AUTORITÉ
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GUIDE OF ASN

BASIC NUCLEAR
INSTALLATIONS

Protection of Basic Nuclear Installations Against External Flooding

GUIDE N° 13

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Contents

(*) The terms figuring in the glossary are underlined and followed by an asterisk.

1. INTRODUCTION

1.1. Context and regulatory references

- ❑ Environment Code, particularly title IX of book V;
- ❑ Decree 2007-1557 of 2 November 2007 amended, relative to basic nuclear installations and to the regulation of the transport of radioactive substances in terms of nuclear safety;
- ❑ Order of 7 February 2012 setting the general rules concerning basic nuclear installations.

1.2. Purpose of the guide

The French regulations require that the flooding hazard be taken into consideration in the demonstration of nuclear safety[1] of basic nuclear installations (BNI).

This guide details the recommendations concerning the external flooding hazard which is defined, for the purpose of this guide, as being a flood whose origin is external to the structures, areas or buildings of the BNI accommodating systems or components to be protected, whatever the cause(s) of that flooding (rainfall, river spates, storms, pipes failures, etc.). An external flood therefore means any flood originating outside the perimeter of the BNI[2] and certain floods originating within the BNI perimeter[3].

The terms "**flood**" or "**flooding**" as used henceforth designate external flooding.

The purpose of this guide is to:

- ❑ define the situations to consider when assessing the flood hazard for the site in question;
- ❑ propose an acceptable method of quantifying them;
- ❑ list recommendations for defining means of protection adapted to the specifics of the flooding hazard, implemented by the licensee according to the life cycle phases of the installation.

The guide has taken climate change into account when the state of knowledge so allows. It is necessary to take into account – on the basis of current knowledge – the predictable climate changes for a period representative of the installations' foreseeable life times, and until the next safety review.

The use of this guide necessitates prior identification - for the installation in question - of the functions[4] required to demonstrate nuclear safety and which shall be preserved in the event of flooding. These functions are called "**safety functions**" in this guide.

1.3. Scope of the guide

This guide applies to all the basic nuclear installations defined by article L. L.593-2 of the Environment Code. With regard to radioactive waste disposal installations, this guide only applies to above-ground facilities.

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[1] As defined in article 1.3 of the order of 7 February 2012, that is to say "all the elements contained or used in the preliminary safety report and the safety reports mentioned in articles 8, 20, 37 and 43 of the abovementioned decree of 2 November 2007 and involved in the demonstration mentioned in the second paragraph of article L. 593-7 of the environment code, which prove that the risks of accidents, whether radiological or not, and the extent of their consequences are, given current state of knowledge, practices and the vulnerability of the installation environment, as low as possible under acceptable economic conditions"

[2] "External flooding" in this case is an off-site hazard in the sense of the order of 7 February 2012 (see article 3.6 of this order)

[3] "External flooding" in this case is an on-site hazard in the sense of the order of 7 February 2012 (see article 3.5 of this order)

[4] Article 3.4 of the order of 7 February 2012 more specifically identifies certain functions that shall be ensured

This guide can be used to assess the external flooding hazards and the associated protective measures for both new installations and installations already in operation. For the latter installations, the periodic safety review (article L.593-18 of the Environment Code) provides an ideal framework for such an assessment or re-assessment. In the report mentioned in article L.593-19 of the Environment Code (report containing the conclusions of the periodic safety review), or earlier, when the review orientation file is prepared, it is worthwhile for the BNI licensee to indicate whether or not the recommendations of this guide will be followed, and if not, to explain why not (use of alternative methods...) and why it considers that this adequately prevents the hazards associated with external flooding.

Without waiting for the periodic safety review, this guide can also be taken into consideration in the authorization procedures associated with the submission of a safety report (commissioning, final shutdown / decommissioning, significant modification).

1.4. Status of the guide

This guide supersedes basic safety rule RFS 1.2.e of 12 April 1984 relative to consideration of the hazard of flooding of external origin, now considered obsolete in the light of the advances in knowledge in this area.

This new guide is the result of a collaborative effort spanning several years involving experts from the IRSN (French Institute for Radiation Protection and Nuclear Safety), other organizations specialised in the areas of hydrology, hydraulics and meteorology, and representatives of the licensees.

