

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

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Abstract: An important research and development task is to continuously enhance, extend, and validate methods for Probabilistic Safety Analysis (PSA[†]) and to improve the corresponding analytical tools for efficiently carrying out PSA. Accordingly, for determining the site and plant specific risk of a nuclear power plant (NPP) from internal as well as external hazards, methods applied for Level 1 PSA have been comprehensively extended and enhanced. While the generic systematic screening approach has been completed for all individual hazards and resulting hazard combinations, the focus of extending the existing Level 1 PSA plant model for systematically considering internal and external hazards was in a first step laid to hydrological hazards and hazard combinations with potential flooding. For those hazards and hazard combinations the Level 1 PSA fault trees have been extended by additional basic events. The model extension considers existing dependencies between different hazards and hazard specific failure modes for structures, systems and components (SSCs). The failure modes are related to initiating events induced by the hazards, which are allocated to the corresponding plant operational states (POS). The extended methodological approach has been validated for two groups of internal and external hydrological hazards with potential flooding for an exemplary German pressurized water reactor NPP site.

Keywords: Probabilistic Risk Assessment (PRA), Nuclear Power Plant (NPP), Operating Experience, Internal and External Hazards, Hydrological Impact, Screening Approach, PSA Methods.

1. INTRODUCTION

PSA are an important tool more and more used for assessing the safety of nuclear power plants supplementing deterministic assessment. In particular, PSA enables to merge knowledge on the design and operation of the plant, from the operating experience from the plant being analyzed and from other, similar plants as well as insights from reactor safety research and general expertise within a comprehensive assessment of the state with respect to the safety of the plant under investigation. PSA as a supplementary analytical tool allows for quantitatively assessing the effect of estimates on the overall result. In that way PSA provides a reliable basis for decisions on the necessity and the benefits of safety improvements. Probabilistic risk analyses have been carried out for nuclear power plants in Germany for more than 35 years. Insights from PSA performed in the past have resulted in improving nuclear safety and contributed significantly to the high safety level of German nuclear power plants. An important task of GRS as the competent institution for probabilistic safety analyses in Germany is to continuously enhance, extend, and validate PSA methods according to the state-of-the-art as well as to improve the corresponding analytical tools for efficiently carrying out PSA up to Level 2.

The operating experience of nuclear facilities worldwide has increased the evidence that it is of fundamental importance to perform site and plant specifically PSA that systematically evaluate the potential risk provoked by external and internal hazards including potential combinations of hazards and other events. Even, if these hazards did not pose any significant harm to the plant where the

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† In this paper, the terms *Probabilistic Safety Assessment (PSA)* and *Probabilistic Risk Assessment (PRA)* are used interchangeably.

hazard occurred, they do represent important precursors, which should be considered in deterministic as well as probabilistic safety assessment. Therefore, appropriate research and development for safety assessment is essential to continuously enhance, extend, and validate PSA methods according to the state-of-the-art as well as to improve the corresponding analytical tools for efficiently carrying out PSA.

Accordingly, GRS has enhanced and improved the existing methods and tools with respect to determining the site-specific risk of nuclear power plants in the example of a comprehensive flooding analysis in the frame of the research and development project RS1539 “*Enhancing Methods and Tools for Probabilistic Safety Analyses for Site-specific Hazards PSA and Prognosis of Accident Sequences and Source Terms*” in order to make these applicable for future safety assessments. Based on the evaluation of the worldwide NPP’s operation experience the methodological improvements made include a detailed screening approach for all internal and external hazards including hazard combinations to be principally anticipated as well as a systematic extension of the PSA plant model.

The focus of extending the existing Level 1 PSA model was put on hydrological external as well as internal hazards with potential flooding. The PSA model extension considers interdependencies between the different hazards. In addition, failure modes for SSCs have been defined. These failure modes are related to hazard-induced initiating events which are allocated to the corresponding plant operational states (POS). The PSA fault trees have been extended by additional basic events and quantified based on those hazards and hazard combinations remaining after screening.

2. INSIGHTS FROM THE OPERATING EXPERIENCE WITH RESPECT TO HYDROLOGICAL HAZARD IMPACTS ON NPP AS BASIS

More recent operating experience from NPP worldwide has demonstrated the potential safety significance of hydrological hazard impacts. In the following typical examples for hydrological hazard scenarios are presented. All these scenarios indicate that the impact of hydrological hazards is non-negligible and therefore such hazards as well as related hazard combinations need to be appropriately addressed in order to perform a realistic PSA.

2.1. Events Resulting from Hydrological Hazards

2.1.1. Rainwater Ingress into Reactor and Turbine Building due to Heavy Rainfall

In 2011, a thunderstorm with heavy precipitation (rain) occurred in the area around a German single unit NPP with boiling water reactor (BWR). The high rainwater quantity caused an overload of pipe connectors at the downpipe bends of the roof drainage system. Approx. 20 min after the onset of precipitation, water ingress into the reactor building (RB) sump was signaled. Inspections revealed the downpipe leakage of the RB roof drainage and leakages in the turbine building (TB). Due to the leakage in the rainwater conduits, the barrier integrity was impaired. The total water ingress of 100 m³ into the RB and the TB had no effects on items important to safety. Nevertheless, the event showed that a failure of the rainwater drainage systems may lead to barrier function degradation of buildings. The subsequent flooding may impair safety functions, particularly in case of precipitation amounts exceeding the design basis.

2.1.2. Rainwater Induced Flooding of a Reactor Building

In 2016, a precipitation induced flooding event occurred at a Japanese multi-unit NPP site with two BWR units [1]. At the time of the event, the heavy rainfall caused flooding of the road, with water entering cable ducts leading to the RB reaching the floor above a room on the first basement floor where batteries for emergency use in case of loss of offsite power were installed. Approx. 6.6 t of rainwater entered the RB of the second plant unit. It was not expected that such a volume of rain could flood the building. Therefore, such a flooding hazard was not considered in the plant safety concept.

