Systematic Approach for Comprehensive Consideration of Hydrological Hazards in Level 1 PSA

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Introduction

- Probabilistic risk analyses have been carried out for NPPs in Germany for more than 35 years
- Insights from PSA have resulted in improving nuclear safety and contributed significantly to the high safety level of German NPPs
- Operating experience has demonstrated the significance of the potential risk from external and internal hazards including hazard combinations

➢ GRS has enhanced and extended existing methods and tools regarding the site-specific risk of hazards

- Level 1 PSA for hydrological external as well as internal hazards with flooding potential
- PSA model extension considers interdependencies between different hazards
- Additional failure modes for SSCs related to hazard-induced initiating events allocated to the corresponding plant operational states (POS)

Lessons Learned from Operating Experience

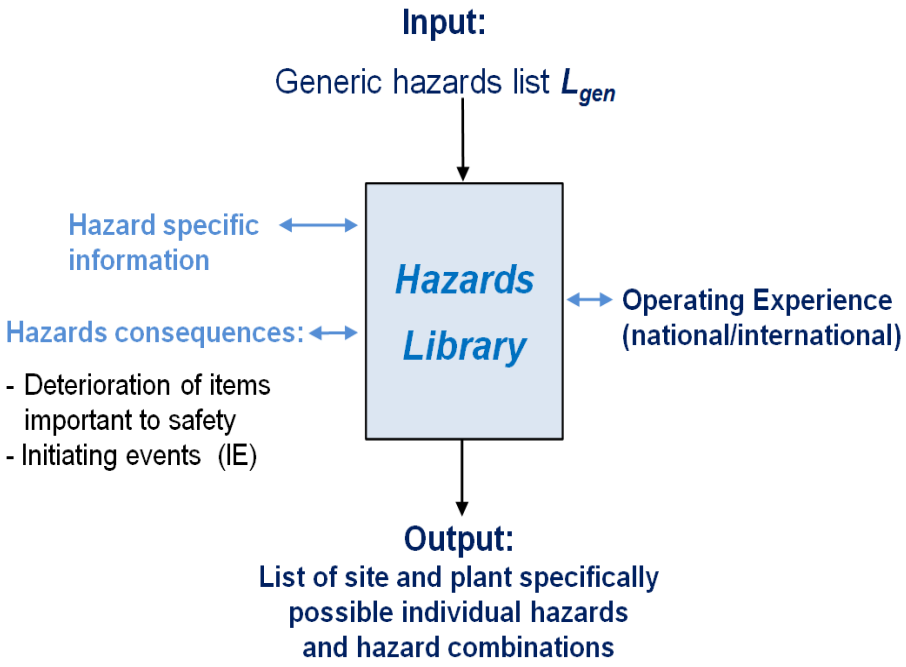
- Combinations of hydrological hazards with other internal or external hazards should be taken into account in PSA because of their non-negligible contributions to CDF and/or FDF

- Events investigated demonstrate the importance of re-evaluating risks from often neglected support and peripheral systems, particularly with respect to issues related to infrastructure and surrounding environment

➢ For an appropriate and comprehensive analysis of the operating experience a screening approach has been developed for systematically screening those hazards and hazard combinations to be addressed in PSA site and plant specifically

Analytical Tool *Hazards Library*

- GRS has developed the tool *Hazards Library* for systematically considering the variety of external and internal hazards in safety assessment
  - Compilation of as much as possible generic information for each individual hazard
  - Detailed information characterizing hazard and impact consequences
  - Complete information on all types of hazard combinations
  - Consideration of insights from operating experience worldwide as far as possible
  - Library contains qualitative and quantitative criteria for hazards screening (partly automated, by pre-formatted queries, keyword searches, etc.)



Hazards Library - Overview on Different Hazard Classes

External hazards	
Natural hazards:	
Class A:	**Seismotectonic hazards**
Class B:	**Flooding and other hydrological hazards**
Class C:	**Meteorological hazards**
Class D:	**Extraterrestrial hazards**
Class E:	**Biological hazards**
Class F:	**Geological hazards**
Class H:	**Natural fires**
Man-made hazards (Class Z)	
Internal hazards (Class I)	

Hazard Screening Principles

- Categorization of hazards to be considered for the NPP site under investigation regarding level of detail needed for the probabilistic analyses
  - L_0 Hazards with a negligible contribution to the overall risk
  - L_{rough} Hazards with a risk contribution low enough that a rough quantitative assessment is sufficient
  - L_{detail} Hazards that need in-depth probabilistic analysis
- Identification of hazard combinations starts from those individual initial hazards not screened out on a site and plant specific basis in order to reduce the effort for screening of hazard combinations
- Probabilistic analyses can be systematically carried out for all hazards and hazard combinations remaining after screening based on the Level 1 PSA model for internal events

