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Hazard assessment in case of external flooding

Keywords

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Abstract

Risks relating to external hazards, either natural or man-made, have to be taken into consideration in the design of nuclear and other industrial facilities. These risks have to be studied to guarantee the availability and efficiency of safety functions which, e.g. in the case of power reactors, enable a safe shutdown, maintain the reactor in a safe shutdown state, ensure the residual heat removal and the containment of radioactive products. With a view to design protection against risks related to external hazards, these hazards have to be assessed in an appropriate manner. The methods used can be either deterministic or probabilistic. In both cases, the method strongly relies on observations (e.g. flood records) that are processed to define a maximum event for the respective facility design. Moreover, the validity of these records over a certain time frame like 100 years has to be checked. Coping with external hazards such as flooding in the future requires an in-depth assessment taking into account new data, further developed methodologies and criteria. Some of these ideas, developments and applications are provided.

1. Introduction

The effects of flooding on a nuclear power plant site may have a major bearing on the safety of the plant and may lead to a postulated initiating event that is to be included in the plant safety analysis. The presence of water in many areas of the plant may be a common cause failure for safety related systems, such as the emergency power supply systems or the electric switchyard, with the associated possibility to lose the external connection to the electrical power grid, the decay heat removal system and other vital systems [16].

Moreover, flooding has the potential to damage multiple structures, systems and components (SSCs).

In addition, the accessibility of the plant may be impeded due to flooding of the plant environment. These consequences are so severe that, (re)assessments of flood risk and flood protection measures should be based on accurate state-of-the-art methods.

A challenge for external flooding is that there is a variety of potential sources of flooding that may need to be considered. Each of these different flood hazards may need to be evaluated using a different technical approach. For example, the assessment of the likelihood of a precipitation-driven riverine flood is based on technical issues that are different from those for a dam failure-driven flood, as well as different from the technical issues for a storm-surge-induced flood.

Furthermore, the performance of a technically defensible probabilistic flood hazard analysis requires the combination of statistical information and mechanistic modeling. This can be a fairly resource intensive undertaking and is highly site specific. Thus, it is not feasible to draw generic conclusions about the likelihood of external flooding events for all sites; the assessments of external flooding frequency are, necessarily, site specific.

All hazards associated with external flooding events that may affect the site should be evaluated by performing a site-specific flood hazard assessment and should consider all potential sources of flooding (see for example *Table 1*).

Table 1. Possible sources of flooding

Event	Sources
River flooding	Precipitation, snow melt, debris jam, ice jam, rapid sedimentation
Dam failure	Earthquake, flood, volcano, landslide, static failure
Levee or dike failure	Earthquake, flood, static failure, upstream dam failure, landslide, volcano
Flood run-off/drainage	Precipitation, ponding, drainage capacity
Tsunami	Earthquake
Seiche	Earthquake, wind
Storm surge	Hurricane
Wave	Wind, Tsunami
Groundwater	Precipitation, ponding, flooding, drought and over-pumping
Mudflows	Volcano, earthquake
Subsidence-induced flooding	Fluid extraction

The assessment process requires, therefore, a strong interconnection between the deterministic and the probabilistic procedures in order to properly evaluate and examine the performances of the nuclear facilities (short and long term safety assessment). When dealing with the short term safety assessment, the use of a deterministic approach, supported by conservative assumptions, is expected to lead to improved safety and a more rational allocation of the limited resources available.
Regarding the probabilistic procedure one approach is illustrated in *Figure 1*.

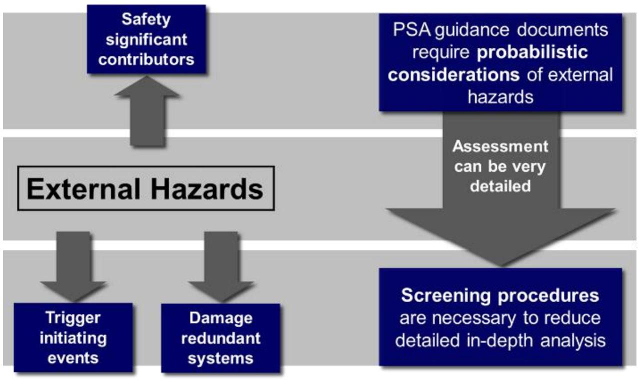

Figure 1. Consequences of external hazards and one approach to apply probabilistic procedures

To the aim, and in the light of the events that occurred in Fukushima, the vulnerability of fundamental safety functions system and components, e.g., the outer containment building of the nuclear power plant (NPP) has to be analyzed in design conditions as well as the exposure to external hazards in the case of prolonged loss of power and cooling water supplies. Therefore, the objective of the safety margin assessment, by deterministic approach, is to evaluate the robustness of an existing plant in terms of design features and procedures against the impact of extreme events, such as the external flooding or the tsunami inundation phase, focusing on fulfilment of the fundamental safety functions.
The design input parameters should be established by deterministic methods or probabilistic methods or using a combination of the two methods. In both cases, the methods strongly rely on observations (e.g. flood records) that are processed to define a maximum event for the respective facility design. Moreover, the validity of these records over a certain time frame like 100 years has to be checked. Estimated flood hazards should be compared to historical data to verify that the specified design basis conservatively exceeds the historical extreme.
The design-basis flood parameters should be defined in terms of:

- A deterministic peak flood level or a probabilistic peak-flood level corresponding to the mean hazard annual exceedance probability including the combination of flood hazards,
- Estimated duration of the flood level and applicable flood combinations,
- Corresponding loads associated with the design basis peak-flood level and applicable load combination such as hydrostatic and / or hydrodynamic forces, debris loads, sedimentation, erosion and scour phenomenon),
- Estimated duration of loads associated with the design basis peak-flood level and applicable load combinations.