2.1.3. Reactor Scram and Containment Isolation caused by Seawater Ingress into the Reactor Building

In 2015, a severe weather event occurred at a BWR unit of a coastal multi-unit NPP site of different types located at the Baltic Sea. The hazard started with a storm which together with heavy rain caused high seawater levels up to 1.4 m above normal. During the event, seawater seeped through the bedrock to a bedrock gap surrounding the RB. However, since the strainers in the two drain lines from the bedrock gap to the sea were clogged by sediments, the water level in the bedrock gap continuously increased up to a level of 2.5 m. The accumulation of water took place without being detected. After several hours, a safety hatch in the RB outer wall approx. 1.5 m above ground level opened inadvertently and the water flow opposite to the intended flow direction into the RB and subsequently through the building sump into a room containing systems connected to the primary system. The water level reached approx. 0.3 m and caused floor level transmitters to actuate automatic reactor scram and containment isolation. More extensive flooding of the RB and an increase of a loss of safety functions both might have been possible during this event.

2.1.4. Ingress of Plant Debris into Raw Water Pumping Station

In 2009, adverse cooling water conditions led to a series of circulating water system pump trips at a multi-unit NPP site situated on a river estuary. These trips were caused by clogging of the drum screens due to massive ingress of biological debris and sediments from the river. In three cases these trips also caused reactor scrams. The incidents were caused by a combination of several events: (i) floods at two tributaries upstream of the site in early 2009 that displaced sediment which had accumulated since a previous flood event in 2004, (ii) a heavy storm and high tide with a height of 6.50 m (normal level: 6.00 m) in 2009 that inundated the river banks and caused substantial re-suspension of biological debris and sediments taking more vegetation than usual to the NPP pumping station, and (iii) no dredging performed around the water intakes of the NPPs on the river. The reactor trip sequences went correctly. However, the severe drum screen clogging that led to the reactor scrams may also have induced a total loss of heat sink. This would have caused an aggravation of core melt risk at one or more of the NPP units of this site. The event shows, that it is necessary to consider possible combinations of natural phenomena/hazards in PSA together with potential effects on the safety systems of nuclear facilities.

2.1.5. External Flooding and Independent Fire

In 2011, a combination of a long-duration external flooding and an independent fire was observed in a U.S. nuclear power plant located at the Missouri river. The accessibility of the plant is necessary even under such extreme conditions to ensure that technical support from outside, in this case by the local fire department, can be provided. Potential impacts of such hazard combinations should be assessed within PSA.

2.1.6. Rainwater Induced Event and Consequential Hazards

Observations from the international fire events database OECD FIRE [2] have shown one event of extreme weather with heavy rainfall conditions resulting in a plant internal fire. The precipitation (external hazard) caused a high energy arcing fault (HEAF) with consequential fire (both internal hazards). The event sequence was as follows: Rain water penetrated through the gap of a cable duct located outside the TB. The water caused a short circuit with a longer duration arc resulting in a HEAF event at a 6.9 kV bus duct resulting in a fire in a room for electric equipment. Events resulting from rainwater penetrating through building ceilings have also occurred at other nuclear sites. These events did not cause fires, however similar event combinations of consequential events may occur. These types of event sequences were a trigger to consider such more unlikely NPP states for risk estimation and for implementation of preventive actions.

2.2. Lessons Learned from the Operating Experience

One lesson learned from the operating experience is that combinations of hydrological hazards with other internal or external hazards should be taken into account in PSA, since their contribution to core or fuel damage frequency (CDF or FDF) is not necessarily negligible. Furthermore, the events presented as examples 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 by GRS for systematically screening those hazards and hazard combinations, which need to be addressed in PSA site and plant specifically.

3. HAZARDS LIBRARY – AN ANALYTICAL TOOL FOR HAZARD CHARACTERISATION AND SCREENING IN THE FRAME OF HAZARDS PSA

For systematically considering the variety of external and internal hazards in the frame of safety assessment, GRS has developed the analytical tool *Hazards Library* for compiling as much as possible generic information on each hazard to be analyzed itself as well as on the potential consequences of the impact by the hazard and/or hazard combinations. This also covers the deterioration of items important to safety, resulting in initiating events, etc. for each individual hazard. Moreover, observations and insights from the operating experience from nuclear installations regarding external and internal hazards are collected and compiled in this library. The tool can then be used for the screening of individual hazards as well as for generating possible hazard combinations and their screening providing qualitative screening arguments as well as criteria for quantitative screening.

The *Hazards Library* comprises a variety of tables containing information needed for hazards screening and a final selection of those hazards and hazard combinations, for which either a simplified or a more detailed analysis is needed in the frame of Hazards PSA. In addition, the *Hazards Library* contains some further information related to the NPP site being analyzed and needed for PSA purposes, such as (i) list of the initiating events (IE) for different types of reactors and plant operational states (POS), (ii) list of potential types of damage for the entire SSCs, (iii) compilation of site specific parameters relevant for the analysis, (iv) compilation of reported events from hazards observed from the operating experience of the site under investigation, and (v) compilations of Hazards PSA being available.

Moreover, the *Hazards Library* substantially supports the screening of hazards and hazard combinations needed to limit the analytical effort. In the following, the different steps of the hazards screening are briefly outlined. A systematic hazards screening requires a comprehensive compilation of all individual hazards. Based on the corresponding activities carried out on an international basis in the frame of the international project of the European Commission (EC) ASAMPSA_E (cf. [3] and [4]), GRS has further enhanced the screening approach starting by a systematic collection and binning of the different types of hazards as outlined in [5] and [6]. The different hazard classes with the individual hazards can be found in [7] and with more details on their characteristics in [8].

3.1. Screening of Hazards and Hazard Combinations

The screening approach in line with the *Hazards Library* tool developed by GRS and schematically outlined in Figure 1 starts by identifying those individual hazards from a generic list L_{gen} of the entire individual hazards, which must be assumed to potentially occur at the NPP site being analyzed. These are compiled in a list $L_{total,individual}$. After the hazards identification, a two-step qualitative and quantitative screening of hazards is performed for the individual hazards compiled in $L_{total,individual}$.