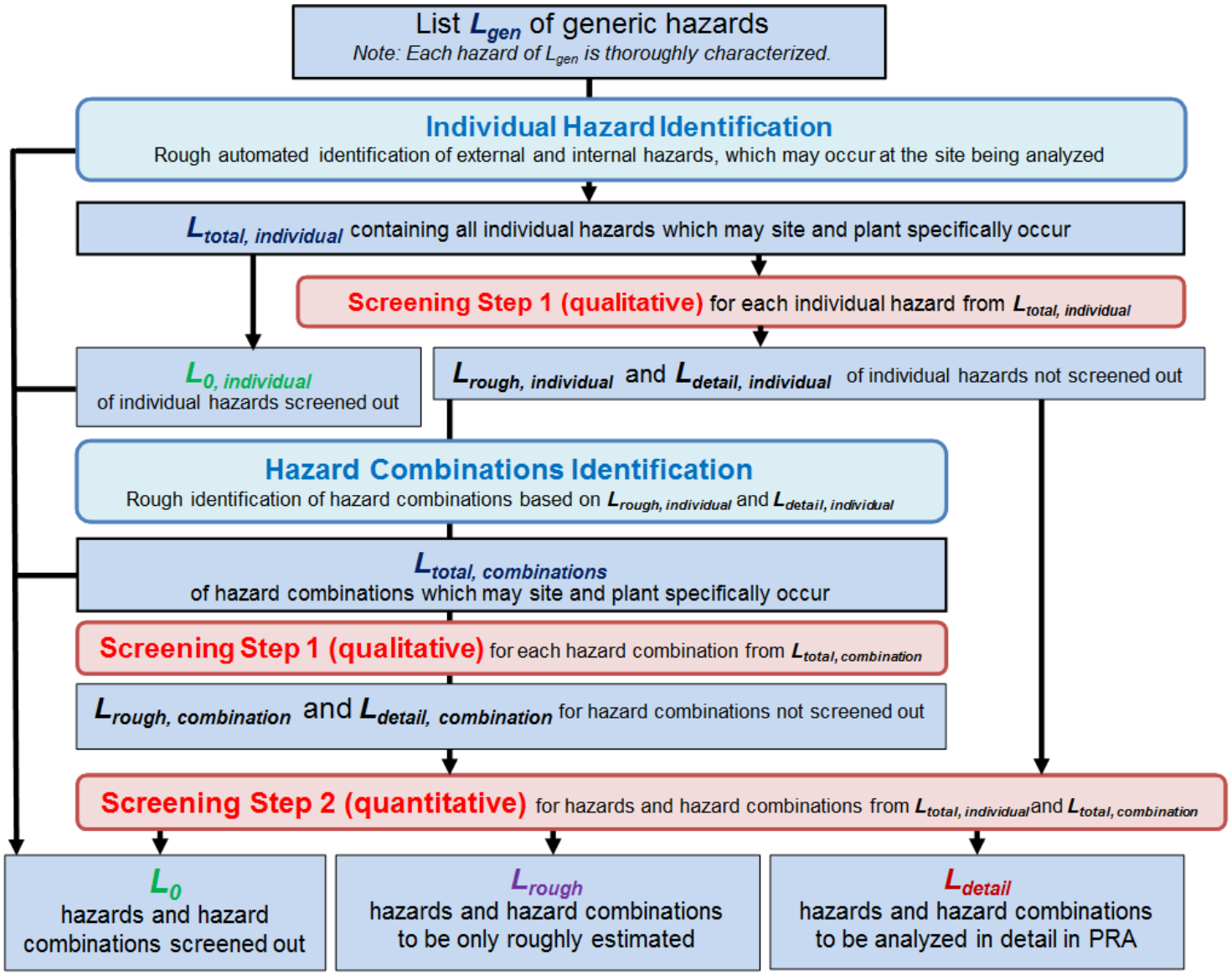
Information on Hazard Combinations

- **Causally related events:**
  Hazards subsequent or consequential to other hazards including event chains of 3 or more hazards

- **Correlated events:**
  An initial common cause event (including external hazards) results in one or more hazards, which even may occur simultaneously

