns and propagation conditions would be beneficial for other bio-monitoring applications

Technology for monitoring and forecasting could be applied to other flora and fauna

Jellyfish Bloom Detection and Forecasting at Intakes

- Once-through cooling systems are increasingly vulnerable to disruptions caused by jellyfish blooms
  - Clog intake structures
  - Damage intake screening equipment
  - Force partial or complete shutdowns
- Warm and nutrient/salinity profiles shift creating conditions conducive to more frequent and larger bloom patterns
- Detecting jellyfish in the water column is challenging
  - Gelatinous, translucent bodies blend into the surrounding water
  - Distribution is often patchy and unpredictable
  - A successful forecasting system must integrate advanced sensor technologies capable of directly detecting jellyfish or identifying the environmental precursors indicating the probability of bloom

The ability to anticipate these events could greatly improve operational resilience

Jellyfish Study Objectives

- Develop an understanding of the biological and environmental drivers of jellyfish blooms
  - This includes identifying the species most associated with power plant disruptions
  - Environmental conditions that promote their propagation
  - These drivers will help identify the parameters to monitor for anticipating bloom formation.
- Identify available sensor technologies that could detect jellyfish or environmental indicators preceding blooms
  - Assess technical capabilities and operational feasibility
  - Review technologies may be deployed in the water or from above with UAVs or satellites
- Engage with the industry to gather operational insights and historical data on jellyfish events.
  - Can be used to hindcast events
  - Aid in identifying trends and inform the design of a practical and effective forecasting system
- The potential use of artificial intelligence to analyze large environmental datasets will also be explored to identify predictive patterns
- A successful outcome could be applicable to monitoring and projection other bio-blockage events

Multiphase Evaluation for Projection of Impending Events

Closing Thoughts

- What climate vulnerabilities are you uncovering or struggling with related to:
  - Intake blockage
  - Generation optimization
  - Safety System performance
  - Equipment degradation
- How are you currently managing the issues related to extreme environmental conditions (EECs)?
- Have you noticed a change in biodiversity impacting your heat sinks?
- Are you approaching or exceeding discharge temperature limits?
- Are you considering EECs when planning for uprates?
- Would you be interested in piloting a holistic assessment process led by EPRI?

CLIMATE READi
RESILIENCE AND ADAPTATION INITIATIVE

EPRI Climate Resilience and Adaptation Initiative (READi)

- **COMPREHENSIVE:** Develop a *Common Framework* addressing the entirety of the power system, planning through operations
- **CONSISTENT:** Provide an informed approach to climate risk assessment and strategic resilience planning that can be replicated
- **COLLABORATIVE:** Drive stakeholder alignment on adaptation strategies for efficient and effective investment

Workstream 1

Physical Climate Data & Guidance

- Identify climate hazards and data required for different applications
- Evaluate data availability, suitability, and methods for downscaling & localizing climate information
- Address data gaps

Workstream 2

Energy System & Asset Vulnerability Assessment

- Evaluate vulnerability at the component, system, and market levels from planning to operations
- Identify mitigation options from system to customer level
- Enhance criteria for planning and operations to account for event probability and uncertainty

Workstream 3

Resilience / Adaptation Planning & Prioritization

- Assess power system and societal impacts: resilience metrics and value measures
- Create guidance for optimal investment priorities
- Develop cost-benefit analysis, risk mitigation, and adaptation strategies

Deliverables: Common Framework "Guidebooks"

- Climate data assessment and application guidance
- Vulnerability assessment
- Risk mitigation investment
- Recovery planning
- Hardening technologies
- Adaptation strategies
- Research priorities

EPRI

Climate READi Compass

Navigating Physical Climate Risk Assessments for the Power System

EXECUTIVE SUMMARY | MAIN REPORT | APPENDICES

TOGETHER…SHAPING THE FUTURE OF ENERGY®

www.epri.com