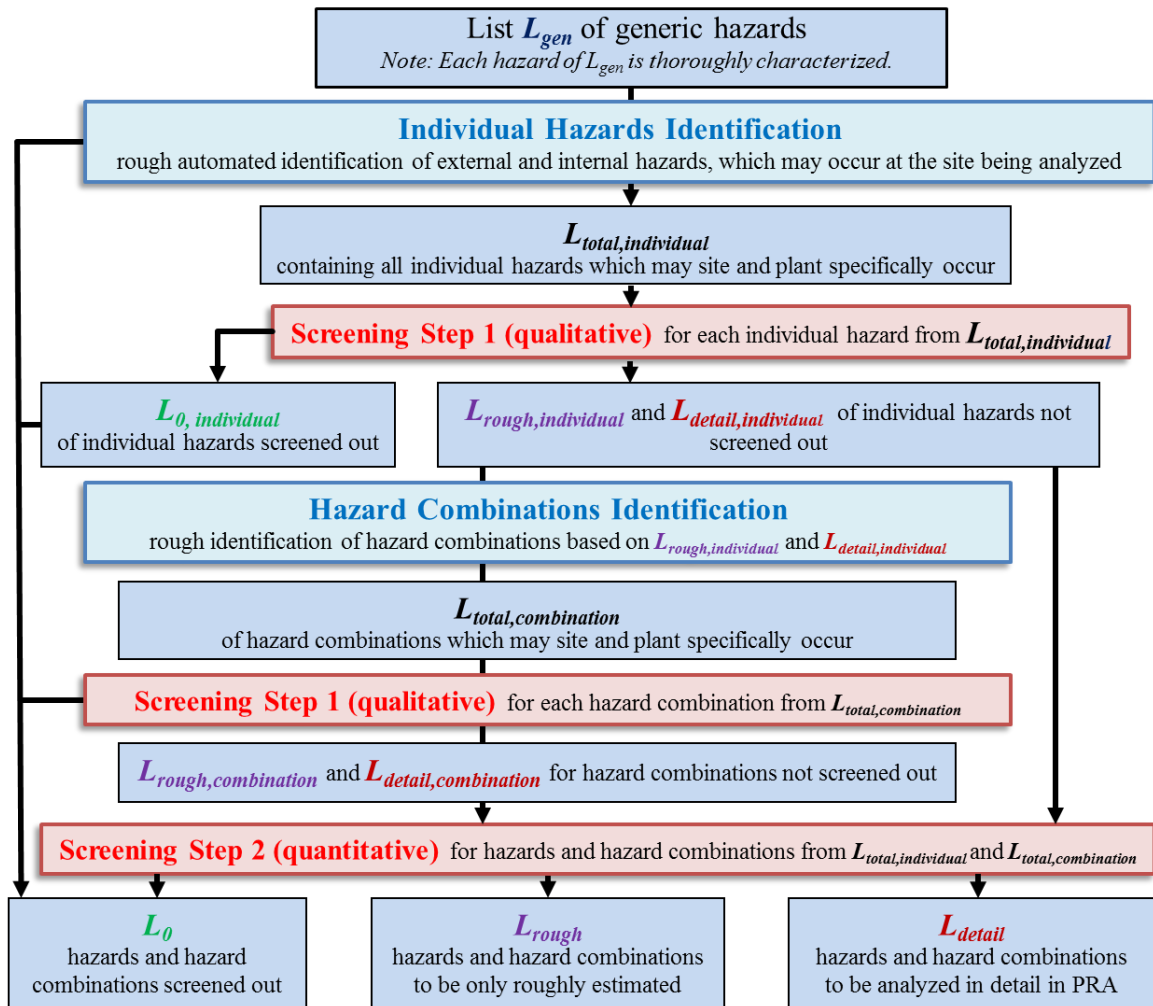
For the qualitative screening, partly semi-automated search queries provided in the *Hazards Library* for the different hazards, which either can be answered easily by “yes” or “no” (e.g., the question “Is the plant site a riverine one?”) using pre-defined keywords or for which qualitative arguments for screening these out can be given (e.g. that a specific phenomenon, such as a tropic cyclone is not

possible at a site in Northern Finland). Moreover, results from the plant site including regular updates of site characteristics (validated and/or accepted by regulatory reviews) stored in the *Hazards Library* can also be used as qualitative arguments. Individual hazards screened out qualitatively are compiled in a list $L_{0,individual}$.

For the hazards remaining after the qualitative screening the second screening step applying quantitative screening criteria is carried out. For this purpose, from a list of nationally or internationally typically used quantitative screening criteria stored in the *Hazards Library*, the analyst can select those ones applicable for the analysis to be carried out depending on the plant and the regulatory framework for performing the Hazards PSA.

The result are two hazard lists: (i) $L_{rough,individual}$, for which rough conservative risk estimates are sufficient and no detailed event sequence analyses must be performed, and (ii) $L_{detail,individual}$ containing those individual hazards to be included in detail in the Level 1 PSA plant model.

Figure 1. Overview of the hazards screening approach [5,6]



Basis for the site and plant specific identification of potential hazard combinations is again the list of those individual hazards not qualitatively screened out. For those hazard combinations identified as physically possible at the plant under investigation (compiled as $L_{total,combination}$), again the two-step qualitative and quantitative screening already performed for individual hazards is carried out. Results are the corresponding hazard lists $L_{rough,combination}$ and $L_{detail,combination}$.

As result of the hazards screening, finally a complete list L_{detail} of all those individual hazards and hazard combinations to be analyzed in more detail site and plant specifically is obtained. More detailed information regarding the screening approach of individual hazards and hazard combinations can be found in [5] to [8].

