System Dynamics Analysis of Flood-Induced LOOP/SBO Progression and Recovery in Nuclear Power Plants

Jiyun Jeon[a], Hoyeon Kim[a], Jaehwan Yoo[a], Hyeri Jang[a], Byunghyun Kim[a*]
[a] *Department of Civil Engineering, Kyungpook National University, Daegu, Republic of Korea*
**Corresponding author: bhkimc@knu.ac.kr*

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1. Introduction

External flooding of nuclear power plants can be caused by extreme rainfall, storm surge, river overflow, or their combined effects. International nuclear safety guidance therefore treats meteorological and hydrological hazards as important considerations in site evaluation and plant design [3,4]. When floodwater enters emergency diesel generator rooms or other electrical equipment spaces, the event may contribute to loss of offsite power (LOOP), station blackout (SBO), delayed restoration, and progressive degradation of plant support functions. The safety significance of an external flood is consequently governed not only by the maximum water level, but also by the sequence and duration of flood arrival, equipment exposure, power loss, and recovery.

Conventional flood-safety assessments often emphasize maximum inundation depth, flooded area, or equipment threshold levels. These indicators are essential, but they do not directly describe how system performance changes during an accident or how quickly the system can recover. The time required for floodwater to reach an equipment room, the duration of threshold exceedance, the recognition and administrative delay before repair, and the repair time itself can produce different performance trajectories even under similar peak flood levels. A dynamic framework is therefore needed to connect the physical flood process with equipment reliability, power-loss states, restoration, and resilience.

System dynamics is well suited to representing accumulation, time delay, and interactions among coupled system components [1,2]. This study develops a scenario-based system dynamics model for the dynamic assessment of flood-induced power loss at nuclear power plants. The model integrates flood-scenario generation, physical travel delay, mean time to failure (MTTF)-based power-failure risk, LOOP/SBO occurrence and recovery, performance degradation and restoration, system performance, and a Resilience Index. The present work focuses on the formulation and analysis capability of the model rather than on plant-specific prediction.

2. System Dynamics Model

The model is organized into eight linked modules that reproduce the temporal sequence from an external flood to power-system degradation and recovery. Flood and equipment-room water levels provide the physical forcing; MTTF-related variables translate exposure into changing failure risk; LOOP and SBO modules describe accident states and restoration; and the performance modules integrate degradation and recovery over the full simulation period. Figure 1 shows the overall model structure.

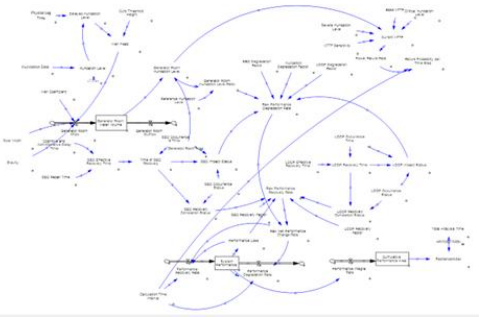


Fig. 1. Overall configuration of the system dynamics model.

2.1 Flood Scenario and Physical Delay

The external water-level scenario is generated using three principal variables: maximum flood level, time to peak, and recession duration. Together, these variables define the intensity and temporal shape of the imposed flood. A separate physical-delay variable represents the travel time required for floodwater outside the protected area to reach the emergency generator room. The generator-room water level is therefore evaluated independently from the external water level, allowing the model to distinguish hazard occurrence from actual equipment exposure.

A critical inundation level is assigned to the power equipment. Below this level, the equipment remains in the reference reliability state. When the generator-room water level exceeds the critical level, the model activates the MTTF-based risk mechanism. This structure permits explicit evaluation of the time at which equipment exposure begins and the duration for which the critical level is exceeded.

2.2 MTTF-Based Failure Risk and Power-Loss States

The failure-risk module uses a basic MTTF and an MTTF-sensitivity parameter. Once the critical inundation level is exceeded, Current MTTF is modeled to decrease according to the specified sensitivity relation, while the corresponding power-failure rate and hourly failure probability increase. The framework does not assume that floodwater instantaneously produces SBO; rather, it provides a time-dependent risk signal that can be linked to the occurrence and duration of LOOP and SBO states.

