



Title: Quantifying compound hazard risk to energy and water systems

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Focal Area(s): Identification and quantification of the risk of combined (compound) hazards on water and energy systems and their interactions.

Existing Challenge: Addressing risk and consequences to energy and water systems by compound hazards is an emerging area of study. Individual hazards are typically well documented in the published literature, but information about combined risk and consequences still has many gaps. These gaps include:

1. Complexity of Hazard Interactions: Many hazard interactions involve nonlinear dynamics and system feedbacks, which makes them difficult to forecast or model (e.g., how drought could exacerbate wildfire risk or how storms driven by atmospheric rivers result in landslides) (Alcántara-Ayala, 2025; Zscheischler et al., 2018).

2. Lack of Comprehensive Data and Inadequate Modeling Techniques: High-resolution, multi-hazard data sets are often siloed within agencies, incomplete across geographic areas, or unavailable. Compound hazards are inherently rare, and the limited number of occurrences in historical records constrains data-driven characterization and the development of comprehensive models. Models continue to face challenges and uncertainties in characterizing compound hazards. Often the models fail to account for socioeconomic factors and infrastructure interdependencies that amplify risks during compound events. Development of coupled/integrated modeling frameworks is needed to address these challenges (Dulin et al., 2025).

4. Regional Variability in Hazard Types and Policies: Compound hazards manifest differently across regions due to varying geography, climate, infrastructure, and population exposure. In addition, federal, state, and local agencies often address hazards individually rather than through a multi-hazard lens (Dulin et al., 2025).

5. Uncertainty of Hazard Drivers and Compound Risk: Future increases in the frequency and intensity of hazards complicate hazards analysis because they are harder to predict

due to uncertain trajectories in temperature, precipitation, and extreme weather patterns. Uncertainty also compounds across interacting hazards, as errors in individual hazard projections propagate through coupled systems, amplifying the difficulty of quantifying cascading risks to energy and water infrastructure (Dulin et al., 2025; Zscheischler et al., 2018).

Near-Term Opportunity: There are several opportunities for activities that could result in substantial gains in mitigating compound hazard effects on water and energy systems. Mitigation of compound hazards could have an immediate and high value impact on economic activities and public safety. A range of both physical and social science efforts is needed to identify, quantify, and communicate the existing and future risk of compound hazards. Progress towards addressing the risks for the energy and water systems requires an integration of federal, state, and local engagement. This engagement will consist of data sharing, numerical modeling, policy analysis, and public meetings. Near-term opportunities include:

1. **Advances in Data Integration and Technologies:** The proliferation of tools such as remote sensing, geospatial analysis, and big data analytics allows for better integration of hazard data sets. Synthetic data generation through an integrated modeling system provides a promising pathway to fill gaps left by limited historical records. Technologies like AI and machine learning can more effectively capture non-linear dynamics to model and predict compound hazard scenarios and pinpoint hotspots of vulnerability. In addition, harmonizing data across agencies and hazards will be important for development of these tools.

2. **Interdisciplinary Research and Collaboration:** Encouraging collaborations between climatologists, engineers, sociologists, economists, data scientists, and public health experts could improve understanding and mapping of compound hazards. Federal initiatives (e.g., through NOAA, FEMA, and USGS) could support cross-sector partnerships to create more holistic hazard assessment frameworks.

3. **Expansion of Climate and Hazard Modeling:** Developing interactive models that represent feedback among atmosphere, land, water, and human systems is critical for quantifying compound hazard risks. Near-term efforts should prioritize modular, climate-informed hydrological and energy-water system models that integrate socioeconomic drivers and infrastructure interdependencies. These frameworks should move beyond one-way forcing to capture nonlinear interactions and cascading effects at decision-relevant scales, producing actionable data products for policymakers and utilities. Incorporating generative AI to model the human components of the framework (e.g., socioeconomic drivers, decision making) enables digital twin-like simulation and scenario generation capabilities.

4. Infrastructure Risk Assessments: Updating infrastructure risk assessments, using compound hazard scenarios as design benchmarks, could help mitigate or prepare for cascading risks.

5. Leveraging the National Risk Index: There could be expanded opportunities to assess compound risks by layering hazards and their interdependencies. This framework could also be adapted to account for regional variability by incorporating locally relevant indices—such as wildfire risk metrics tailored to vegetation type, fuel moisture dynamics, ignition sources, and meteorological conditions. Embedding these region-specific drivers within a national framework would enable more accurate comparisons across geographies while preserving the nuances critical for local decision-making.

6. Resilience Policies: Resilience policies, if strategically designed to include future weather conditions, could incentivize projects that address compound hazards effectively. The policies could be strengthened, accelerated, and effectively executed through a mutually reinforcing loop with public awareness campaigns. There are opportunities for effective and transparent coordination between federal agencies and local agencies that is vital for specific local needs and vulnerabilities.

Success Measure: Success in quantifying compound hazard risk to energy and water systems means improving the understanding of multi-hazard impacts, identifying critical vulnerabilities, and creating actionable pathways for mitigating risks. It also means transitioning from a reactionary system to one that is proactive, equitable, and resilient. These measures will ensure that critical infrastructure systems can continue to provide services sustainably, even in the face of increasingly complex and novel hazards.

Metrics for long-term success related to water and energy systems include:

- Reduced service disruptions during actual compound hazard events compared to historical baselines
- Decreased recovery times following compound events
- Targeted investments in critical vulnerabilities identified through assessment
- Improved planning/response coordination between energy and water sectors
- Enhanced equity in service maintenance across different communities

References:

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