3.2. Selected Screening Results for the Reference Plant

The hazards screening has been performed for the entire hazards listed in [7]. From the natural hazards' classes A to H, only hazards of the classes A (seism tectonic hazards), B (hydrological hazards), C (meteorological hazards), E (biological hazards) and F (geological hazards) remained. Moreover, various man-made hazards (class Z) and internal hazards (class I) also remained for further analysis. In the following, only the results of the screening for external hydrological hazards with flooding potential are presented as an example.

3.2.1. Screening of Individual Class B Hazards with Flooding Potential

After identification of external hydrological hazards with flooding potential at the reference plant site – these were all class B hazards besides those with low water levels – the qualitative screening provided the result that for the reference plant site located at a river far away from any maritime influences only the hazards B2 (“flash flood”), B3 (“flooding by melting snow”), B4 (“flooding by extreme precipitation outside the plant boundary”), B6a (“high water level due to obstructions in the course of the river”), B8 (flooding by high fresh water waves), and B9a (high water level with wave formation due to failure of water control or retention systems) remained for the second screening step.

The quantitative screening, required to estimate conservatively the ranges of the occurrence frequencies of these hazards and to compare them to cut-off frequency values corresponding to given screening criteria, was based for the reference plant on quantitative screening criteria (regarding hazards occurrence and hazards induced damage frequencies) from the German regulatory requirements for PSA to be performed in the frame of Periodic Safety Reviews (PSRs), which were chosen from the list of quantitative screening criteria offered in the *Hazards Library*. This second screening step provided the result that only B2, B3 and B4 remained in $L_{detail,individual}$. Details can be found in [6] to [8].

3.2.2. Screening of Hazard Combinations with Class B Hazards

As explained in more detail in [7], the following three different categories of hazard combinations are possible. Therefore, in a first step, possible combinations of each category need to be identified for the plant site being analyzed before performing the two screening steps: (i) Category 1: combinations of consequential hazards, (ii) Category 2: combinations of hazards correlated by common cause hazards, and (iii) Category 3: combinations of unrelated hazards occurring independently of each other but simultaneously.

To reduce the number of combinations to be investigated, the identification of hazard combinations for the plant site under investigation starts from those individual hazards, which have not been screened out qualitatively. It should be noted that for Category 1 and Category 2 combinations, GRS consistently performs the analyses for combinations of related hazards as part of the PSA for the initial hazards (e.g., a seismically induced hydrological hazard in the Seismic PSA, not in the PSA for the hydrological hazard). However, it could be done vice versa. It is only important that the approach is consistent for the same site to avoid any double counting. It also should be noted that higher order event chains of more than one consequential hazard (e.g., external flooding induced internal fire with consequential internal flooding) should only be generated and screened, if the lower order combinations have not been screened out quantitatively. The result of the qualitative screening of the individual hydrological hazards with flooding potential B2, B3, B4, B6a, B8 and B9 was the following for the reference plant site (details see [8] and [9]:

- **Category 1 combinations:** B3 or B4 with consequential I2 (“internal flooding”) and B2, B3, B4, B8, or B9a with consequential B17 (“water flotsam”);
- **Category 2 combinations:** B2, B3 and B4 correlated by the same root cause (e.g. extreme weather conditions) or even together with the C1 (“precipitation”); B2 or B4 correlated by F1 (“subaerial slope instability”);
- **Category 3 combinations:** B2, B3, B4, B6a, B8, or B9 can occur independently of, but simultaneously to any other hazard, even if the likelihood of such combinations is low. Therefore, more detailed analyses are only needed if at least one of the combined hazards has a longer duration resulting in a longer list of combinations remaining for the reference plant.

The quantitative screening (screening by frequency) of those hazard combinations not quantitatively screened out – applying the same screening criteria as for individual hazards – provided the following result for the reference plant site:

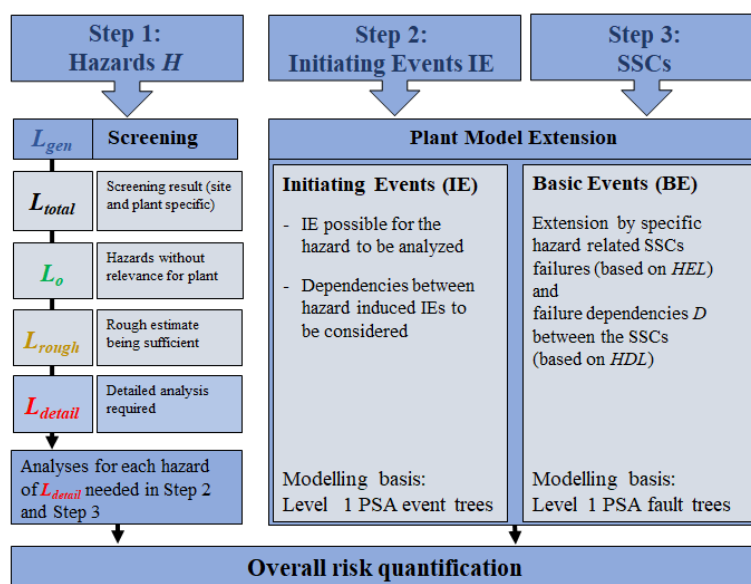
- No Category 1 and Category 2 combinations involving class B hazards remained.
- Two Category 3 combinations remained: B2 (“flash flood”) occurring independently at the same time as the longer duration flooding hazards from B3 (“flooding by melting snow”) or B4 (“flooding by extreme precipitation outside the plant boundary”).

For these combinations, in-depth analyses have been included in the Level 1 PSA plant model.

4. SYSTEMATIC EXTENSION OF AN EXISTING LEVEL 1 PSA MODEL FOR INTEGRATION OF HYDROLOGICAL HAZARDS AND HAZARD COMBINATIONS

The overall approach developed by GRS for systematically extending an existing Level 1 PSA Model for integration of individual hazards as well as hazard combinations does not only cover a complete hazards screening (extension step 1), but also model extensions concerning the initiating events (IA) from hazards (extension step 2) as well as extensions related to those SSCs, which may fail as a result of the impact by hazards not screened out (extension step 3). This approach originally developed for Seismic PSA by GRS, has been further advanced and adapted to cover the variety of different hazards. An overview is shown in the following Figure 2.

