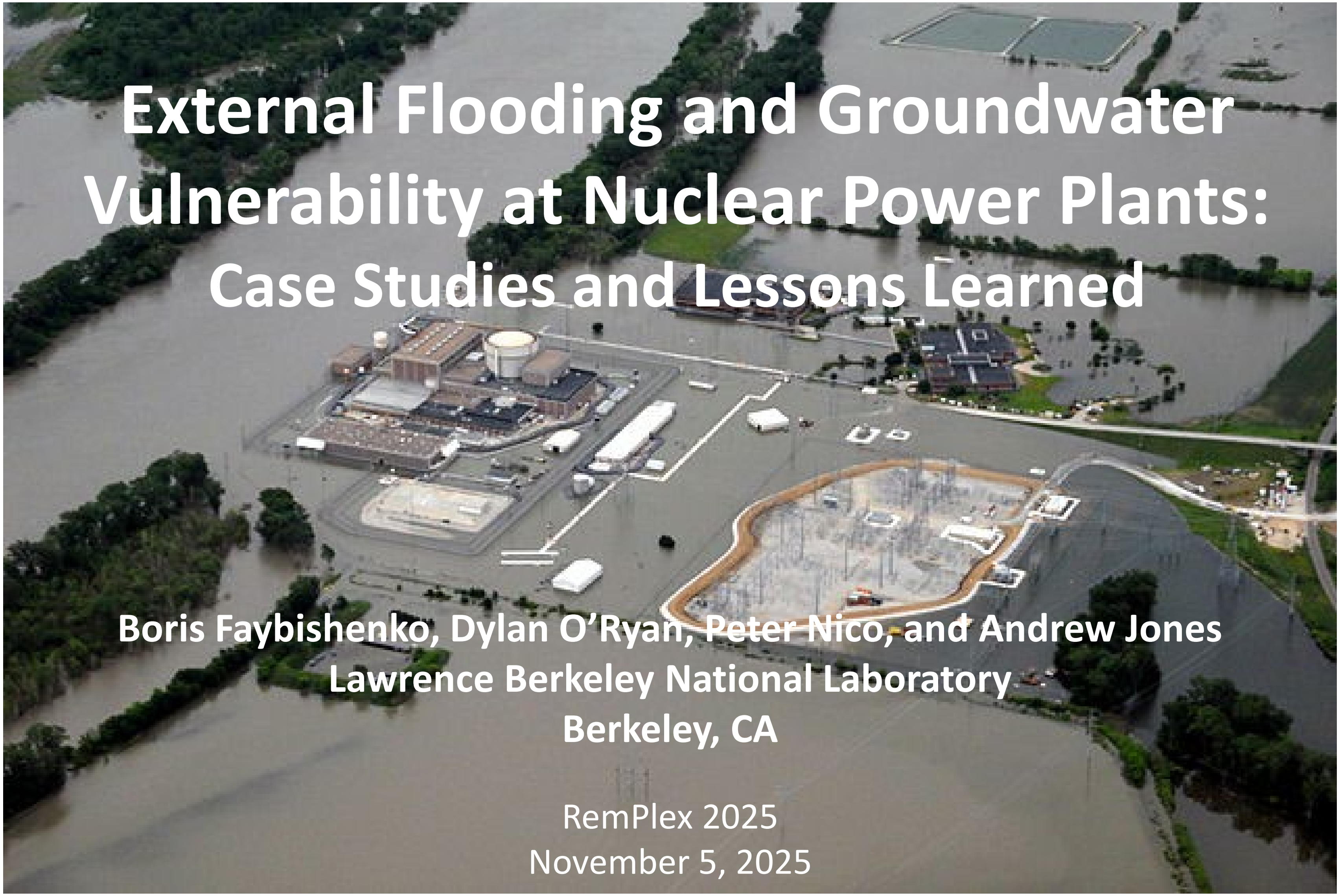
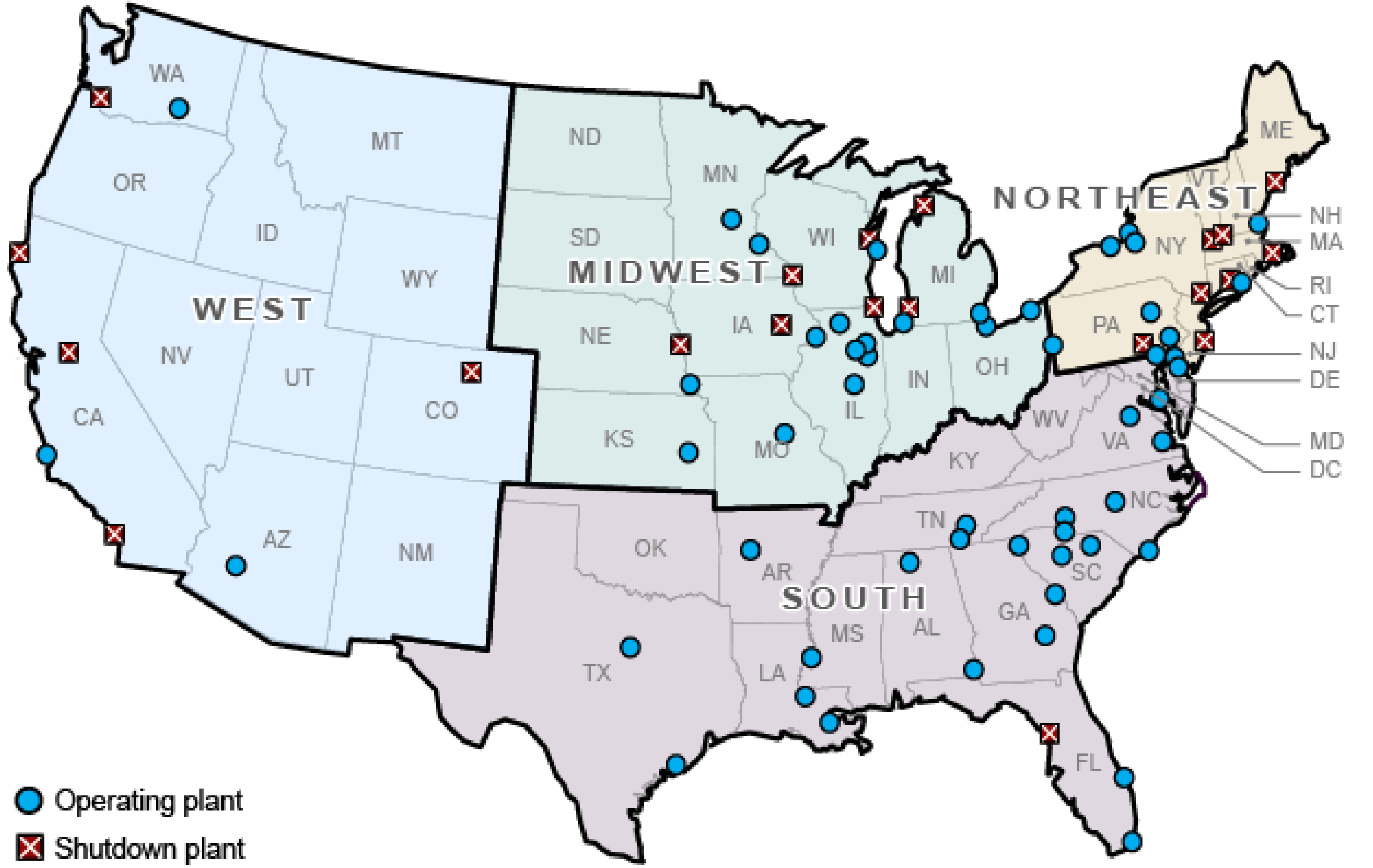