This guide was moreover open to a public consultation from 15 June 2010 to 15 September 2010. The last version of the guide, taking account of the remarks made during the consultation, was submitted to the Advisory Committee of Experts for Nuclear Reactors (GPR) and for Laboratories and Plants (GPU) on 24 May 2012 for their opinion. These advisory committees approved it, considering that *"the changes introduced in the draft guide constitute an improvement with respect to RFS 1.2.e"*.

1.5. Structure of the guide

The guide structured in three parts:

1) Part II presents an approach for defining the reference flood situations (RFS) to consider in the flood hazard study, and then defines 11 RFSs;
2) Part III is devoted to the quantification of the parameters characterising the physical phenomena involved in the defined situations;
3) Part IV identifies the particularities of the flood hazard and the principles guiding the design choices and the means of protection to implement against the flood hazard.

2. REFERENCE SITUATIONS TO BE TAKEN INTO ACCOUNT FOR ASSESSING THE FLOOD HAZARD

2.1. Identification of water sources

The first step in the approach is to list the water sources that could initiate or contribute to a flood affecting the site in question:

- ❑ rainfall (1);
- ❑ groundwater (2);
- ❑ seas and oceans (3);
- ❑ watercourses (rivers and canals) (4);
- ❑ natural reservoirs (lakes, glaciers) (5);
- ❑ man-made reservoirs (storage dams, tanks, water towers, pipes, etc.) (6).

This step is illustrated in figure [1]; the numbers identifying the water sources correspond to the above definitions.

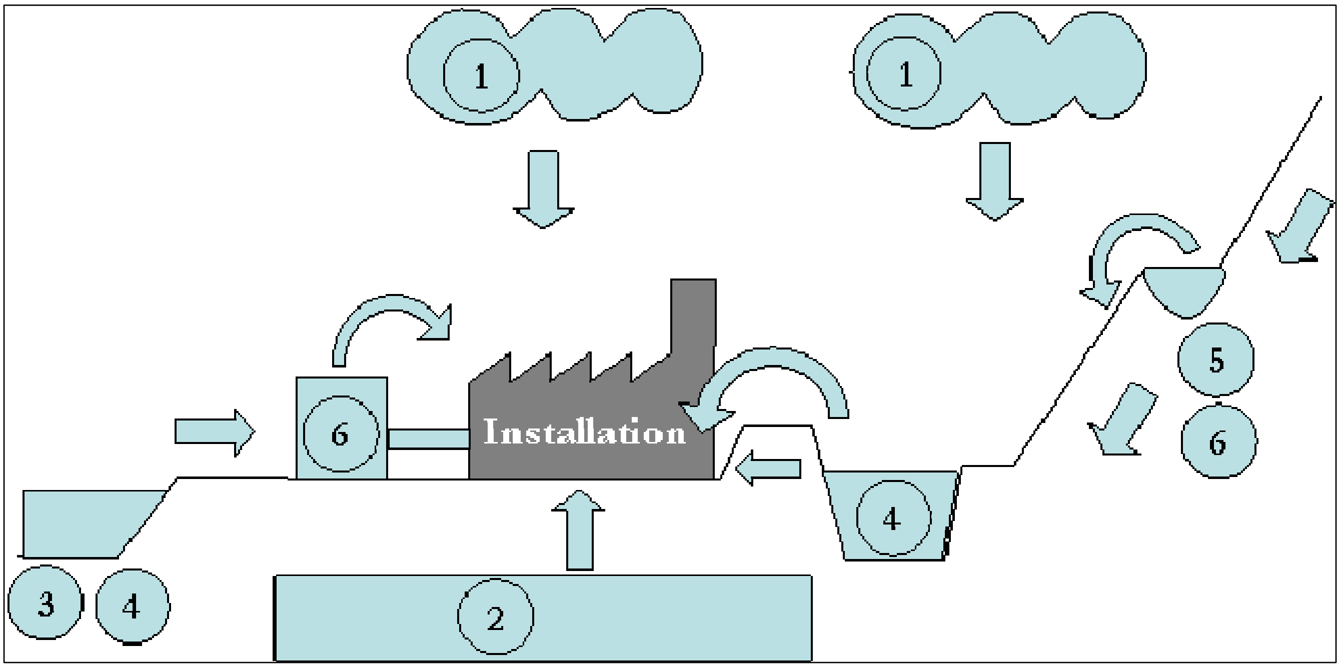

Figure [1]: Water sources

2.2. Identification of causes of flooding

The second step in the approach is to list the events or combinations of events that could cause a flood hazard for the installation in question, for each of the identified water sources.