Figure 2. Overview of the hazards risk assessment approach by GRS [5,6]



In the following paragraphs, the most important enhancements of the approach are provided for the example of plant external hydrological hazards with flooding potential.

4.1. Generation of Hazard Equipment Lists and Hazard Dependencies Lists

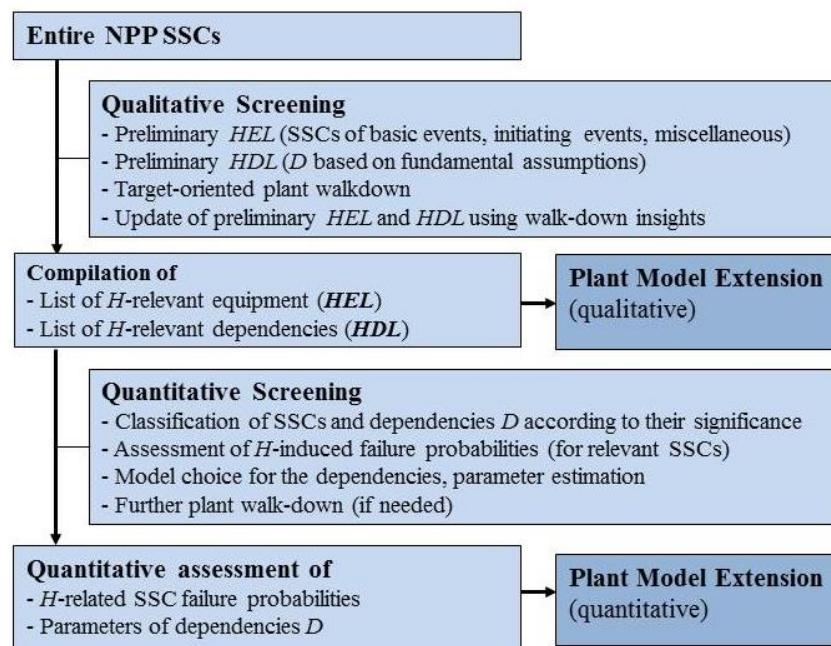
Two lists have to be generated for each individual hazard and hazard combination to be analyzed in order to extend the Level 1 PSA plant model: a so-called *Hazard Equipment List (HEL)* and a corresponding *Hazard Dependencies List (HDL)*. After the hazards screening, for each hazard not screened out for the NPP site being analyzed, the analysis has to be continued with respect to the initiating events from the respective hazards and the SSCs which may be impaired (failure of their required function) by the hazard or hazard combination.

For these two analytical steps for the plant model extension again some screening as shown in Figure 2 is needed. After the hazards screening representing the first step of the Hazards PSA the plant model needs to be extended in a second step for considering plant and site specifically all initiating events (IEs) from those external and internal hazards including hazard combinations.

In the third Hazards PSA step, the list of basic events (BE) in the plant model needs to be extended by failures of those plant SSCs related to the external hazards to be considered as well as the corresponding failure dependencies. This requires that the potential hazards induced initiating events are identified and screened out regarding their significance. In a further step, the unavailability of SSCs as a result of each hazard or hazard combination must be analyzed. The existing Level 1 PSA model has to be extended by including hazard induced failures or unavailability of SSCs for each hazard or hazard combination remaining after hazards screening.

This extension should be performed by means of the *HEL* and *HDL* derived for each hazard or hazard combination by a comprehensive qualitative and quantitative screening (as example see [6]). Figure 3 gives an overview on the qualitative and quantitative screening of SSCs as part of a Hazards PSA for generating for each hazard not screened out the corresponding *HEL* and *HDL* needed for the qualitative and quantitative extension of the Level 1 PSA plant model.

Figure 3. Screening steps for the entire SSCs of the NPP and corresponding Level 1 PSA model extension [5,6]



The SSCs screening (for generating hazard equipment lists *HEL*) starts with a compilation of such a list for each individual hazard and hazard combination remaining after the hazards screening. The result of the qualitative screening is a compilation of the final hazards equipment list *HEL*, which can

be applied for extending the plant model qualitatively. The *HEL* for a single hazard H_k covers the entire number j of SSCs (named SSC_j) identified to be vulnerable to H_k , and for which their failure contributes to the risk induced by H_k : $H_kEL = \{SSC_1, \dots, SSC_m\}$ (cf. [6] and [8]).

For quantifying the failure probabilities of the remaining SSCs vulnerable to H_k , information from the NPP being analyzed is needed, e.g., equipment failure rates and other factors affecting the hazard induced event sequences such as human reliability in case of actions to be taken within in a pre-defined period for preventing damage.