External Flooding and Groundwater Vulnerability at Nuclear Power Plants: Case Studies and Lessons Learned

Boris Faybishenko, Dylan O'Ryan, Peter Nico, and Andrew Jones
Lawrence Berkeley National Laboratory
Berkeley, CA

RemPlex 2025
November 5, 2025

Operating and shutdown of the U.S. Nuclear Power Plants



Sources: GAO analysis of U.S. Census Bureau and Nuclear Regulatory Commission data; U.S. Census Bureau (map). | GAO-24-106326

20% of U.S. electricity via 93 Reactors at 54 Sites

Nuclear power plants have a dual vulnerability to flooding

- NPPs require a large water supply for cooling, making them vulnerable to water damage.

Kakhovka dam destruction, Ukraine (Dnieper River). 2023.

- Meanwhile, floodwaters can disable safety systems, such as backup generators and cooling mechanisms, as seen at Fukushima.

The Fort Calhoun Nuclear Generating Station, Nebraska, USA (Missouri River). 2011.

External flooding and groundwater vulnerability

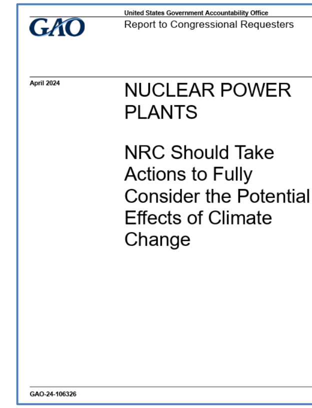
- External flooding results from natural events or failures outside the plant, such as severe weather or dam breaches

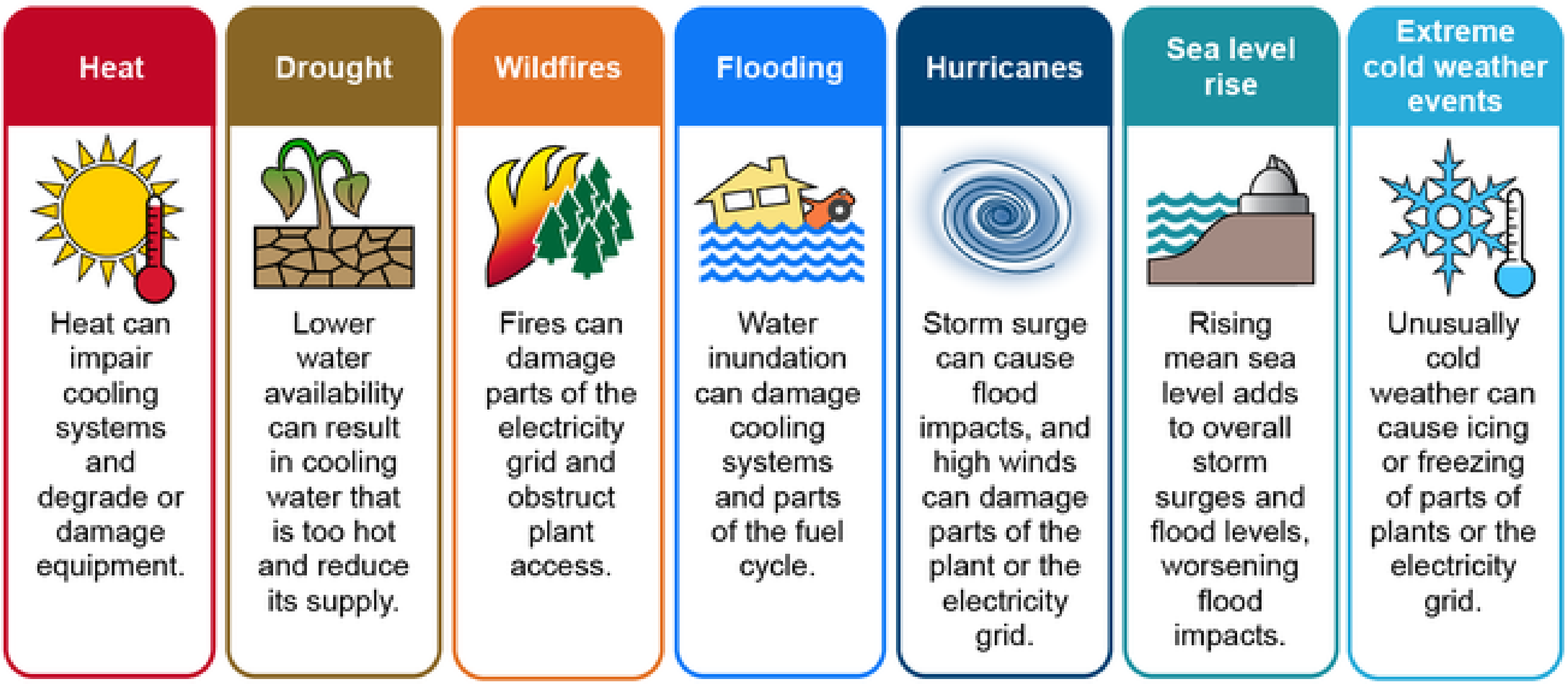
- Groundwater vulnerability is the susceptibility of a groundwater system to contamination from activities at the land surface and to changes in the groundwater levels.