2. Modelling of external flooding

Losses due to natural hazard events can be extraordinarily high and difficult to cope with. Natural hazards including the Fukushima accident frequently surprised the designers or operators of critical infrastructures by their unexpected magnitude and the resulting consequences. These events were not predicted by hazard assessment methods currently in practical use independent from their degree of sophistication. Therefore, there is considerable interest to estimate the potential impact of current and future extreme events in as much detail. Flood risk is often defined by probability and consequences. It has been well accepted as the main methodology for flood risk assessment.
However, purely probabilistic methods cannot be used for the hazard prediction if a meaningful decision criterion is missing. The use of the mean of the probability distribution of hazard curves has clearly failed in the case of the Fukushima accident because of the underlying incorrect assumptions. According to [18] such unpredicted events can be considered as so-called black swan events.

Another approach using copula models includes that risk assessment must take into account interrelations between regions. Neglecting such interdependencies can lead to a severe underestimation of potential losses, especially for extreme events. This underestimation of extreme risk can lead to the failure of risk management strategies when they are most needed, namely, in times of unprecedented events.
As a third methodology 3D simulations are presented which allow a more complete picture of complex system behavior.

2.1. Black swan approach

During the past 10 years the nuclear society several times was surprised by significant extreme natural events as for example earthquake and tsunami in Fukushima. Such extreme events have clearly demonstrated the limitations of our capability to consider such events in the design of critical infrastructures. As part of the Post-Fukushima supplementary safety analysis and seismic design review a new method has been developed how to review the seismic design basis of the plant taking into account the “surprise” events [18].
It shall be well understood that such events most typically are screened out from probabilistic safety assessment (PSA) based on their very low frequency. The problem is that we are not able to predict the frequency of such events accurately enough.
Despite the problems for accurately predicting rare extreme events, a general assessment of their magnitude and of the likelihood of their occurrence during the limited lifetime of a NPP is possible. First of all one has to note that a surprising event is an event that exceeds all previous historical observations in magnitude. That means that in a mathematical sense a black swan event represents a record.
To be very surprising the magnitude of the event must be significantly higher than observed for the last record event. Such a surprising effect is associated with events whose occurrence and magnitude are described by the theory of super heavy tail distributions.
For the applicability of these mathematical theories it is necessary to make the following assumptions:

- The extreme event in the region considered follows a common, but unknown mechanism (i.i.d. - assumption),
- The occurrence of extreme events follows a super heavy tail distribution. This is equivalent to the usual power law assumption.

These assumptions are not unusual in seismic hazard analysis and can easily be extended to the assessment for external flooding. The properties of records can be illustrated with the help of the following equations:

- The expected number of records (denoted as N_n) in a sequence of n observations is given by:

$$\mathrm{E}(N_n) = \sum_{i=1}^{n} \frac{1}{i}, \tag{1}$$

- The ratio between the largest and the second largest record in a record counting process for a super heavy tailed distribution converges asymptotically to a factor of 2. The probability that the next record value will exceed the second largest (the previous) record value by a factor of 2 or more is equal to:

$$p = \frac{2}{n}, \qquad \text{for } n \geq 2. \tag{2}$$

From these general properties one can derive a set of interesting conclusions. The longer the historical period of observations the more reliable one can predict a reasonable design value. This conclusion can be expanded by estimating the probability of observing a new record value during the remaining lifetime for a NPP. For this purpose the number of record values has to be estimated in dependence of the number of flood observations or of time. Then the probability that the largest historical event will be exceeded during the lifetime of the plant can be estimated roughly as:

$$P_{record} \approx \frac{\tau_{obs}}{(j_{N+1} - j_N + j_{N+i \neq Record}) \times \tau_{Re,av}}, \tag{3}$$

- P_{record}: Probability of observing a new record,
- τ_{obs}: Position of observer (plant lifetime),
- $(j_{N+1} - j_N + j_{N+i \neq Record}) \times \tau_{Re,av}$: Time, (till next record event).

The approach can be easily extended so several natural hazards. An application of this method is described for the NPP Goesgen [18].

2.2. Copula models

In Europe, current flood models only consider risk information in terms of loss distribution at a very local scale. Information at larger scale is available, but is typically developed for special scenarios or expressed in terms of average losses only. As a consequence, risk management approaches for extremes cannot be applied at these scales as necessary probabilistic information is not available.

To overcome this limitation a copula-based methodology is suggested in [25]. They introduced a methodology using a Clayton copula approach to obtain loss distributions at larger scales.