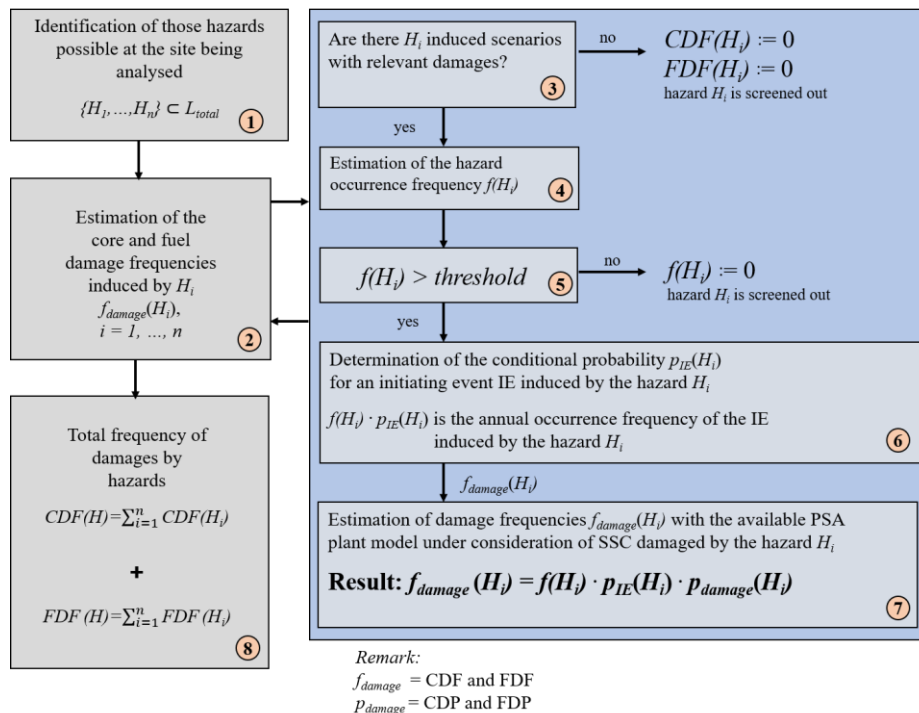
In a further analytical step, the dependencies among the failure characteristics of the vulnerable structures, systems and components need to be investigated. The result of the quantitative screening step is a conservative estimation of those parameters characterizing the dependencies D_k . The corresponding values are applied when extending the plant model quantitatively. Each dependency in the HDL list named $H_kDL = \{D_1, \dots, D_n\}_{H_k}$ is characterized by a triple $D_k = \{A_k, S_k, c_k\}$ of parameters, which include the set of dependent SSCs S_k , the common characteristics of the elements of S_k (in the example of flooding hazards the water level as cause for a flooding hazard induced dependency) A_k , and a correlation factor c_k for the strength of the relation (dependency). For adequately modeling the dependencies between the SSCs and/or the hazards impact, the fault trees of the analytical risk analysis model must be modified and multiplied for the different hazards to be considered. In addition, new elements of the fault trees need to be specified [10] within the database representing a probabilistic model of a plant system.

4.2. PSA Model Extension

A schematic overview of the approach for the plant model extension by hazards is given in Figure 4.

For analyzing the impact of e.g. hydrological hazards within PSA, site specific conditions with respect to NPP design and operation need to be considered accordingly. For the probabilistic analyses of these scenarios, several facts related to plant specific structural, operational and technical conditions need to be considered and several assumptions are made for implementation in the PSA model:

Figure 4. Extension of Level 1 PSA plant model [7]



For considering the effects of a given hazard or hazard combination on SSCs within the PSA model, it is necessary to implement the hazard induced scenarios with potential damage on SSCs important to safety in the PSA model. The conditional probability of initiating events (IE) induced by the hazard and the corresponding damage frequencies taking into account those SSCs being damaged can then be determined.

For flooding hazards, this requires identifying so-called flooding areas, where - depending on the plant operational state (POS) being analyzed and the given hazard – the required function of SSCs may fail due to their exposure to water. For the corresponding scenarios the event and fault trees are generated and analyzed taking into account the availability not only of permanent flood protection means but also temporary measures to be taken according to plant specific procedures. For determining core or fuel damage frequencies from such hazards, plant specific accident management measures must be accounted for.

5. APPLICATION OF THE APPROACH FOR FLOODING HAZARDS AT A GERMAN REFERENCE PLANT

5.1. In-depth Analyses of Potential Flooding Scenarios for the Reference Plant Site

For the individual flooding hazards B2, B3 and B4 and the Category 3 hazard combinations of B2 and B3 and of B2 and B4 remaining after screening for the reference plant site, the Level 1 PSA plant model of the reference plant has been extended and in-depth investigations have been performed. In this context, it should be noted that for demonstration of these extensions low power and shutdown states are not covered in this paper. Moreover, it has to be mentioned that no plant model extensions were necessary for the longer duration hydrological hazards with flooding potential B3 and B4, since these were already included in the existing Level 1 PSA of the reference plant. Flash floods, however, had so far not yet been included in the PSA. Therefore, a site-specific hazard analysis regarding the risk of flash floods has been performed first.

5.1.1. Hazard Occurrence Frequencies

In a first step of the in-depth analyses, the occurrence frequencies of hydrological hazards and hazard combinations with flooding potential had to be determined for the reference plant. For the individual longer duration river flooding hazards B3 and B4, these occurrence frequencies had already been estimated and updated in the frame of the most recent PSR for the reference plant. Completeness and plausibility of these frequencies have been reviewed and applied for further analyses in the frame of the extended hydrological hazards PSA.

Flash flood hazards B2 were so far not yet considered in the PSR. Since neither site specific nor operating experience from nuclear power plant sites in Germany as well as worldwide could be found, the occurrence frequencies of B2 have been estimated by GRS by means of a superpopulation approach [11] coupling the a-priori state of knowledge with plant specific observations (for details see [8] and [9]). This method revealed a mean value of approx. 1 E-03/ry (with a standard deviation of 2 E-03/ry) for the reference plant.

For further PSA analyses several cases have been categorized and investigated distinguishing between different estimated water levels l at the site considering possible combinations of the flash flood B2 with the longer duration flooding hazards B3 or B4. These cases are presented in Table 1. Their occurrence frequencies and water levels are based on observations from flash floods in the near past in an area in Germany with quite similar geological and structural conditions.

Table 1. Analysis cases considered within the extended Level 1 Flooding PSA for a German reference plant

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

¹ It is assumed that the temporary protection measures where heavy lifting gear is required are not carried out within the pre-warning period.

² Items important to safety are located at elevated positions and are therefore assumed not to be affected.