A particular "**event**" is usually characterised by a physical quantity that defines its intensity (volume, height, flow rate, etc.) and if applicable, a probability or frequency of exceedance of that intensity, and a duration. For example, the hundred year return period river flood is an event for which the discharge flow rate has an annual frequency of exceedance equal to 10^{-2}/year used to qualify a river flood.

Floods can be caused by either a single event of high intensity or a combination of events of other order of magnitude (simultaneous or successive natural events, failure of a structure or protection equipment, etc.).

2.3. Definition of flood situations

2.3.1 Definition

A "**Reference Flood Situation**" (**RFS**) is defined on the basis of an event or a combination of events whose characteristics may be increased if necessary (unfavorable combination or margin to compensate for the limits of current knowledge).

2.3.2 General

A list of RFSs shall be drawn up according to the characteristics of the site accommodating the installation. The design of the installations with regard to the flood hazard shall be justified in view of these RFSs, taking into account any dynamic effects.

The list of RFSs shall take into account the various water sources at and around the site, and the identified events or combinations. The way the RFSs are listed and characterised is based on the following recommendations for each type of site.

Whatever the case, the identified RFSs shall at least encompass all the situations corresponding to the experience feedback which is relevant for the site in question.

The recommendations given below for defining and characterising the RFSs result from a generic analysis of the flood hazard for different types of site, in the light of current knowledge (accessible data and methods of characterising events) and an expert appraisal based on knowledge of the existing French BNI sites.

The RFSs are expressed either on the basis of a statistical analysis of the available data or deterministically. With regard to the statistical extrapolations, the peak over threshold methods that consist in using a sample of observations exceeding a chosen value, such as the « renouvellement » method*, are considered acceptable.

A clear distinction shall be made between the frequency of the consequences of an event and the frequency of the event itself. This is because there is not necessarily a one-to-one relationship between cause and consequences. For example, a rainfall whose average intensity corresponds to a one-hundred-year return period will not necessarily cause a maximum one-hundred-year return period flow rate nor a hundred-year return period maximum water height at the site.

Combinations of events have been chosen inter alia where there is a proven or presumed dependency between events likely to cause flooding. In addition, when the potential for concomitance has been identified in the light of the duration and frequency of any one of the events, their combination has been included.

The list of RFSs is illustrated in figure [2].