Large-scale flood risk analysis is a sophisticated procedure that consists of several steps and should incorporate interdependencies between all considered basins, regions and countries. Neglecting underlying dependencies will lead to the underestimation of risk and to the potential failure of risk management strategies.

In order to answer the question about the flood risk in multiple regions, it is necessary to estimate the probability loss distribution that gives information on the probability of rare events (10-year event, 100-year event, etc.) and the amount of loss in case of these events.

For this the following three steps are requested:

- To receive the marginal loss distributions for each of the basins it is required to calculate the joint probability distribution for the entire region. The total loss after a flood is just the sum of the losses in the individual regions that were affected by the hazard.
- The marginal loss has to be coupled in such kind that the large-scale probability distribution is estimated correctly and fits the multi-regional data on losses.
- It is necessary to understand from the available data and river structure which groups of the basins can be considered as dependent and which as independent.

For the comprehensive analysis of the interdependencies of the basins, a copula type should be chosen so that the following can be hold:

(i) A copula type should be chosen so that it describes the flood loss behavior in a satisfactory manner.

(ii) A chosen copula should be able to explicitly model fat tail interdependencies.

(iii) Coupling of copulas of the same type should again produce a copula of the same type.

There are three possible copula types for the flood risk analysis:

Flipped Clayton copula (θ>0), i.e.

$$C_\theta^{FC}(u,v) = u + v - 1 + \left[(1-u)^{-\theta} + (1-v)^{-\theta} - 1\right]^{-\frac{1}{\theta}}, \quad (4)$$

Frank copula ($\theta \neq 0$), i.e.

$$C_\theta^{F}(u,v) = -\frac{1}{\theta}\ln\left(1 + \frac{(e^{-\theta u}-1)(e^{-\theta v}-1)}{e^{-\theta}-1}\right), \quad (5)$$

Gumbel copula ($\theta \geq 1$), i.e.

$$C_\theta^{G}(u,v) = \exp\left[-\left[(-\ln u)^\theta + (-\ln v)^\theta\right]^{\frac{1}{\theta}}\right]. \quad (6)$$

In [25] the results for the Flipped Clayton Copula are presented by satisfying all the necessary properties (i)-(iii). Romania was chosen as a case study as it is a very flood-prone country and has been significantly affected by floods in the past, causing significant damages.

That approach is beneficial as it provides information on the risk of extreme losses at higher scales, highly important for determining suitable risk management strategies. Risk information may provide guidance on appropriate size of emergency funding programs that provide financial assistance to member states. The proposed copula approach allows to estimate up to which return period the existing funds can cover the losses or how large the funds should be in order to cover losses up to a certain return period.

2.3. 3D simulations

Incorporating 3D simulations allow analysts to obtain a more complete picture of complex system behavior in a straightforward manner. Therefore, external events such as flooding can be analyzed with existing and validated simulated physics toolkits. Integrating 3D simulation methods into computational risk analysis provides a spatial/visual aspect to the design, improves the realism of results, and can prove visual understanding to validate the analysis of flooding.

The 3D simulation is described specific to flooding-based analysis using an approach called Smoothed Particle Hydrodynamics (SPH), which was originally designed for solving astrophysical problems. SPH has important potential benefits such as the ability to handle complex boundaries and small-scale phenomena. SPH works by obtaining approximate numerical solutions of the equations of fluid dynamics by representing the fluid with particles, where the physical properties and equations of motion of these particles are based on the continuum equations of fluid dynamics. Furthermore, physical quantities are estimated by interpolating existing fluid quantities using the neighboring particles.

Being able to virtually run a predetermined scenario it can provide useful risk information and can enable to understand plant behavior prior to seeing actual events such as floods. However, it is necessary to be assured that these simulations can deliver valid and practical results.

Testing against real world data has been performed for a dam break. The dam break scenario is a typical test case to validate movement and forces. It is simulated by many SPH programs to demonstrate its power in dealing with free-surface slamming phenomena. In this case, the force exerted by fluid particles onto a post from the dam failure is measured and compared with the results from experimental data. The simulation is one-to-one scale to real experiments. For comparing the results with the real case, the water properties such as the fluid parameters are used.

Different measuring tools are available during the simulations that are able to evaluate conditions over time. These tools include water contact detection, fluid pressure, debris movement and impact forces, water height, and flow through openings. Such simulations can not only help to determine the likelihood of major system failures leading to off-normal scenarios, but also smaller events that cause facility damage and extended shut down periods.

A possible scenario to show how some 3D simulations can be used is the seawall analysis. Multiple variations of the seawall configuration for a hypothetical facility were modeled and simulated at different wave heights. These simulations can be used to determine water levels and to show which areas are most at risk depending on the size and duration of the wave with a given configuration. This data can help to improve initial designs or to modify existing facilities.

The theory, validation, and example applications of the 3D flooding simulation are described in more detail in [5].

3. International activities

Flooding of nuclear power plants by external water sources has occurred for instance at the French Blayais NPP in 1999 (storm surge), at the US Fort Calhoun NPP in 2011 (high river) and at the Japanese Fukushima Daiichi NPP in 2011 (tsunami). These events illustrate the potential for flooding to damage multiple SSCs and to impact on large areas. They also led to changes in the evaluation of flood.