Abbreviations:

AB: auxiliary building, ACWB: auxiliary cooling water building, EB: electrical building, ECWPS: emergency cooling water pump station, EDB: emergency diesel building, SB: switching building, SSB: supply systems building, TB: turbine building

5.1.2. Protection Concept of the Reference Plant against Hydrological Hazards with Flooding Potential

Scenarios for Longer Duration Flooding Hazards B3 and B4

The reference plant is located at a riverine site. Accordingly, the flooding protection concept preferably considers scenarios resulting from the river water regime. The plant is designed against a flooding of a 10,000 years return period (design basis flooding, DBF) with an exceedance probability of $1 \text{ E-}05/\text{a}$ resulting in a corresponding flood protection level (this level is called *NPP Level 0*). For the DBF with $l = 0.16 \text{ m}$ over *NPP Level 0*, a safety margin of about 0.84 m remains to the protected height at $l = 1.00 \text{ m}$. The protection against B3 and B4 is provided through the given height of the

plant. Openings in the buildings are either placed above the protected height or can be closed by setting or closing temporary flood partitions according to the plant operational manual. These active preventive measures limit the water ingress to the buildings to be protected.

Preventive measures must be taken as soon as the river water reaches $l = -0.50$ m. In this context, it is assumed that it takes 30 h until the water level reaches NPP Level 0. Hence, a long pre-warning period of more than 30 h is available in case of riverine floods being sufficient for taking temporary flood protection measures and to shut down the reactor. A conservative temporal development of the water level at the site is shown in Figure 5. The protection of buildings important to safety against B3 and B4 are presented in Table 1; case 6 represents the DBF.

Flash Flood B2 Scenarios

In contrast to B3 or B4 the water level at the site and the pre-warning time can be remarkably shorter in case of flash floods. Flash floods can be caused by very strong precipitation. Extreme precipitation events have occurred in Germany with up to 292 l/m^2 within approx. 7 h. Hence, events with $200 \text{ l/(m}^2\text{h)}$ precipitation can be no longer excluded in various parts of Germany including the region of the reference site. Extreme precipitation at the NPP site can cause high water levels.

In case of extreme local precipitation, the surrounding regions are also affected. Therefore, water flowing to the plant site due to the topographic conditions needs also to be taken into account. For the reference site, this is in principle possible via a smaller waterway adjacent to the plant site with a non-negligible slope in the direction of the plant. GRS studies (more details see [8]) show that water levels higher than the DBF level due to flash floods cannot be excluded, e.g., it is assumed, that the water level may locally reach a little more than 1.5 m within 60 min. Note that pessimistic assumptions have been used and that the available data base is extremely limited resulting in high uncertainties.

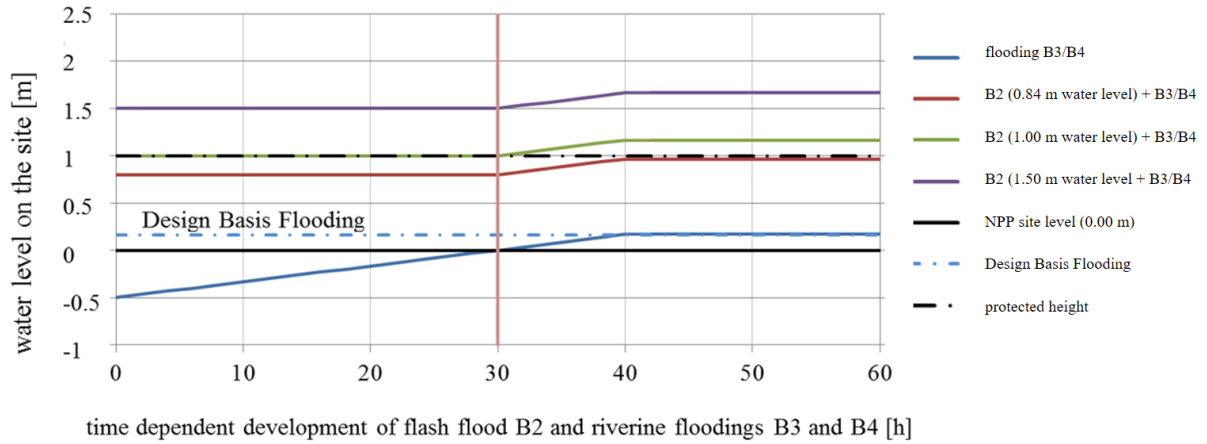
Local extreme precipitation events can be only predicted a few hours in advance, therefore the pre-warning period is much shorter for B2 than for B3 or B4. Corresponding severe weather warnings for the region (e.g., of more than 40 l/m^2 within 1 h or of more than 60 l/m^2 within 6 h) by the German Weather Service DWD are available at the reference site and noticed by the plant operators. The minimum time from the DWD warning to the start of precipitation is assumed to be approx. 2 h. This is also the time available to initiate flood protection measures, since it is additionally assumed for the analyses that such measures cannot be taken successfully anymore after the heavy rainfall has started. The flood protection measures which must be taken for safety related buildings and the corresponding minimum pre-warning time periods are again presented in Table 1.

As soon as the flash flood reaches the reference site the water may follow two different major flow paths named Alternative A or Alternative B in Table 1. Only buildings which are in the direction of the assumed major water flow are assumed to be affected (see column “Flooded buildings” in Table 1). Without detailed knowledge of the site-specific water levels and local flow conditions, the occurrence probability of both alternatives is roughly assumed to be 50 % of the total one for B2.

Scenarios of B2 and B3 or B4 Occurring Independently but Simultaneously

The river flooding scenarios B3 and B4 typically have longer durations. Hence, the independent occurrence of a much shorter duration of flash flood hazards B2 – resulting for example from a typical summer thunderstorm with heavy rainfall – a B3 or B4 flooding event cannot be excluded. Water levels resulting from such combinations of B2 with B3 or B4 are shown in Figure 5. With respect to the available pre-warning period, several analytical cases for these hazard combinations need to be considered. Those cases 7 to 11 are outlined in further detail in Table 1; in terms of the flooded buildings these cases are the same as the cases 1 to 5.