The LOOP and SBO modules define occurrence status, occurrence time, recovery time, impact status, and recovery-completion status. For SBO, the model separates

recognition and administrative delay from the actual repair time. The effective SBO recovery time is expressed as the sum of these two components. This separation is important because organizational response and technical repair may contribute differently to the total outage duration, even when the physical damage condition is unchanged.

2.3 System Performance and Resilience

Performance degradation and restoration are represented as competing rates. Flood exposure and active LOOP/SBO states increase the degradation rate, whereas completion of recovery actions activates the restoration rate. The time-dependent system performance P(t) is calculated by integrating the difference between the recovery rate and the degradation rate:

$$P(t) = P(0) + \int_0^t [r_rec(\tau) - r_deg(\tau)]\, d\tau \quad (1)$$

where P(0) is the initial system performance, r_rec is the performance-recovery rate, and r_deg is the performance-degradation rate. The Resilience Index (RI) is then calculated as the cumulative system performance divided by the total simulation time T:

$$RI = (1/T) \int_0^T P(t)\, dt \quad (2)$$

When performance is normalized to the initial condition, a larger RI indicates that degradation is smaller, recovery is faster, or both. The index therefore combines the magnitude and duration of performance loss in a single measure while retaining the full performance time history for interpretation.

3. Scenario Variables and Analysis Scope

Minimum and maximum values can be assigned to the principal inputs so that alternative flood and recovery scenarios can be compared. The main variables and their functions are summarized below. The model outputs include the external and generator-room water levels, Current MTTF, power-failure rate, hourly failure probability, LOOP/SBO status, system-performance trajectory, and RI.

3.1 Main Input Variables

Flood scenario: Maximum flood level, time to peak, and recession duration define flood intensity and temporal shape.

Physical exposure: Travel delay and critical inundation level determine the onset and duration of equipment exposure.

Failure risk: Basic MTTF and MTTF sensitivity control Current MTTF, failure rate, and hourly failure probability.

Power-loss states: LOOP/SBO occurrence and state variables represent accident initiation, impact, and restoration.

Recovery process: Recognition/administrative delay and repair time define the effective SBO recovery time.

3.2 Interpretation of Scenario Outputs

The scenario structure supports several comparative analyses. Increasing the maximum flood level or extending the recession duration can lengthen the period of critical exposure. A longer physical delay shifts the beginning of equipment impact and may change the available response window. Lower basic MTTF or greater MTTF sensitivity increases the modeled failure risk under the same generator-room water level. In the recovery stage, the effective SBO recovery time directly controls the duration of the outage and the area of performance loss used in the RI calculation.

At the present stage, these outputs should be interpreted as a comparative scenario-analysis framework rather than as plant-specific failure probabilities. Application to a particular nuclear power plant requires site-specific flood simulations, verified equipment threshold levels, component-reliability data, and observed or procedurally defined recovery times. Linking these data to the model would allow the relative importance of flood intensity, travel delay, equipment vulnerability, and recovery delay to be evaluated on a consistent time basis.

4. Conclusions

A system dynamics model was developed to assess the dynamic resilience of nuclear power plants under flood-induced power-loss scenarios. The model distinguishes external flood level from generator-room water level, incorporates physical travel delay, represents changes in MTTF-based power-failure risk above a critical inundation level, and tracks LOOP/SBO occurrence and recovery. System performance is calculated from the balance between degradation and recovery rates, and the Resilience Index summarizes cumulative performance over the simulation period.

A key feature is the explicit separation of recognition and administrative delay from repair time in the effective SBO recovery time. This enables the influence of both organizational response and technical restoration on outage duration and resilience to be examined. Coupling the framework with plant-specific hydraulic results, equipment thresholds, reliability information, and recovery records can support flood-response planning and comparative resilience assessment. Further work will focus on data-based parameterization and validation for realistic nuclear power plant flood scenarios.

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