The International Atomic Energy Agency started comprehensive activities in that context and several documents are under preparation. One document is developed around a sequential set of activities which include hazards assessment and characterization, identification of the SSCs that are needed to maintain the plant safety functions under the different scenarios considered, the process of safety margin assessment using deterministic and probabilistic approaches [17]. It also includes actions and measures that need to be implemented to address scenarios that incorporate severe accident management during station blackout and loss of the ultimate heat sink with the goal to retain or regain control of at least the plant fundamental safety functions: reactivity control, residual heat removal and containment/confinement functions until the reestablishment of emergency power source and alternative heat sink. However, this document is mainly focused on seismic hazards only applying the same methodology to external flooding.

In the hydrologic community in the USA, it has long been recognized that estimating the annualized frequency of severe floods tends to be restrained to a great extent by the historical record available, with significant effort made in the development of methods and approaches to extend frequency estimates beyond typically observed events. The result is based on existing significant uncertainties depending on the quantity and quality of data available as well as the refinement of the methodology used to derive such estimates. The Unites States Nuclear Regulatory Commission (US NRC) had been engaged in risk assessment of natural hazards already before the accident in Fukushima; however, the formation of a specific team to review insights from this event and subsequent activities (see, e.g. [26]) including a reevaluation of potential flooding hazards for nuclear facilities have refocused the review and potential enhancement of the treatment and evaluation of events with very low probability but very high consequences with respect to critical infrastructure. In particular, there is a strong interest for further development in the following areas in applications related to the risk assessment of nuclear facilities [13]:

- Development of methods to consistently estimate annualized flood frequencies in the ranges of interest of US NRC applications with respect to potential contributors to core damage frequency, including extrapolations beyond the available historical record,
- Possible probabilistic treatment of flood protect ion structures and barriers (including temporary barriers), while considering potential for degradation from debris impact, erosion, and other effects during severe flooding events,
- Developing a probabilistic assessment of the capacity of mechanical, structural, and electrical systems relied on for safe operation of nuclear facilities to withstand flooding impacts, similar to fragility curves typically associated with seismic risk assessments (e.g., conditional probability of failure with respect to a specific loading or flood level),
- Feasibility of operator manual actions during extreme flooding events in a probabilistic

framework, which may be associated with actions such as the installation of flooding protection (e.g. floodgates), construction of barriers (e.g. sandbag barriers), and other actions.

Many plants in the USA have been sited and evaluated based on the concept of a probable maximum event. The probable maximum event, which is determined by accounting for the physical limits of the natural phenomenon, is the event that is considered to be the most severe reasonably possible at the location of interest and is thought to exceed the severity of all historically observed events [6].

A probable maximum flood (PMF) is the hypothetical flood generated in an identified drainage area by the probable maximum precipitation (PMP), combined with the probable maximum storm and the probable maximum storm surge generated by the probable maximum hurricane or the probable maximum windstorm.

However, it is widely recognized that the probable maximum event concept is, in fact, neither "probable" nor "maximum." These events do not address the probability of the event, nor do they define the maximum condition that could occur. A simple depiction of the probable maximum event concept for the PMF is shown in *Figure 2*.

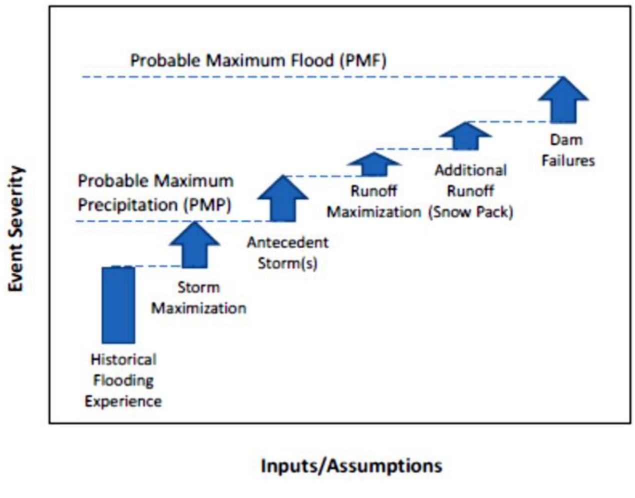

Figure 2. Simplified characterization of the development of a PMF

The starting point is the set of worst historical precipitation events. The potential effects of these events are "maximized" by considering how much more moisture could have been present at the time they occurred. These conditions define a PMP event that is used as an input to the evaluation of the flood. In assessing the PMF, the PMP is combined with additional impacts intended to add margin to the evaluation. These might include assumptions regarding antecedent storms that would saturate the soil and fill reservoirs, maximum runoff assumptions (for example, minimal absorption in soil), additional runoff from a hypothetical snow pack, and non-mechanistic assumptions of dam failures [6].