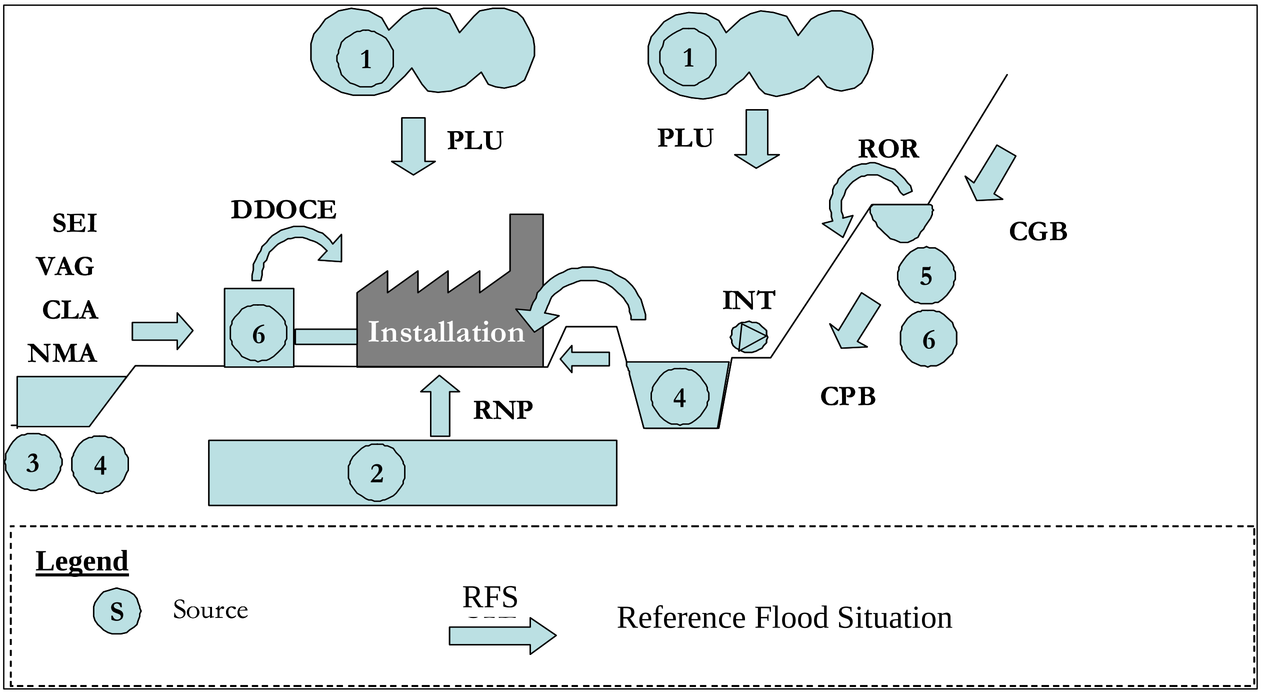

Figure [2]: Schematic diagram of the RFSs

Legend for the acronyms of figure [2]:

PLU	Local rainfall
CPB	Small watershed flooding*
CGB	Large watershed flooding
DDOCE	Deterioration or malfunctioning of structures, circuits or equipment
INT	Mechanically induced wave* – Malfunctioning of hydraulic structures
RNP	High groundwater level
ROR	Failure of a water-retaining structure
CLA	Local wind waves
NMA	Sea level
VAG	Ocean waves
SEI	Seiche*

2.3.3 RFSs to be taken into account for all sites

At least five RFSs have to be taken into account for all sites: local rainfall, small watershed flooding, deterioration or failure or structures or equipment, mechanically induced wave and high groundwater level.

2.3.3.1. Local rainfall

Each rainfall event is characterised by a height of precipitation totalled over a given period of time. The reference rainfall events are defined by the upper bound of the 95% confidence interval for the one-hundred-year return period rainfall events calculated from the data of a weather station that is representative of the conditions of the site.

When the stormwater drainage system design requires the defining of a water level at the outlet, it is defined considering:

- ☐ for drainage systems that discharge into another system, a pond or a watercourse whose level is sensitive to local rainfall events, the behaviour of these outlets following the reference rainfall events defined for the watersheds situated upstream of these outlets, or failing this, the one-hundred-year return period water flow rate or water level in the receiving environment,
- ☐ the average flow rate or water level for drainage systems that discharge directly into watercourses whose flow rate at the site is independent of the weather conditions at the site,
- ☐ the 10-year return period high tide level.

To take account firstly of the potential for obstruction of the stormwater drainage system during extreme events, and secondly for events rarer than those defined in the reference rainfall events, the installation shall be able to cope with a surface water runoff scenario when its local stormwater drainage system is completely blocked. This reference surface water runoff scenario is defined by the one-hundred-year return period rainfall event (value of the upper bound of the 95% confidence interval) lasting 1 hour.

Additional studies shall be carried out using the similar approach for the watersheds situated upstream of the installation. With regard to water inflows from rural watersheds with a surface area of 10 km² or less, the licensee shall verify that the protection measures include a significant margin for the occurrence of water runoff exceeding the levels defined by the reference rainfall event. The licensee shall examine the particular points on and near the site where debris jams* might occur and could aggravate the situation, and shall address them in the safety demonstration (see 4.3.3.2).

2.3.3.2. Small watershed flooding

The reference small watershed flooding is defined by an instantaneous peak flow rate, for a ten-thousand year return period.

The reference small watershed flooding where the watershed surface area is between 10 and 5,000 km² shall be evaluated preferably using a method that models the asymptotic behaviour of the mean rainfall-runoff transformation for a time step appropriate for the watershed's concentration time. One method of obtaining the instantaneous peak flow rate consists in working with a sample of average flow rates and multiplying the extrapolated flow rate by a shape factor.