Risks of rising groundwater near nuclear power plants and toxic sites

- **Flooding**
  - Rising groundwater can contribute to flooding, which could affect the infrastructure of nuclear power plants and site barriers.
- **Contamination**
  - A risk of flushing out buried toxic waste from nearby sites, which could contaminate the surrounding area.
- **Structural Integrity**
  - The impact on the foundation and structural integrity of the facility in a low-lying coastal area can be significant.
- **Erosion**
  - Increased erosion could expose buried waste and cause other problems.

Examples of natural hazards that may pose risks to Nuclear Power Plants and Toxic Sites


GAO
United States Government Accountability Office
Report to Congressional Requesters
April 2024
NUCLEAR POWER PLANTS
NRC Should Take Actions to Fully Consider the Potential Effects of Climate Change
GAO-24-106326

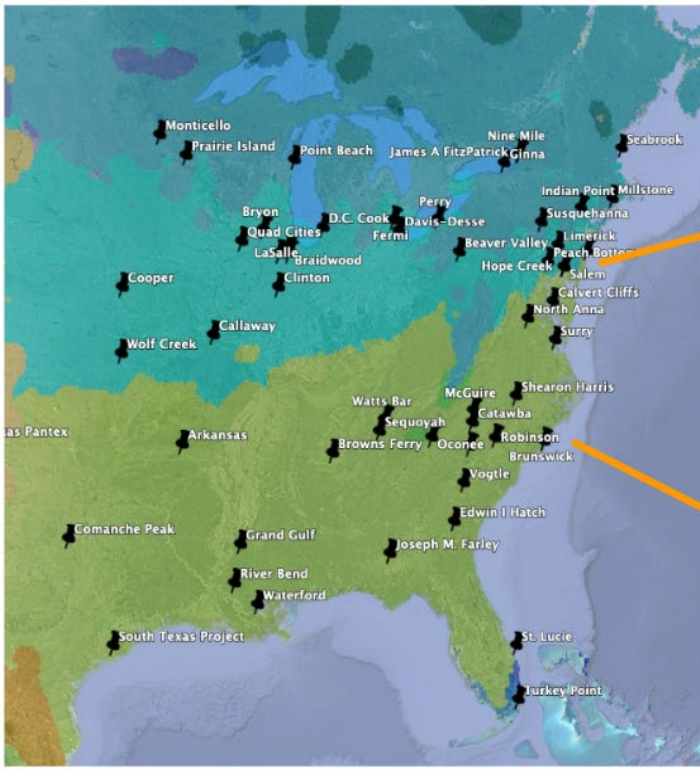


Sources: Nuclear Regulatory Commission documents; summary of literature; GAO (icons). | GAO-24-106326

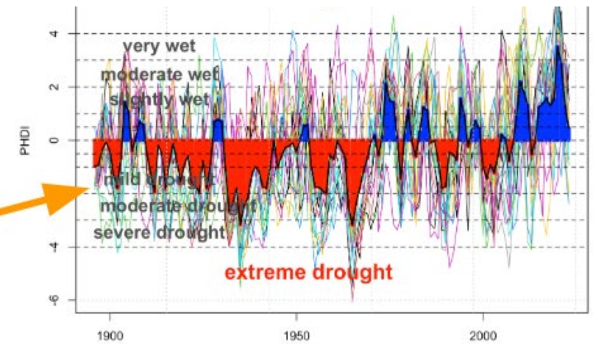
https://www.gao.gov/products/gao-24-106326#:~:text=What%20GAO%20Found,reduced%20operations%20or%20plant%20shutdowns.

The Palmer Hydrological Drought Index (PHDI) indicates the prevalence of wet conditions over the recent decades