The European Union (EU) also reacted to the accident in Fukushima, see for instance the notion of extreme external natural hazards used in a recent EU directive [4]. Supporting documents addressing specifically natural hazards are provided by WENRA ([28] and [29]). Moreover, all countries belonging to the EU and Switzerland have performed stress tests and resulting improvements have to be described in national actions plans. By 31 December 2014, each country was obliged to update its original national actions plans to reflect developments since its issue and the current status of the measures and their implementation. The results were discussed in the respective European Nuclear Safety Regulators Group.

In some countries national guidelines have been issued such as in Belgium [9] and the United Kingdom [21].

4. Assessment of external flooding for nuclear power plants in Germany

PSA guidance documents have been elaborated for a comprehensive integrated safety review of all NPPs in operation. The German safety concept for NPPs gives priority to the deterministic approach. PSA is seen as a supplementary tool to the deterministic approach. In 2015, a revision of the national nuclear safety regulations has been successfully completed [12] and these regulations require an appropriate assessment of external hazards as part of the German safety concept.

The German regulatory framework for flood events requires a determination of a sufficient water level as design-basis and appropriate structural protection measures against this hazard in the design of the plants to avoid radiological consequences for the environment. The adequacy of the protection measures have been shown in the past only on a deterministic basis. The PSA guideline as well as the corresponding technical documents prescribe also probabilistic analyses of external hazards including flooding [8]. An updated technical document is expected to be issued in 2016.

PSA regulations consider extreme events of recurrence intervals of 10,000 years. Beside the frequently occurring extreme storm surges, also other events have to be considered. One example is the possible impact of a tsunami type of event simulating the propagation and development of extreme waves in the North Sea towards the German Bight, initiated by a hypothetical slide at the continental margin off the Norwegian coast. This scenario has been analyzed as a consequence of the tsunami in December 2004 in Indonesia [3].

With respect to the phenomena leading to a flooding event, the German NPPs can be divided into two basic categories: "River-Site NPPs" and "Tidal-River NPPs". In the first case a high water-level situation arises from an unfavorable ratio of water inflow to outflow, in the second case the coincidence of storm, flooding and high tide is the determining factor. In case of sites on inland waters (and rivers), the design-basis water level shall be based on a flood runoff from a flood with probability 10^{-4}/a. In case of sites on tidal-rivers, the design-basis water level shall be based on a storm-tide water level with probability 10^{-4}/a. In the proposed method, the frequency of reaching extremely high water levels is determined by an extrapolation of actually measured water-level data according to various established methods [2].

According to [20], it is necessary to determine statistically the storm-tide water level with an exceeding frequency of 10^{-2}/a plus a site-specific addend. In conclusion, a storm-tide must be covered with an exceeding frequency of 10^{-4}/a. In the context of the analysis, design-basis flood is that particular flood event which is the basis for the flood protection of the respective plant, specifically with regard to meeting the safety objectives. The permanent flood protection is that flood protection which is effective at all times (e.g. protection by flood-safe enclosure, by structural seals).

Table 2. The graded safety assessment approach regarding external flooding

Criterion	Record verification	Comment
Due to the topography and the plant design, a failure of vital functions can be practically excluded. Temporary measures are not included.	No analysis necessary	Is assumed that the design of the plant complies with the basic level according to RSK SÜ (Safety Review). Compare also the understanding of the safety philosophy of the RSK to the interpretation of the term "(practically) excluded"
If the analysis of flood-related event sequences shows that the contribution to the core damage frequency of this event is well below 10^{-6}/a, further considerations are not required.	The measures of the plant-specific flood protection concept acc. to KTA 2207 be probabilistically. It is set out that the conditional probability of an uncontrollable water entry is much smaller than 10^{-2}/a to assess. There are potential penetration paths for water-related structures and equipment to identify. For the assessments to the water entry, only the buildings (including subsequent tube and cable channels) of importance, to the emergency power supply and to the subsequent heat dissipation systems are included. The conditional probability of failure of required for the core cooling systems for the design flood is then to estimate. Insights from qualified plant inspections remain here to consider.	Only permanent protective measures are used in the analysis. Plant-internal accident management measures can be taken into account. The shut-down of the plant according to BHB either at a water level, which includes a significant distance to the design flood or occurrence of defined situational plant-specific conditions, such as when a foreseeable failure of the main heat sink.
Other design	In-depth event sequence considerations are necessary. Temporary facility-specific safeguards can be considered.	If the simplified procedure does not lead to success, an increased effort is necessary.

In particular in case of probabilistic analyses of external hazards, their assessment can be very detailed and time consuming. Therefore, there has been developed a graded approach for the extent of a probabilistic assessment in case of external flooding containing deterministic and probabilistic elements and taking into account site-specific aspects like the NPP grounded level compared with surroundings level and plant-specific aspects such as design with permanent protection measures and prescribed shut down of the plant according to the instructions of the operation manual at a specified water level which is significantly below the level of the design flooding. Appropriate screening procedures are those which on the one hand allow to constrain the complexity of the analysis and, on the other hand, ensure that relevant information are not lost during the screening process and all safety significant parts of the plant are taken into account [8]. A graded approach for the extent of a PSA in case of external flooding containing deterministic and probabilistic elements has been developed and is provided in *Table 2*.