- **Unrelated events:**
  Initial event (including hazards) occurring independently from, but simultaneously to a hazard

Overview of the Hazards Screening Approach



Qualitative Screening of Individual Hazards – Starting Point

- Identification of those individual hazards from L_{gen} in principle possible to occur at the plant and site under investigation ➔ $L_{total,individual}$
- Qualitative screening of individual hazards, see example for Class B "*flooding and other hydrological hazards*"

Hazard	Type of Individual Hazard
B1	Tsunami
B2	Flash flood by local extreme precipitation
B3	Flooding by melting snow
B4	Flooding by extreme precipitation outside the plant boundary
B5	Extreme groundwater increase
B6	
a	High water level due to obstructions in the course of the river
b	Low water level due to obstructions in the course of the river
B7	
a	High water level by natural changes in the course of the river
b	Low water level by natural changes in the course of the river
B8	Flooding by high fresh water waves due to volcanism, landslide or snow slide

Hazard	Type of Individual Hazard
B9	
a	High water level with wave formation due to failure of water control or retention systems (e.g., damns, dykes, etc.)
b	Low water level with wave formation due to failure of water control or retention systems (e.g., damns, dykes, etc.)
B10	Seiche
B11	Tidal bore (running extremely river-up)
B12	Tidal high water, spring tide
B13	Storm induced waves and monster waves
B14	Storm surge
B15	Corrosion resulting from contact with salt water
B16	Instability of coastal areas (of rivers, lakes, oceans) by erosion due to strong water flows or sedimentation
B17	Water flotsam (mud, debris, etc.)

Qualitative Screening of Individual Hazards – Results for a German Pilot NPP Site

- NPP site under investigation: riverine site
  - B1, B10, B11, B12, B14, B15 screened out
- Analysis only of hazards with flooding potential
  - B6b, B7b, B9b, B17 screened out
- Site specific information of hazard analysis (Periodic Safety Review)
  - B5, B7a screened out
- Individual class B hazards remaining after qualitative screening: B2 (flash flood) and B3, B4, B6a, B8, B9a (riverine flooding due to different reasons)

Quantitative Screening of Individual Hazards – Results for a German PilotNPP Site

- Definition of quantitative screening criteria (in the example by national PSA guidance)
  - Occurrence frequency (e.g., < E-06 / ry)
  - Core and/or fuel element damage frequency (e.g., << E-08 / ry)

➢ Class B hydrological hazards with flooding potential remaining after quantitative screening for the pilot plant site:

- **B2** (flash flood by local extreme precipitation)
- **B3** (flooding by melting snow)
- **B4** (flooding by extreme precipitation outside the plant boundary)

Screening of Hazard Combinations

- Qualitative screening
  - Screening of hazard combinations starts from all individual hazards remaining after qualitative screening
    - Category I: Causally related (consequential) hazards
    - Category II: Correlated hazards
    - Category III: Independently, but simultaneously occurring hazards
  - Screening of first order combinations
  - Identification of potential event chains (higher order combinations)
  - Screening of higher order combinations
- Quantitative screening
  - Application of same criteria as for individual hazards
  - Iterative quantitative screening of higher order combinations

Hazards Combinations Screening for a German Pilot NPP Site

- Results of quantitative screening:
  hazards to be analyzed roughly or in detail

		I	I1	I2	I3	I7	A	A1	B	B2	B3	B4	C	C1	C16	Z	Z16
I. Internal hazards																	
I1	Internal fire							‖			‖	‖					
I2	Internal flooding		↙														
I3	Component (incl. high energetic) failure		↙	↙													
I7	Internal explosion		↙	↙	↙												
A. Seismotectonic hazards																	
A1	Earthquake		↗	↗	↗	↗					‖	‖					
B. Flooding and hydrological hazards																	
B2	Flash flood by local precipitation			↗							‖	‖					
B3	Flooding by snow melt			↗								‖			‖		
B4	Flooding by precipation outside plant boundary			↗											‖		
C. Meteorological hazards																	
C1	Precipitation (by rain or snow)		↗		↗	↗					↗	↗					
C16	High wind				↗												
Z. Man-made hazards																	
Z16	Accidental aircraft crash in flight corridors or zones		↗		↗	↗											