For watersheds with a surface area of between 10 and 100 km², the flow rate associated with this RFS can be calculated from the one-hundred-year return period rainfall events (upper bound of the 95% confidence interval) by multiplying the resulting flow rate by a factor of 2.

If necessary, the downstream condition of the watercourse, at the watershed outlet, is defined taking into account the possibility of concomitant flooding of the watercourse and an unfavorable water level in the receiving environment. If the flooded watercourse flows into the sea, the ten-year return period high tide level can be used. Likewise, if the flooded watercourse flows into another watercourse, the mean flow rate of this latter watercourse may be used unless it could also be affected by the weather conditions that caused the flooding of the first watercourse.

The licensee shall examine the particular points where debris jams might occur and could aggravate the effects of the reference flood on the site.

The reference flood and the justifications to be provided for small watersheds exceeding a surface area of 100 km² shall be examined on a case-by-case basis.

2.3.3.3. Deterioration or malfunctioning of structures, circuits or equipment

The question here is to characterise the consequences of possible malfunctioning or deterioration of structures, circuits or equipment that could lead to the discharging of a significant quantity of water on the site.

An exhaustive analysis of these structures, circuits and equipment shall be carried out. Those close to or on the site, outside buildings housing important protection elements associated with nuclear safety are taken into account.

The types of structures, circuits and equipment to be taken into consideration include:

- basins, reservoirs, ponds, tanks,
- the circuits, pipes, filling and discharge structures, water-retaining structures,
- dykes along watercourses and canals and the associated hydraulic structures, except for the structures considered in the "failure of a water-retaining structure" RFS defined in paragraph 2.3.4.2 and dry dykes.

The failure or overtopping of structures, circuits or equipment can for example result from:

- malfunctioning of these structures, circuits or equipment,
- intrinsic failures such as hydraulic deterioration for embankment structures or failure due to ageing,
- external hazards that could affect the site (earthquake, explosion, fire, aircraft crash, etc.),
- specific hazards related to a particular geographic situation of the structure, circuit or equipment.

The rupture failures to be taken into consideration are simple failures or multiple common mode failures.

2.3.3.4. Mechanically induced wave

The reference mechanically induced wave is a wave resulting from a rapid change in flow rate in channel, situated on the site or upstream or downstream of it. It is characterised by its intensity (maximum overtopping flow rate, corresponding maximum water height on the site, volume discharged) and its duration (taking account of the different dynamics associated with the main wave and the effects accompanying this main wave).

A study of the possible causes of mechanically induced wave should identify the mechanically induced wave scenario(s) that could affect the site. The reference situation is chosen considering the initial level and flow rate conditions leading to the worst-case mechanically induced wave situation. When characterising the initial level, no situation less probable than the flood or sea level RFSs defined in sections 2.3.4 and 2.3.5 shall be taken into consideration.

Malfunctions of hydraulic structures can also lead to a difference between inflow and outflow of a reach* and cause a rise in the water level at the site. When studying this situation, justification shall be provided for the methods used to rebalance flow rates in order to correct any such differences.

2.3.3.5. High groundwater level

The reference groundwater level is characterised on the basis of a hydrogeological study of the site, depending on the available data, using one of the following two methods.

1. The combination of an "initial level" and the rise effect caused by an "initiating event".

In this guide, the "initiating event" is the one event among those examined in order to characterise the RFSs (flood, sea level, rainfall events, deterioration of structures, etc.) that causes the greatest rise in the groundwater level. The duration of the initiating event is chosen so as to maximise the rise in the groundwater level, particularly in the case of large watershed flooding (to take into account the effect of a flood of equivalent volume spanning a longer period of time) and in the case of rainfall events (the durations to take into consideration can range from a few hours to several months).

The "initial level" of the groundwater on the date of occurrence of the large rises in level sets a fixed magnitude to the contributions from all the phenomena considered to be secondary. In the absence of the initiating event in question, the initial level is defined as the maximum level observed over a period of at least 10 years. The ten-year return period level can be used as an alternative to this level. If the available data do not allow this approach to be used, the value chosen shall be justified by expert opinions, taking into consideration the available observation period.