In connection with the accidents in the Fukushima NPPs, the Federal Parliament called upon the German Federal Government on 17th March 2011 to conduct a comprehensive review of the safety for all German NPPs. On request by the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) its advisory body, the Reactor Safety Commission (RSK), performed this review. The RSK endorsed a catalogue of requirements for plant-specific reviews of German NPPs in the light of the events in Fukushima [23]. Requirements for external flooding have been:

- Review of the boundary conditions for the site-specific determination of the design flood,
- Review of the design and precautionary measures on the basis of the design flood, stating the reserves,
- Review with regard to the maintenance of vital functions in case of a beyond design basis flood, e.g. by failure of dams/barrages or major flood protection measures, long-lasting flood, extreme storm surge, tsunami, effects of flotsam, taking into account the destruction of infrastructure and impairment of staff availability,
- Review of the impacts on accident management measures in case of beyond design basis water level (maybe after short advance warning time).

In the framework of the RSK safety review the safety of the German NPPs was assessed in particular with respect to the external hazards 'earthquake' and 'flooding'. This assessment was mainly focused on the resilience of the NPPs, i.e. the safety margins available for beyond design basis events. Due to this focus, the appropriateness of the design basis itself was not re-evaluated. From a comparison of the site specific hazard and the design of the NPPs as well as additional questions regarding potential effects of beyond design basis events and available accident management measures for such events, conclusions regarding the safety margins were drawn by the RSK. To quantify the resilience of the plants the RSK has defined robustness levels. For flooding these robustness levels were defined as follows [22]:

- Basic level: The safety of the plant is demonstrated for a design basis flood (10,000-yearly flood).
- Level 1: Design margins with respect to the design basis flood (10,000-yearly flood) determined plant-specifically according to the state of the art in science and technology are shown such that maintaining of the fundamental safety functions is ensured for river sites in the case of a water discharge increased by the factor 1.5 and for tide sites in the case of flood higher than one meter with respect to the design basis flood and in the case of postulated failure of barrages due to a common cause failure of dikes or similar structures. Effective accident management measures may also be taken into account.
- Level 2: In addition to Level 1, design margins with respect to the design basis flood (10,000-yearly flood) determined plant-specifically according to the state of the art in science and technology are shown such that maintaining of the fundamental safety functions is ensured for river sites in the case of a water discharge increased by the factor 2.0 and for tide sites in the case of flood higher than two meters with respect to the design basis flood and the resulting water level. Effective accident management measures may also be taken into account.

  The sites of the NPPs in Germany are mostly located inland at rivers and, in some cases, at estuaries with tidal influences. In most of the cases, sites have been selected which are located sufficiently high. In all other cases, the structures important to safety were sealed for water tightness and were built with waterproof concrete. Furthermore, the openings (e.g. doors) are located above the level of the highest expected flood. If these permanent protective measures should not be sufficient, mobile barriers are available to seal the openings.

  The results of the RSK safety review can be summarized as follows [10]:

- All German NPPs have safety margins against flooding. With permanent and temporary measures they reach protection heights above the level of their 10^{-4}/a design basis flood event.
- No realistic cliff edge effects have been identified because the necessary water volumes for such scenarios are physically not possible in Germany. Respectively, dyke failures would lead to discharge of large water volumes into retention areas before the water level can reach relevant heights above the height of design basis flood at the sites.
- At tide influenced sites, in particular the influence of the tides practically limits the time during which high water levels are present at the site and consequently the loads on the flood protection measures.
- According to the results in most of the plants no additional measures are necessary. Some plants consider improvements to further reduce risk.

Against the background of recent international regulations, various aspects of determining the design basis have been discussed and verified. The recommendations of the RSK statement [24] are the following:

- The aleatory and epistemic uncertainties of the flood hazard analysis should be systematically captured and assessed in terms of their need for consideration of a conservative result. With regard to the aleatory uncertainties, the assessment can be carried out by the usual statistical methods. For the evaluation of the epistemic uncertainties, the RSK recommends several different methods to be applied (using site-specific scientifically valid extrapolation) for determining the design basis flood. Afterwards their results have to be compared.
- The result of the determination of the design basis flood should be compared with historically recorded flood events in the region to check if the assumptions are conservative. Thereby, the assignability of the historical events on the current boundary conditions has to be observed.
- The German regulations [12] generally require to take into account the duration of external events in the design of the NPP. The consideration of the duration by determining the design basis flood is also required in [20].

On behalf of BMUB the RSK evaluated the results of the EU stress test for the German NPPs and considered them in its further discussions about possible enhancements of safety. The RSK formed the basis of the safety-related assessments and measures yet to be carried out. Thus, the international and the national findings from the reviews of the NPPs have been joined together. On this basis, the BMUB, together with the competent nuclear regulatory authorities of the Länder, drew up the updated National Action Plan [11]. Recommendations N-15 – N-16 of this National Action Plan deal with beyond-design-basis aspect of flooding hazards as they are described in [28]:

- N-15: If a water level that may endanger vital safety functions cannot be excluded due to site-specific conditions, the criteria specified in the RSK safety review for at least Level 1 shall be referred to. Alternatively, it may be demonstrated on the basis of site-specific conditions that a postulated discharge quantity, which is determined by extrapolation of existing probabilistic curves to an occurrence frequency of 10^{-5}/a, will not result in the loss of vital safety function. For sites located near tidal waters, an analogous approach is to be applied. In this respect, the uplift resistance of canals and buildings is to be considered.
- N-16: The impacts of a beyond-design-basis annulus flooding with a flooding level of 2 m at the lower annulus level on safety-relevant installations should be clarified, in particular with regard to transducers and other electrical and I&C equipment. In addition, it is to be specified what measures will be reliably available in the different operating phases for the prevention of impermissible losses [11].