Category 1: causally related (consequential) hazards

A can induce B

B can induce A

A can induce B and B can induce A

Category 2: correlated (by common cause) hazards

A and B are induced by a common cause

Category 3: unrelated hazards

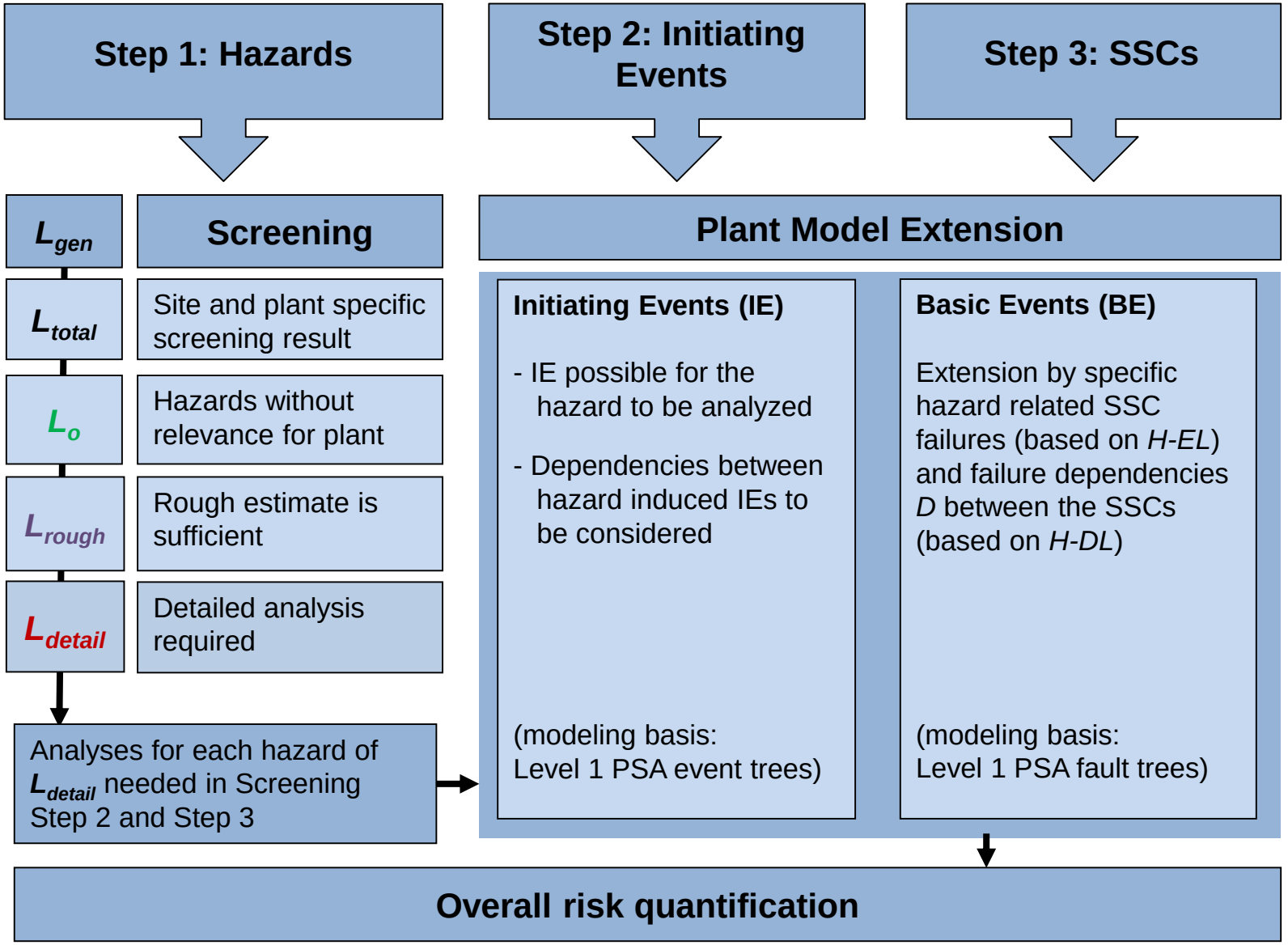
A and B occur independently but simultaneously