2. A statistical analysis of the groundwater levels

The reference level can be defined as the level associated with a one-hundred-year return period, taking the upper bound of the 95% confidence interval. The statistical analysis relates to the highest levels reached in a long series of piezometric levels, established from on-site time series. These time series can be extended by a simulation able to reconstitute the measured series and that extends it on the basis of other data available over a longer period. In view of the relatively short return period available through this statistical analysis, the reference level is calculated using particularly unfavorable hydrogeological hypotheses.

The choice of method and the calculation factors are justified by a hydrogeological study of the site based on piezometric measurements.

This procedure is applied as required to the calculation of the consequences of a given groundwater level: induced pressure, maximum flow rate or total volume of water to be dewatered.

2.3.4 RFSs to take into account for river sites

Three additional RFSs shall be considered for river sites: large watershed flooding, failure of a water-retaining structure and local wind waves.

2.3.4.1. Large watershed flooding

A large watershed generally covers an area larger than 5,000 km^2. This value does however depend on the nature of the watershed, its average altitude, its slope, its geology, etc.

A large watershed flooding is characterised by a reference flow rate, a reference water level and the associated flood plain.

The reference flow rate corresponds to the peak flow rate associated with the thousand-year return period flood, taking the upper bound of the 70% confidence interval, and increased by 15%.

The reference level is the maximum level on the site resulting from the reference flow rate. In some particular site configurations, a higher water level can be reached with a lower flow rate than the reference flow rate; in such cases the reference level is the level corresponding to this lower flow rate.

In the case of an engineered watercourse, the functioning and behaviour of the installed equipment shall be considered (operation rules in flood conditions, head loss due to bridge deck, deterioration of structures, etc.).

The proximity of the studied site to a confluence of watercourses may require that the flood analysis takes this confluence into account.

2.3.4.2. Failure of a water-retaining structure

The analysis of the failure scenarios concerns water-retaining structures that lie across watercourses. In some cases the volume and location of lakes or retaining structures that are not situated on watercourses may justify treating the associated structures in accordance with the recommendations of this section.

The postulated scenario is the failure of the water-retaining structure in the watercourse that would lead to the most serious consequences for the site. The reference level associated with the failure of this structure is the maximum level on the site resulting from propagation of the flood wave. The RFS study shall consider the watercourse on which the site is situated and the various valleys that open out near the site.

In some particular site configurations, a higher water level can be reached with a lower flow rate than the reference flow rate; in such cases the reference level is the level corresponding to this lower flow rate.

In the case of an engineered watercourse, the functioning and behaviour of the installed equipment shall be considered (operation rules in flood conditions, head loss due to bridge deck, deterioration of structures, etc.).

The proximity of the studied site to a confluence of watercourses may require that the RFS study takes into account the effect of propagation of the flood wave into each tributary.

2.3.4.3. Local wind waves

The reference local wind waves are the field of waves resulting from a hundred-year return period wind (upper bound of the 70% confidence interval) propagated over a thousand-year return period flood (upper bound of the 70% confidence interval.

It is characterised by a significant wave height*, a representative period (e.g. the mean period or significant period*) and a dominant direction of propagation.

The duration of the RFS is characterised from statistics on the durations of large wind events.

2.3.5 RFSs to take into account for coastal sites

Three further RFSs shall be taken into consideration for coastal sites: sea level, waves, and seiches.

The situations defined below are applicable for sites situated on the Atlantic coast of metropolitan France; they are not adequate for sites situated on the shores of the Mediterranean Sea.

2.3.5.1. Sea level

The reference high sea level is the conventional sum of:

- the maximum level of the theoretical tide*,
- the one-thousand year return period storm surge* (upper bound of the 70% confidence interval), increased to take into account uncertainties associated to the evaluation of the rare storm surges, and resulting from outliers*,
- the change in mean sea level extrapolated to the next periodic safety review.

As an alternative to the first two points above, a statistical analysis of the tide levels and storm surges may be conducted to determine the probability of exceedance of the water level resulting from the two phenomena combined (joint probability method), considering a ten-thousand-year return period. This approach shall use a statistical extrapolation model that can cover outliers, and include an estimate of the sampling uncertainty that will be covered by the reference sea level.