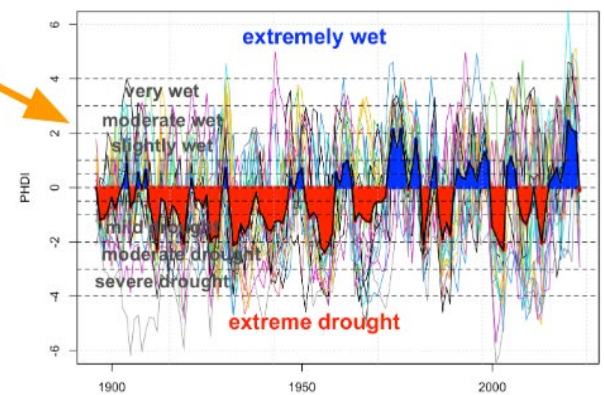
Kopper-Geiger climate zonation map



Dfa: Humid continental, Hot summers, Year-Round precipitation



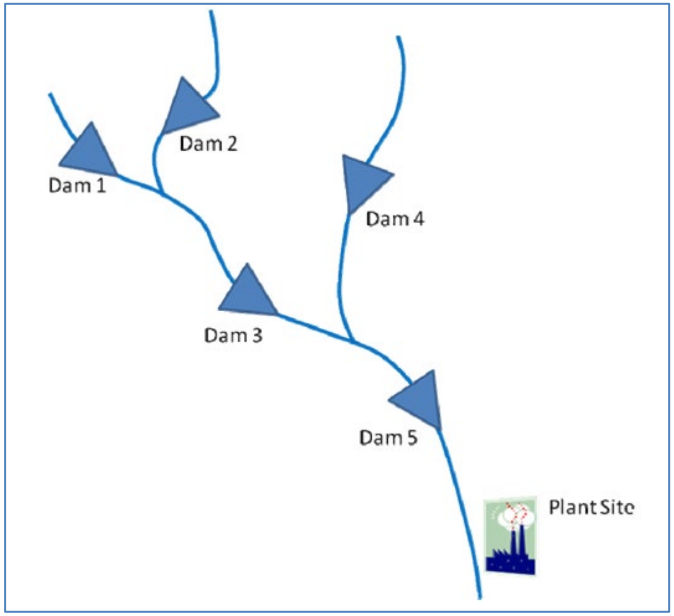
Cfa: Humid Subtropical



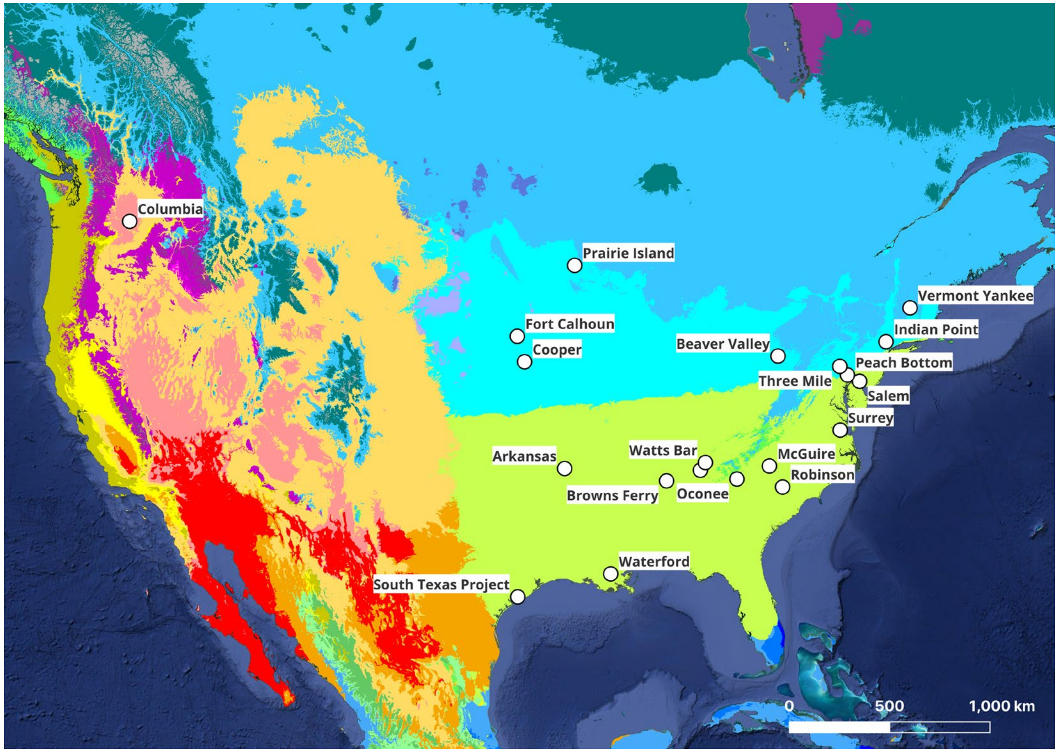
Major Historical Flood Events

- **Fukushima Daiichi Nuclear Power Plant (Japan, 2011):**
  - A massive tsunami overwhelmed the plant's seawalls.
- **Blayais Nuclear Power Plant (France, 1999):**
  - A combination of high tides and strong winds from extratropical storm Martin overwhelmed the plant's seawalls, flooding the site and knocking out several safety-related systems.
- **Fort Calhoun Nuclear Power Plant (**Nebraska)
  - High water levels on the Missouri River caused by heavy rain and snowmelt inundated the plant site, challenging operations despite the plant being in a scheduled shutdown.
- **Gori NPP (South Korea, 2014)**
  - Heavy rainfall caused flooding of the circulating water pump building, impacting plant operation.
- New Jersey nuclear plants (Salem and Oyster Creek, 2012)
  - Hurricane Sandy caused high water levels and flooding, forcing shutdowns.

U.S. Nuclear Plants Downstream of High-Risk Dams

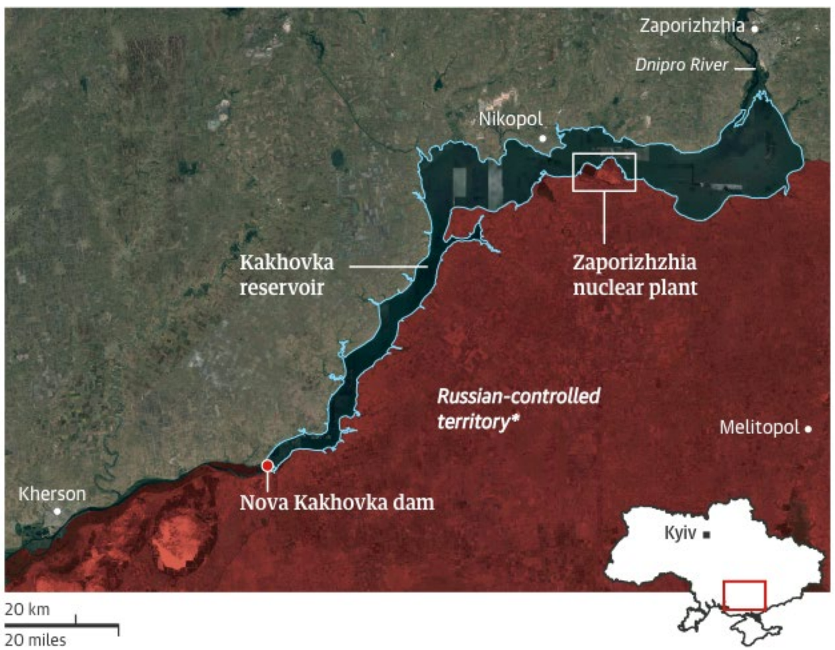


At least 34 reactors at 23 sites were affected by flood from dam breaches, which exceeded the plants' design protection.