5. Examples of improvements

In the following first findings in Germany, Belgium and the USA are presented.

Examples in Germany where improvements of flood protection have been installed are the NPPs in Brunsbüttel and Grundremmingen. The flood protection for NPPs in accordance with [20] presumes a flood event with a probability of 10^{-4}/a.

In 2007 a PSA for external flooding has been performed for the NPP Brunsbüttel in the frame of a periodic safety review. The result of the statistical extrapolation procedure is a storm-tide water level of 6.7 m above mean sea level (MSL). The local tide-related excessive wave amplitude of 0.8 m is not included in the extrapolation. Hence, the required level for the embankment of a storm tide event is 7.5 m above MSL with the probability of 10^{-4}/a.

The dike of the plant was raised to a height of 8.5 m above MSL as well as the overflow edge to the connecting channel between independent emergency system and reactor building has been increased from 0.5 m to 0.7 m. There have been several reasons for the increase of the dam. One of the reasons was the determination of a dam lowering which was figured out by the re-measurement of the dam. Hence, repair work has been necessary. In addition, mobile walls have been provided.

The German National Action Plan [11] provides the improvements for the NPP Grundremmingen. Recent studies have shown that the site will not be flooded in a design flood. The safety margins until the design flooding levels are reached are greater than originally assumed. Notwithstanding, provisions have been made for the temporary installation of mobile sheet pile walls to improve the accessibility of those access doors for which structural flooding protection (staircases) has been realized within the buildings.

In Belgium, the robustness of all NPPs has been analyzed with respect to all external hazards. However, the assessment for the robustness of the NPPs should be realized more systematically with respect to earthquakes and other extreme weather conditions.

The Belgium Peer Review [7] reflects the point of view of the national regulator and additionally complementary requirements to the suggestions for improvement of the operator for each topic.

The design basis flood (DBF) for the NPP site Tihange was originally derived as the highest historically recorded flood level of the surrounding river increased by 20% (i.e. 2200 m^3/s). Based on the flood in 1995 this value was revised to 1995 flood plus 20% margin (i.e. 2615 m^3/s).

The NPP site Doel is not considered to be flooded due to the fact that the NPP is situated on a raised platform and, secondly, the nearby river has an artificial embankment, which serves as a barrier for the site.

During the re-assessment within the latest periodic safety review, new DBF parameters have been derived using the probabilistic approach. Values with return periods of 10,000 years are taken as new design basis values. During the country visit it was reported, that for Tihange the new DBF value has been assessed to be 3488 m^3/s as the best estimate value.

The US NRC has made significant recent efforts in understanding the safety risk of various regulatory activities that include the impact of external flooding via insights from PSA methods [14].

One important example of improvements are the insights of the Missouri flooding event which took place right after the Fukushima accident in April 2011. Between May and September of 2011, the Missouri River was impacted by a number of hydrological and meteorological events that resulted in significant flooding conditions. One of the facilities that experienced this event was the Fort Calhoun site. It also impacted the Cooper Nuclear Station and other power-generating facilities located near the river.

A series of storms in May 2011 raised the total amount of precipitation to exceed more than 300 percent above normal. Certain areas received a total amount of rain within two weeks that would be comparable to the expected total precipitation in one year. The US Army Corps of Engineers, which is responsible for the operation of multiple dams upstream of the Fort Calhoun site, authorized the record release of outflow volume from multiple dams in order to manage the severe flooding across the river system, with significant flooding impacts downstream.

The Fort Calhoun site had entered a planned shutdown in early April 2011 for a scheduled refueling outage. During late May 2011, the impact of the raising elevations in the Missouri River led to the initiation of preparations to protect the site against flooding impacts. The Fort Calhoun site procedures against flooding include actions to protect specific buildings within the site up to 309 m above MSL per licensing basis.

In preparation for the flood, the Fort Calhoun site staged needed materials and equipment for protecting critical areas and functions (e.g., portable pumps, fuel containers, tanks, and generators); and initiated sandbagging and installation of flood gates. For example, an earthen-berm was built around the switchyard for additional protection against flooding.

By early June 2011, the Fort Calhoun site expected the Missouri River level at the plant to reach 306 m above MSL (the base plant elevation). Once 306 m above MSL was exceeded, mobility around the site had to be performed with a series of raised scaffold walkways and bridges. Flood waters eventually surrounded the switchyard, the dry-cask storage area, the power block (i.e., containment and auxiliary buildings), and support buildings, (e.g., administrative building, training center, security building). In addition, the main buildings were protected by a water impounding device (i.e., the terms “aqua-dams” or “aqua-berms” have been used to identify them) which consisted of an empty rubber bladder filled with water. The river level peaked around 307 m in late June. The aqua-dam around the power block was inadvertently punctured due to onsite activities and caused operators to briefly disconnect from offsite power.