Remarks

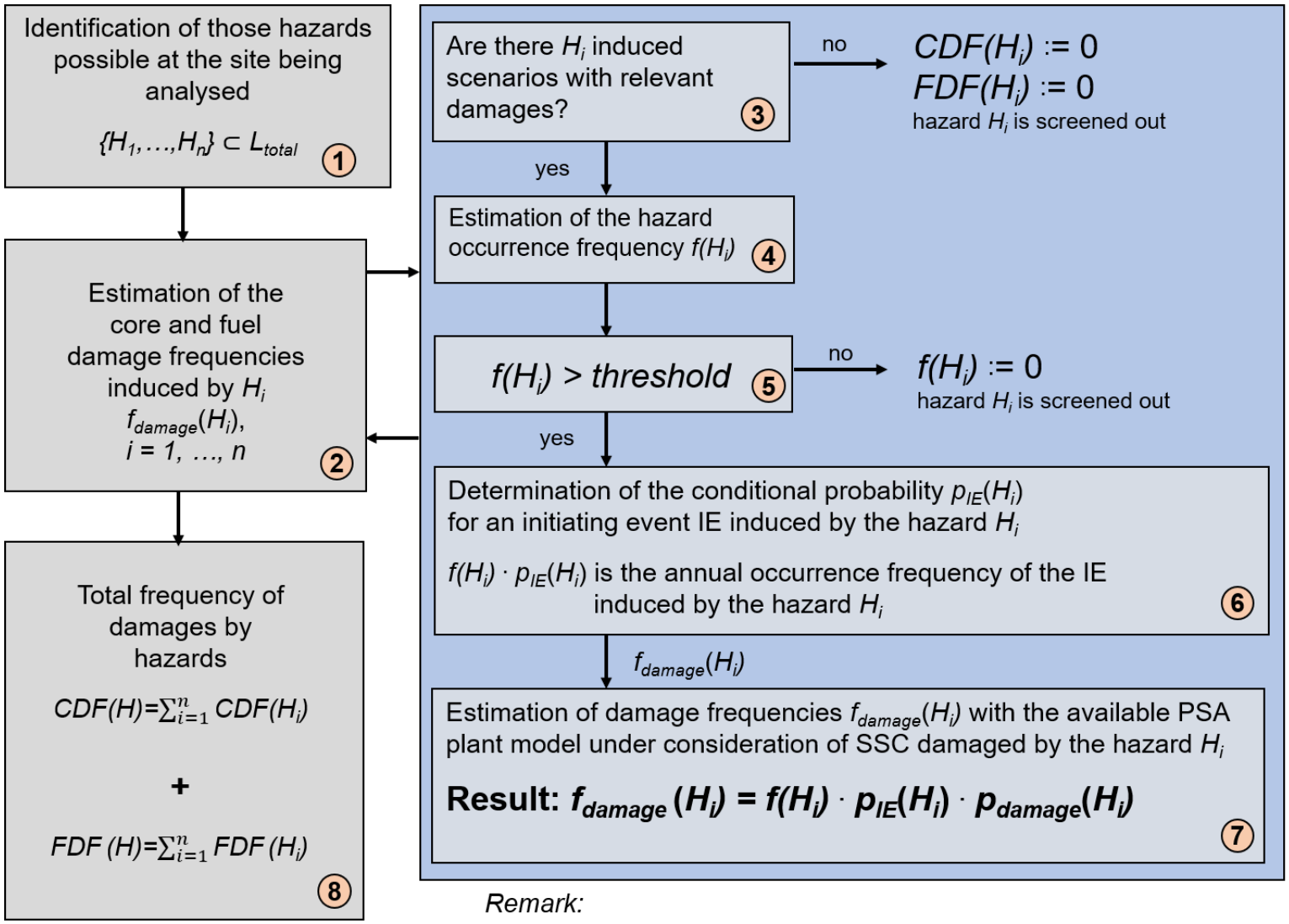
orange/red:	combinations of external hazards
blue/turquois:	combinations with internal hazards
below diagonal:	causally related hazards
above diagonal:	correlated and unrelated hazards

- Detailed PSA needed for the following hazards with flooding potential
  - Individual hazards: B2, B3, B4, I2
  - Hazard combinations: B2, B3 => I2 (covered by I2); no correlations; uncorrelated hazards: **B2 with B3 or B4**

Overview of the Hazards Risk Assessment Approach by GRS



Extensions of Level 1 PSA Plant Model



Remark:
f_{damage} = CDF and FDF
p_{damage} = CDP and FDP

Hazard Equipment List (*HEL*)

- The SSCs screening for generating hazard equipment lists *HEL* starts with such a list for each hazard and hazard combination remaining after hazards screening
- The hazard equipment list for an individual hazard H_k covering the entire number *j* of SSCs $H_kEL = \{SSC_1, \ldots, SSC_m\}_{Hk}$ has the following characteristics:
  - For a given H_i the corresponding H_kEL contains those $j = 1, \ldots, m$ SSCs being vulnerable to the impact of H_k
  - In addition, the failure or unavailability of any such SSC_j should contribute to the hazard induced risk
- First, a preliminary rough *HEL* is generated covering those SSCs related to the basic events (BE)
- Based on a target oriented plant walk-down the list is updated
- Result of the qualitative screening is a compilation of the final hazard equipment list *HEL* applicable for extending the plant model