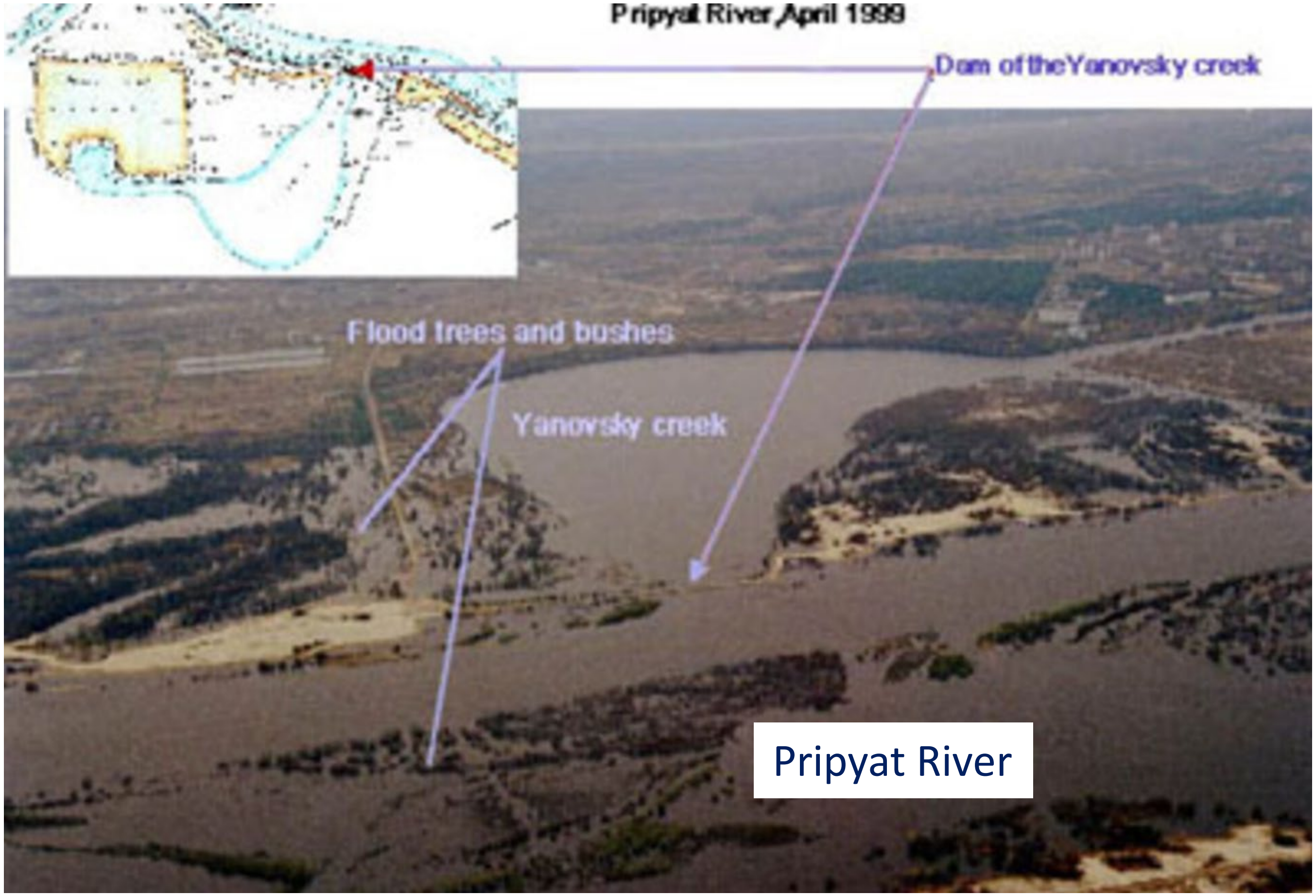
Dam failures at the upstream reservoirs could result in floodwaters exceeding protection measures, potentially overwhelming critical safety systems.

Zaporizhzhia NPP, upstream of the destroyed Nova Kakhovka Dam, has been affected by a water shortage



https://www.theguardian.com/world/2023/jun/06/nova-kakhovka-dam-everything-you-need-to-know-about-ukraines-strategically-important-reservoir

Spreading radioactive contamination due to flooding in the Chernobyl Exclusion Zone, April 1999



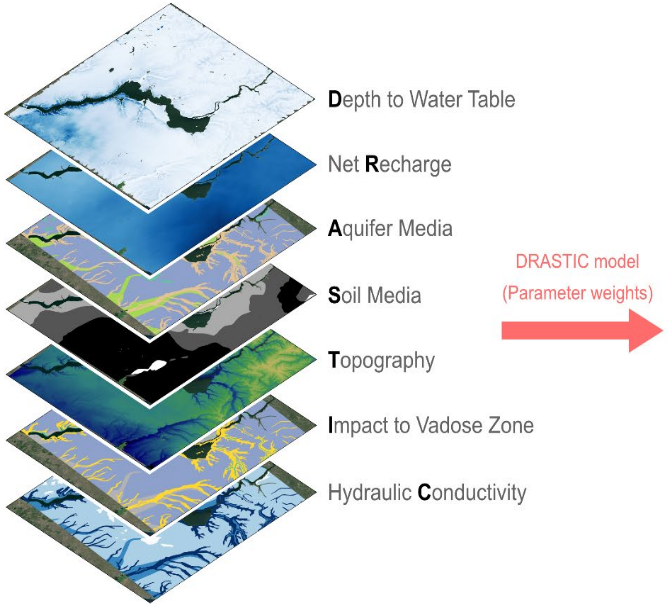
https://www.esa.int/Applications/Observing_the_Earth/Monitoring_Chernobyl_s_radioactive_floods

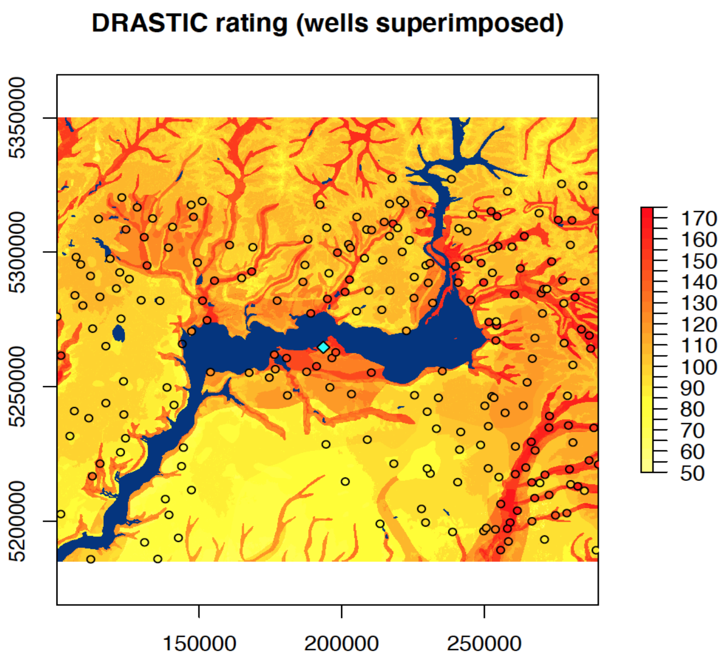
Groundwater vulnerability analysis and modeling using deterministic and probabilistic methods