Figure 5. Water level due to external flooding at the reference site, from [8]



5.1.3. Potential Flooding Areas and Hazard Equipment Lists

For the probabilistic assessment of flash flood B2 hazards, buildings relevant to safety need to be analyzed with respect to potential flooding areas (for details see [6] and [8]). Potential flooding areas have been identified for different cases; the components in the flooding areas have been collected in hazard equipment lists (*HEL*), and the corresponding dependency lists *HDL* (cf. [5] and [8]) have been provided. Model simplifications concern the number of building levels to be considered.

5.2. PSA Model Extension for External Flooding Hazards at the Reference Plant

Basis for the extension of the Level 1 PSA plant model for the reference plant was the event and fault tree modeling of transients during power operation of the plant in the existing PSA plant model. For items important to safety in flooded buildings, a flooding induced failure is generally postulated, if the water level reaches their elevation in the building.

5.2.1. Event Tree Extensions

The failure of items important to safety can cause a transient, e.g., flooding of the turbine building is assumed to result in the failure of the main cooling water supply and the main condensate system with consequential unavailability of the main heat sink. The flooding induced simultaneous loss of feedwater system and main heat sink had already been analyzed as transient T4 in the frame of the existing PSA for the reference PSA. Accordingly, the flooding induced transient T4_FL has been analyzed for the cases 1, 3 and 5 crediting the same safety functions as for T4. For the cases 2 and 4 it has been assumed, that a flooding of the switching buildings causes a loss of offsite power (T1_FL). The expected transients for the cases 1 to 6 are presented in Table 2 in paragraph 5.3. The event sequences have been extended for the B2 analytical cases 1 to 5 respectively.

5.2.2. Fault Tree Extensions

The availability of safety functions required to reach a safe state in case of transients can be reduced by flooding. The probabilistic modeling of this issue requires extensions of the fault trees in the reference plant's PSA model. Therefore, additional basic events have been integrated for flooded components. If components have been flooded, their failure probabilities have been set to $P = 1$.

5.3. Results of the Hydrological Hazards PSA for the Reference Plant

The following results have been received from the model extensions systematically addressing hydrological external hazards with flooding potential in the Level 1 PSA for power operational POS:

Table 2. Initiating event frequency, resulting transient, unavailability of the required system functions and corresponding core damage frequency (CDF)

Case	Frequency [1/ry]	Transient	System functions unavailability	CDF [1/ry] / K95
1a	7 E-04	T4_FL	8 E-04	3 E-08 / 36
1b	7 E-04	T4_FL	8 E-04	5 E-07 / 37
2	2 E-04	T1_FL	8 E-04	4 E-08 / 40
3	2 E-04	T4_FL	8 E-04	3 E-09 / 52
4	2 E-05	T1_FL	1 E-03	1 E-08 / 73
5	2 E-05	T4_FL	8 E-04	1 E-09 / 85
6	1 E-04	T1_FL	8 E-04	3 E-09 / 16

While the occurrence frequencies are all significantly below E-03/ry with the pessimistically estimated highest values for low water levels up to 1 m, the results for the unavailability of system functions strongly depends on the transients induced and the corresponding unavailability of requested systems. The system functions unavailability is similar in all cases except for case 4. Here, amongst others the switching building SB and the electrical building EB are flooded. Correspondingly, the system functions unavailability is comparatively high.

For flooding hazards induced CDF as result of the Level 1 PSA for power operation, accident management measures, such as primary and secondary feed and bleed, must be accounted for. Such measures must be taken in the emergency feedwater building. That requires that either personnel are present in that building for taking such measures or that the building is accessible in case of flooding events. The latter is the case in the reference plant via a protected connection to other buildings.

The resulting CDF values for the different flooding scenarios are all relatively low. Longer duration riverine flooding hazards B3 and B4 were already covered in the licensee's PSA for the reference plant, which did not have to be extended for this analytical case (case 6). A bounding assumption there is that the flooding of the turbine building results in a loss of offsite power. This scenario provided a CDF in the order of some E-09/ry.

For combinations of flash floods occurring independently during longer duration riverine flooding events, the pre-warning periods are different: approx. 2 h for B2 and more than 30 h for B3 and B4. As soon as the river level reaches a critical threshold, the reactor needs to be tripped and brought to the safe state "cold stand-by". In this case, the flash flood does affect only the core cooling after the trip. If the flash flood occurs before such a critical river water level is reached, flash flood scenarios are bounding because of the much shorter pre-warning periods in case of B2.

It should be mentioned that for those analytical cases with flash floods B2 (cases 1 – 5), rough pessimistic estimates for flooding levels with relative high uncertainties strongly affect the results. For demonstration of the applicability of the methodological approach, the rough estimates were sufficient. The effort and time needed for collecting a large amount of geological and meteorological data for reducing the level of conservatism is quite high. However, for an as far as possible realistic model, the data basis needs to be improved.

6. CONCLUSIONS AND OUTLOOK

This paper gives an overview on a systematic approach for comprehensively considering hydrological hazards in Level 1 PSA. For a German reference NPP site, exemplary probabilistic analyses for hydrological hazards with flooding potential have been carried out for the plant operational state ‘power operation’. The model extensions include an as far as possible systematic and detailed approach for screening of individual hazards and of the different types of hazard combinations to be principally anticipated as well as a systematic and comprehensive extension of the Level 1 PSA plant model. The enhanced methodological approach has been successfully applied in the PSA of a German nuclear reference site for hydrological hazards with flooding potential.

Further improvements of the approach and model extensions, in particular for risk aggregation by hazards and for application to multi-unit, multi-source nuclear sites, are ongoing. Other enhancements are intended for a more automated hazards screening including the site and plant specific identification and screening of hazard combinations. Moreover, the approach can be applied to all plant operational states through the entire life cycle of a nuclear power plant. Extensions of the plant model to systematically cover hazards and hazards combinations which may affect more than one facility at a nuclear plant site in PSA up to Level 2 have already been started. First results are expected in the near future.

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