Hazard Dependencies List (*HDL*)

- As part of the Hazards PSA steps 2 and 3 for each hazard and hazard combination not screened out, a hazard dependencies list H_kDL needs to be compiled $H_kDL = \{D_1, \ldots, D_n\}_{Hk}$
  with $D_k = \{A_k, S_k, c_k\}$, characterized as follows:
  - For a given H_k the corresponding H_kDL contains dependencies among the hazard induced failure behavior of SSCs needed to be considered
  - Generally, dependency D can be characterized as a triple of:
    - Set of dependent SSCs S_k,
    - Common characteristics of the elements of S (e.g., the water level as cause for a hydrological hazard H_k induced dependency) A_k, and
    - Correlation factor c_k representing the strength of the dependency

HEL and *HDL* - Example for B2 at Pilot NPP Site (water level < protection height, f = 7 E-04/ry)

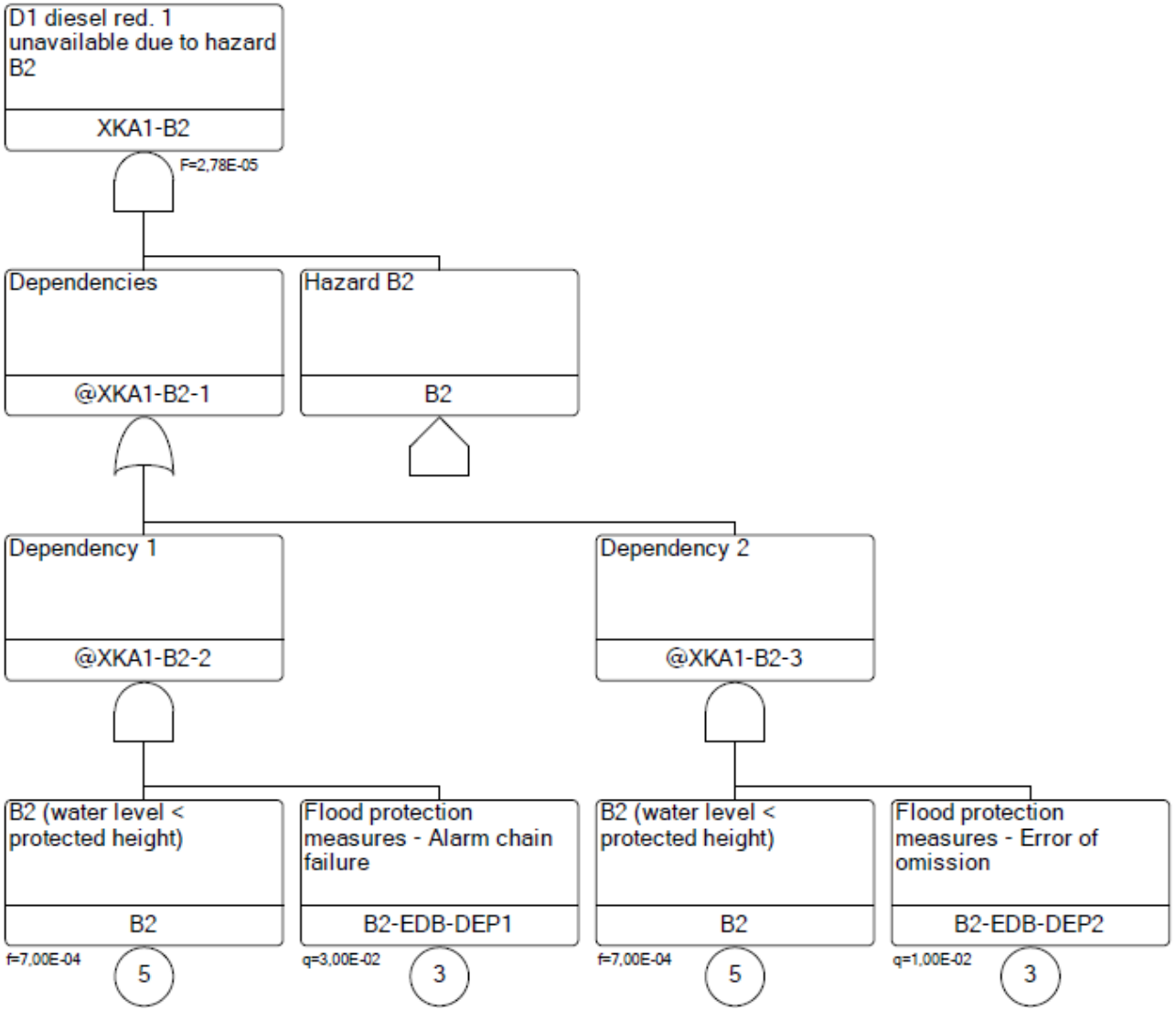
Hazard Equipment List (*HEL*)