- **Flood propagation paths:**
  - The potential pathways for water to enter buildings, such as doors, piping penetrations, and underground galleries.
- **Flood levels:**
  - The maximum water height is calculated to determine if it will overtop protective barriers or reach safety-related equipment.
- **Flow velocities and forces:**
  - Hydrostatic and hydrodynamic forces are evaluated for their potential to damage structures.
- **Warning time and duration:**
  - The time available to take protective or mitigating actions.
- **Combinations of events:**
  - The risk of identifying the worst-case, "design-basis" flood scenario.
- **Site-specific characteristics:**
  - Topography, site grading, the functionality of drainage systems, and the presence and height of protective structures (embankments, seawalls) are all considered.

An illustration of the calculations of the GIS-based DRASTIC groundwater vulnerability index

40,000 km^2 region centered on the Zaporizhzhia NPP,

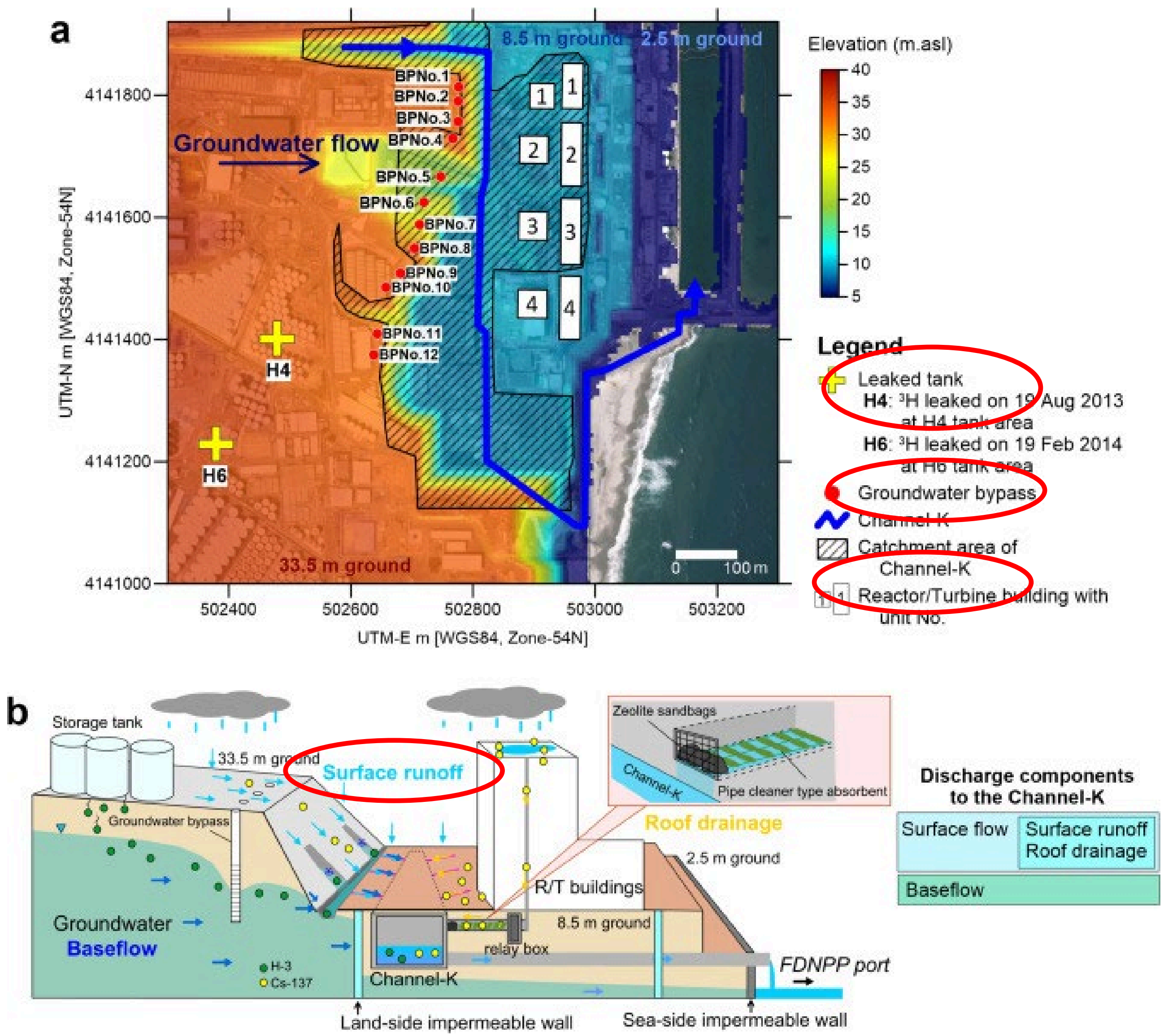




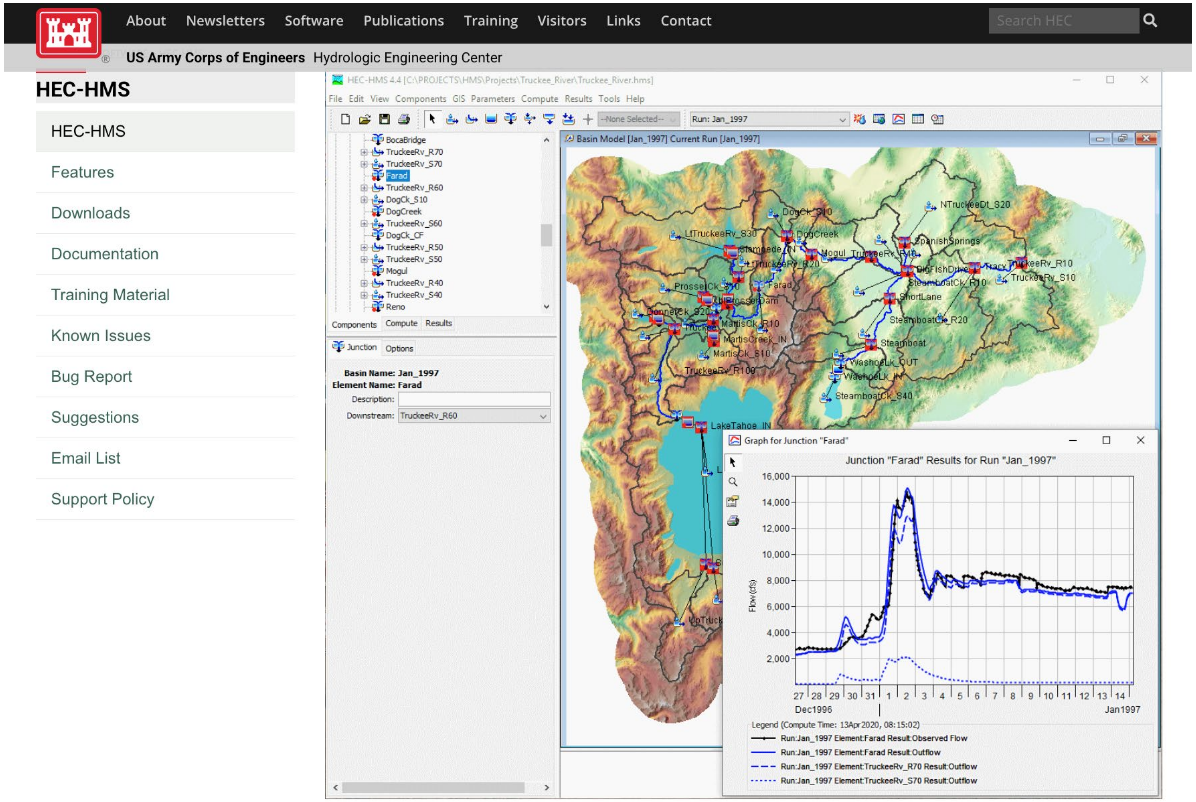
Ramakrishna et al. (2020)

LLNL and LBNL LDRD's project, Slessarev et al., 2024

Watersheds and pathways of radionuclide transport at Fukushima Daiichi NPP: More complex models are required



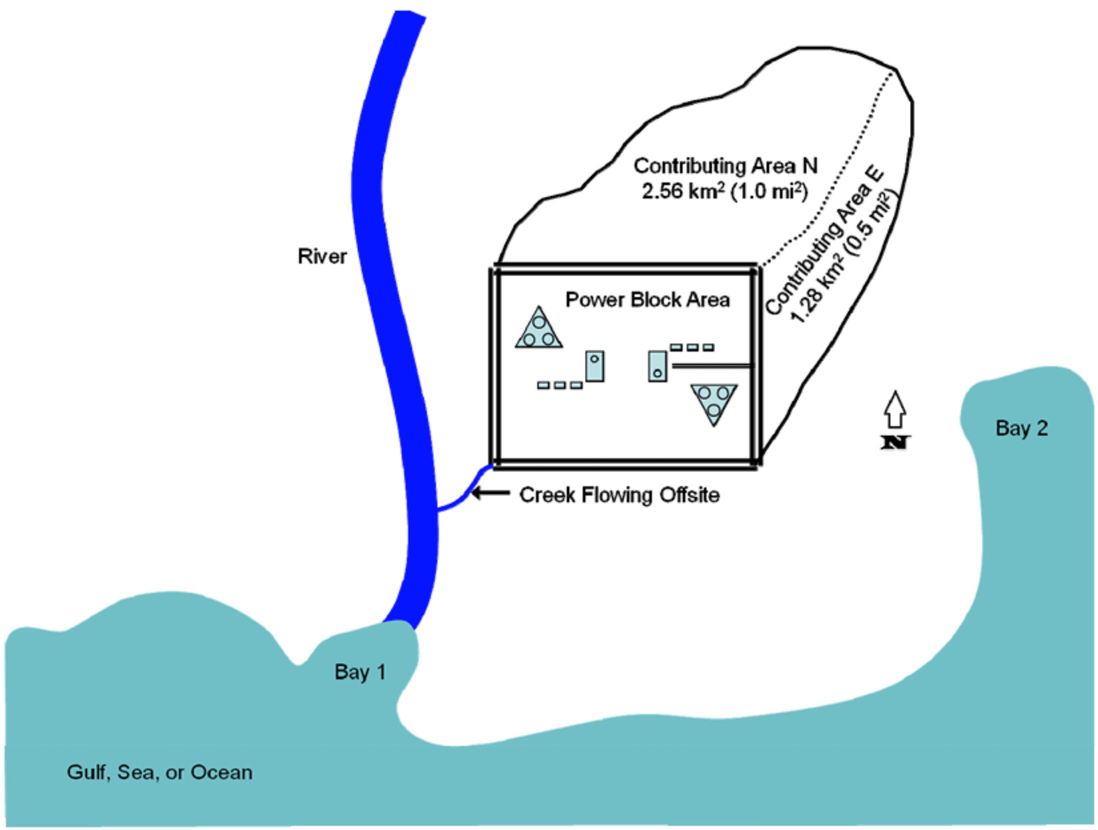
Hydrologic Modeling System (HEC-HMS) is a watershed modeling system to simulate precipitation-runoff processes on a watershed scale