Due to the flooding impacts and other longstanding technical issues, the US NRC determined that special additional oversight was needed for the Fort Calhoun site. The licensee discussed post-flooding recovery actions and agreed not to restart the unit without US NRC approval on July 27, 2011. The flood waters receded below site grade elevation in late August 2011. After further regulatory oversight to ensure commitments were met, the approval for restart was granted and the unit restarted in December 2013.

6. Concluding remarks

Realistic modelling of external flooding scenarios in a PSA requires a multi-disciplinary approach. Next to being thoroughly familiar with the design features of the plant against flooding, like its critical elevations for safety (related) equipment and the strength of buildings, additional knowledge is necessary on design of flood protection measures as dikes and dunes, their failure behavior and modelling. Although the methods to complete a full probabilistic flood hazard analysis have not been fully exercised in nuclear risk applications, there are a variety of methods to estimate the likelihood of flooding events.

These methods necessarily produce results that include large uncertainties at very low frequencies, but are much less uncertain for the more frequent flooding hazards. These more frequent events may be the risk drivers for plants, and assessing these risks can lead to mitigation or prevention schemes that enhance safety at NPPs. Thus, there are technically sound methods that can help to characterize these floods within the risk-significant range of frequencies.

However, independently from NPPs and other industrial facilities floods from rivers, estuaries and the sea threaten many millions of people. Flooding is the most widely distributed of all natural hazards causing distress and damage wherever it happens.

Natural hazards heavily impact land and society. In recent decades, public policy makers and land users have become increasingly conscious of the need to manage risks in order to mitigate or adapt to their causes or consequences. Major disasters such as the Haiti earthquake in 2010 or the Japan earthquake in 2011 are examples of cumulative hazards, which reinforce this consciousness and the need to consider the potentially impacted system as a whole.

Vulnerability of a territory to a hazard results from the interactions between environmental conditions and society: it is a combined effect of hazard exposure, sensitivity of the different components of the territory and society, and capacity or lack of resilience.

Stakeholders and policy makers have a good base of knowledge of their territory and of its main challenges. Managing risk is one of those challenges, with the objective of mitigating and/or adapting to the consequences on society and heritage. Vulnerability assessments are the preliminary step implementation of such risk management strategies.

To assess vulnerability, risk, and risk management, it is essential to have a holistic or global view (addressing the different aspects as a whole). Such an integrated and multidisciplinary approach will allows consideration of the physical context, the complexity and dynamics of social and environmental systems, and the relationship between them. A holistic approach will encourage more effective risk governance and management through the development of preventative strategies to face risks and disasters. A conceptual framework that addresses vulnerability and risk to natural hazards from a holistic and multidimensional point of view has been developed in [27] and is illustrated in *Figure 3*.

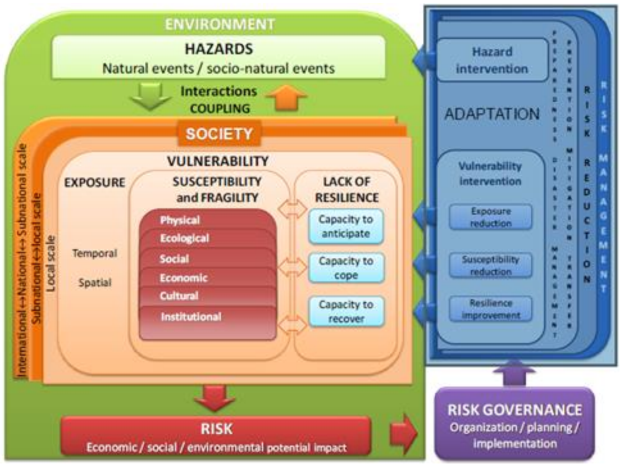

Figure 3. Conceptual framework of a holistic approach to risk assessment and management

It is generic in order to facilitate the initial identification of elements of coupled social-ecological systems (when making a vulnerability assessment) and to guide logical and comparative development of indicators and is a provided as a manual.

Previous research has improved understanding of individual factors but many complex interactions needed to be addressed for flood mitigation in practice. Thus, already in 2002 a project on flood risk management called FLOODsite has been initiated with the aim to cover the physical, environmental, ecological and socio-economic aspects of floods from rivers, estuaries and the sea [15].

However, because it is expected that flood risks from rivers will increase significantly in the coming decades, not only because of climate change, but also due to increasing urbanization of river areas and soil subsidence. To deal with these risks, many European countries focus on building, reinforcing and maintaining flood defense works. The STAR-FLOOD project (2012-2016) takes this focus as a starting point which is not sufficient in order to ensure sustained flood protection (see, e.g., [1] and [19]). From a resilience point of view, the strategy should be broadened with pro-active spatial planning, building prescriptions, warning systems, evacuation- and recovery plans. Final results of this project are expected in 2016.

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