SSC	Basic Event ID	Basic Event Description	Flooding Area/Building
D1 diesel redundancy 1	XKA1-DNR	D1 diesel does not run	Emergency Diesel Building, redundancy 1
…	…	…	…
Main condensate pump 1	LCB1-DNR	Pump does not run	Turbine Building
…	…	…	…

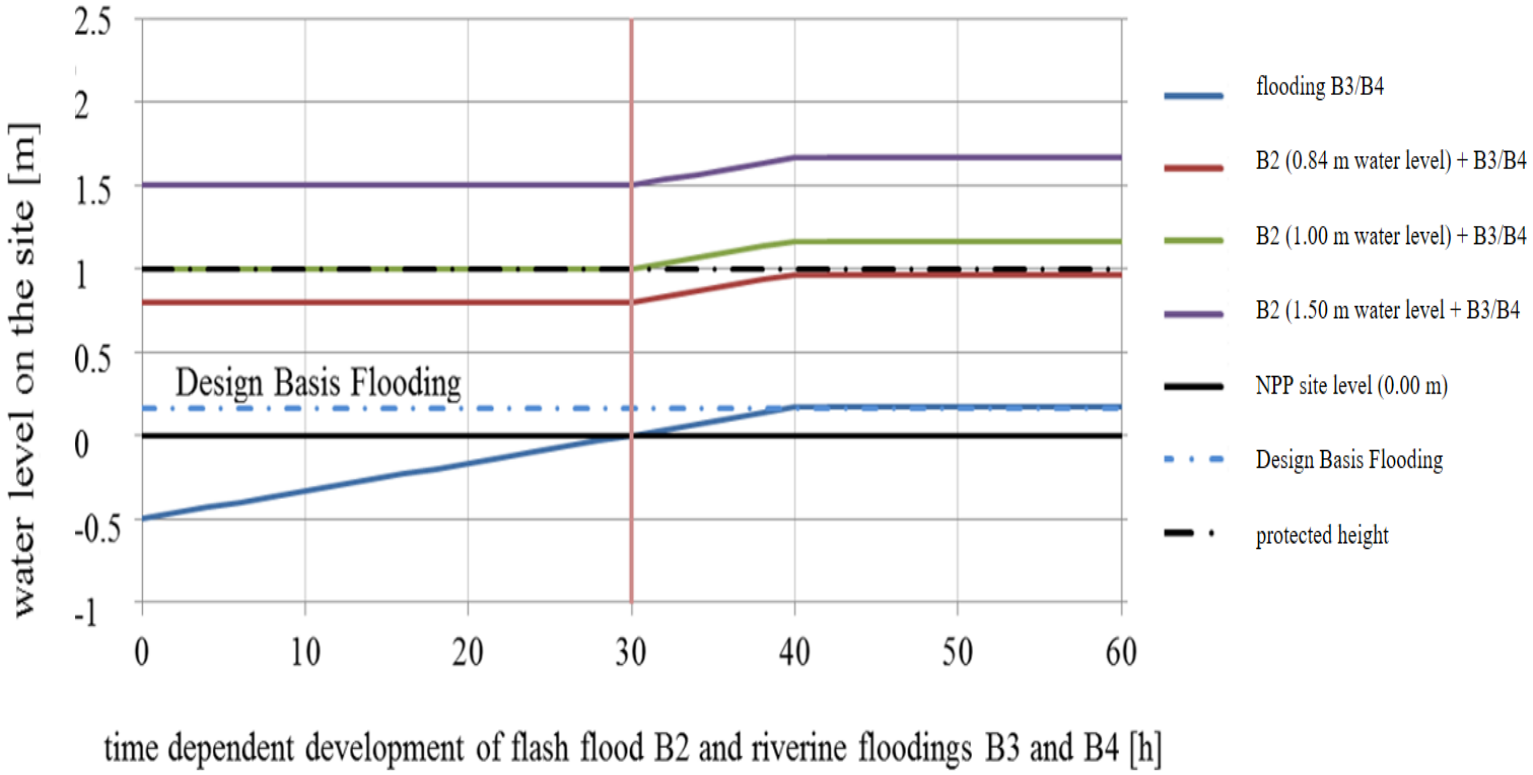
Hazard Dependencies List (*HDL*)