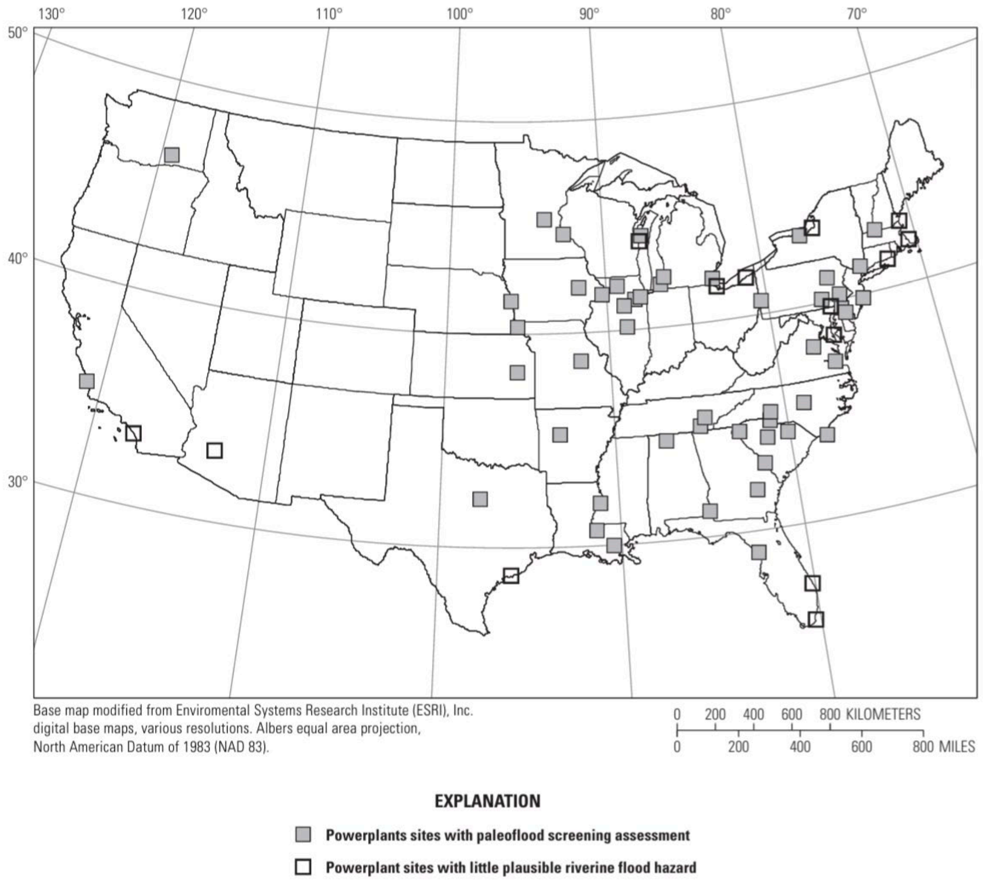
US Army Corps of Engineers, Hydrologic Engineering Center

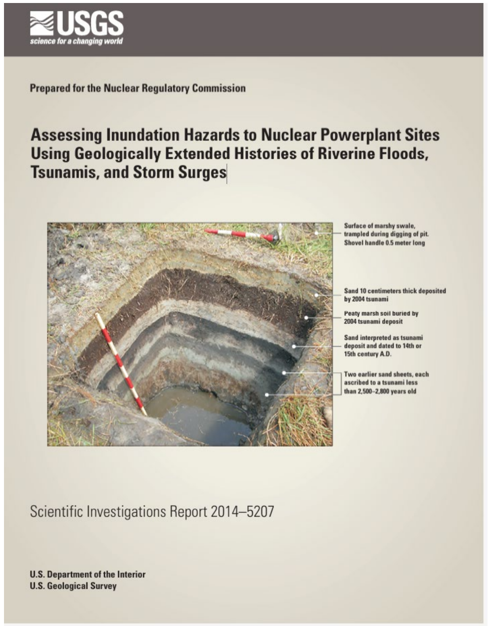
https://www.hec.usace.army.mil/software/hec-hms/

Schematic of modeling of hypothetical nuclear power plant site with respect to a creek, a river, two bays, and an ocean

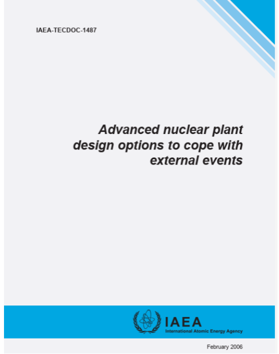


- Paleoflood analysis is the application of the science of paleohydrology,
- 50 NPPs were screened to assess flood hazards in relation to critical infrastructure such as dams, levees, and other flood protection works





Engineering measures for flood resilience, mitigation, and remediation


IAEA-TECDOC-1487

Advanced nuclear plant design options to cope with external events

IAEA

February 2006

- **Physical Barriers:**
  - Flood walls, watertight doors, and modular deployable water barriers (such as the "Aqua Dam"), especially in external threat scenarios.
- **Compartmentalization**:
  - Internal room separations with drainage, sumps, and passive barrier systems to isolate essential equipment from potential water intrusion.
- **Redundancy**:
  - Multi-redundant design so any single component failure will not disable full safety functions
- **Regular Inspections**:
  - Mandated by the NRC—comprehensive flooding and “walkdowns” to verify physical conditions, design compliance, and proper installation of barriers and drainage.
- **Enhanced Emergency Procedures**:
  - Upgraded flood emergency plans and portable backup pumps/generators, especially since Fukushima, to ensure core cooling and electrical backup even if main infrastructure is lost.
- **Cleanup of Contaminated Areas:**
  - If floodwaters come into contact with hazardous or radioactive materials

Conclusions

- Regulatory bodies are increasingly focusing on incorporating both future climate projections and historical flood data to improve flood risk assessment and mitigation.

- The application of modern field monitoring and probabilistic flood and groundwater vulnerability assessment methods is required to enhance the reliability of assessments, simulations, and predictions of extreme flood events at NPP and toxic sites.

References

Ramakrishna, B.; Rajasekhar, P.; Vaheed, S. Assessment of Aquifer Vulnerability of Nizamabad District, Telangana State, India Using GIS and Drastic Method. In *International Conference on Emerging Trends in Engineering (ICETE)*; Satapathy, S. C., Raju, K. S., Molugaram, K., Krishnaiah, A., Tsihrintzis, G. A., Eds.; Learning and Analytics in Intelligent Systems; Springer International Publishing: Cham, 2020; Vol. 2, pp 18–26. https://doi.org/10.1007/978-3-030-24314-2_3.

Slessarev, E. W. , A. Nezgoduk, J. K. Golla, B. Faybishenko, D. Dwivedi, P. S. Nico, J. T. Birkholzer, D. O'Ryan, O. Alvarez, A. B. Kersting, and M. Zavarin, Application of the DRASTIC Model to Assess the Vulnerability of Groundwater Contamination Near Zaporizhzhia Nuclear Power Plant, Ukraine, ACS ES&T Water 2025 5 (1), 366-376