Basic Event ID	Dependency	Failure Probability
XKA1-DNR	Flood protection measures – alarm chain failure	0.03
XKA1-DNR	Flood protection measures – error of omission	0.01
LCB1-DNR	Flood protection measures – not available	1

Fault Tree Extension: Example for B2 at Pilot NPP Site (water level < protection height, f = 7E-04/ry)



Water Levels due to External Flooding at a Pilot NPP Site



Remark:

Assumptions for flash flood heights are highly pessimistic for the waterway at the given plant site according to in-depth investigations carried out after the validation of the Level 1 PSA model extension

Analysis Cases Considered Within Extended Level 1 Flooding PSA for a German Pilot NPP Site

Case	Flooding scenario	Maximum water level	Flooded buildings	Pre-warning period
1a/b	B2; EDB flood partitions set/closed (1a) / not set/closed(1b)	1.00 m	TB, SSB, AB[1]; in case of temporary flood protection measures failure: SBs[2], EDB	~ 2 h
2	B2; Alternative A	1.00 m ≤ **I** < 1.50 m	TB, SSB, SB, EDB	~ 2 h
3	B2; Alternative B		TB, SSB, AB	~ 2 h
4	B2; Alternative A	*1.50 m < **I** < 3.10 m*	TB, SSB, SB, EDB, EB	~ 2 h
5	B2; Alternative B		TB, SSB, AB, ECWPS, ACWB	~ 2 h
6	B3 or B4 (design basis flood)	0.16 m	TB, SSB; in case of temporary flood protection measures failure: SBs[2], EDB, AB	~ 30 h
7	B2 + B3 or B2 + B4; B2 occurs when for B3/B4 I < -0.5 m	< 3.10 m	see Cases 1 to 5	~ 2 h
8	B2 + B3 or B2 + B4; B2 occurs when for B3/B4 - 0.5 m < I < 0 m	< 3.10 m	see Cases 1 to 5	2 h – 30 h
9	B2 + B3 or B2 + B4; B2 occurs when for B3/B4 I ≥ 0 m	0.96 m (0.80 m by B2 + 0.16 m by B3/B4)	see Case 1	~ 30 h
10		1.16 m (1.00 m by B2 + 0.16 m by B3/B4)	see Cases 2 and 3	~ 30 h
11		< 1.66 m and < 3.10 m (< 1.50 m by B2 + 0.16 m by B3/B4)	see Cases 4 and 5	~ 30 h

Important Results for Level 1 PSA for the Pilot NPP Site

Case	Frequency [1/ry]	Transient	System functions unavailability
1a	7 E-04	LOFW + LOMHS	8 E-04
1b	7 E-04	LOFW + LOMHS	8 E-04
2	2 E-04	LOOP	8 E-04
3	2 E-04	LOFW + LOMHS	8 E-04
4	2 E-05	LOOP	1 E-03
5	2 E-05	LOFW + LOMHS	8 E-04
6	1 E-04	LOOP	8 E-04

LOOP: loss off offsite power
LOFW: loss of feedwater
LOMHS: loss of main heat sink

- Results for CDF under very pessimistic assumptions for model validation: E-08 to E-09 / ry
- Recent results under realistic assumptions for flood heights: $\leq$ E-10/ry

Conclusions and Outlook

- GRS has developed systematic approach for comprehensively considering hydrological hazards in Level 1 PSA
- Model extensions include a systematic and detailed approach for screening of individual hazards and hazard combinations and extensions of the Level 1 PSA plant model
- The enhanced approach has been successfully applied within PSA for a German multi-unit, multi-source NPP site regarding hydrological hazards with flooding potential for ‘power operation’
- Applications are possible for all POS through the entire NPP life cycle
- Ongoing improvements, e.g. for risk aggregation by hazards and for application to multi-unit, multi-source nuclear sites
- Planned enhancements: more automated hazards screening for reducing systematically as much as possible potential errors
- Extensions of the plant model up to Level 2 PSA have been started to systematically cover hazards and combinations affecting more than one facility at a nuclear plant site