The reference high sea level shall also integrate the seiche hazard under the conditions defined in paragraph 2.3.5.3.

2.3.5.2. Waves (ocean waves and local wind waves)

Characterising the wave conditions at a coastal site in principle combines ocean waves generated by off-shore wind and propagated beyond the area on which they are generated, and waves generated by the local wind.

The reference waves are characterised from the one-hundred-year return period significant height wave conditions (upper bound of the 70% confidence interval) determined offshore of the site and propagated over the reference sea level. In this case it is recommended not to separate the ocean waves and the local wind waves, and to perform the analysis on the total wave height data.

Depending on the exposure and configuration of the site, it is possible to simplify the analysis by determining the predominance of the contribution of the ocean waves or the local wind waves to the total wave height.

More specifically, if the effects of the local wind are found to be predominant over the ocean waves due to the site configuration or existing structures, reference local wind waves is used. This is defined by the local wind waves resulting from a hundred-year return period wind (upper bound of the 70% confidence interval) propagated over the reference sea level.

The duration of this RFS is determined from the variations in sea level caused by the tide.

2.3.5.3. Seiche

The seiche hazard is analysed on the basis of available experience feedback, for example through the operation of an existing installation or measurements of the water level.

If the seiche hazard is identified in coastal infrastructures (port dock, water intake or discharge channels), the phenomenon is taken into account in the calculation of the reference sea level. As a first approach, the reference sea level can be increased by the estimated height of the annual seiche (statistical or empirical estimate, depending on the available data).

2.3.5.4. Tsunami

Tsunamis are generated by seismic or volcanic activity, or by submarine or coastal landslides. An earthquake can only cause a tsunami if it occurs at a shallow depth and is of a sufficiently high magnitude. For example, the tsunami alert triggering threshold in the Pacific is set at a magnitude of 6.5 for a local bulletin, 7.6 for a regional alert, and 7.9 for a large-scale alert. In the case of a landslide, experience shows that the volume of the collapse is the most important parameter. A tsunami can develop on a local scale (a few kilometres from the source) for collapse volumes of the order of 100,000 m^3, on a regional scale (several tens or even hundreds of kilometres) for volumes of about 1 km^3, or even on a transoceanic scale for larger volumes (of the order of one-hundred km^3). No geological structure that could cause a major tsunami has been identified near the Atlantic coast of metropolitan France (more specifically the coasts of the Atlantic Ocean, the English Channel and the North Sea).

In the last 50 years of seismic and sea-level monitoring, no rise in sea level on the Atlantic coast of metropolitan France has been linked with any certainty to an Atlantic tsunami. In a manner comparable to the seismic hazard studies, historical analyses have been carried out to extend the observation period. These involve analysing the literature to identify observations that could be linked with tsunamis, such as fluctuations in water levels, particularly in ports, related to earthquakes for example. Witness reports compiled from the 18th century to the present day record about fifteen events attributed to tsunamis with varying degrees of uncertainty. In none of the cases do the effects go beyond the flooding of gently sloping coastal areas, the beaching of light vessels and slight damage to lightweight constructions close to the coasts, whereas more severe damage and the highest sea levels have been observed during storms causing high surges, sometimes coinciding with high tides and accompanied by ocean waves.

Moreover, tsunamis are independent of high tides and storms. The probability of a tsunami and the sea level RFS occurring together is therefore very low. The joint occurrence of these two events has therefore been ruled out.

Thus, given that the Mediterranean sites are excluded from the scope of paragraph 2.3.5, the tsunami hazard is considered to be covered by the reference sea level and wave situations.

2.3.5.5. Other events

The hazard associated with the waves produced by the passing of ships is covered by the wave reference situations, given the limited amplitude of these waves and the limitation of navigation during storm events.

2.3.6 Specific case of estuary sites

Estuary sites are subject to both marine influences and river influences.

2.3.6.1. Marine influences

The RFSs defined in paragraph 2.3.5 are characterised considering - at the mouth of the estuary - the maritime conditions defined for coastal sites (reference sea level and reference waves) associated with a hundred-year return period local wind (upper bound of the 70% confidence interval) and an average flow rate of the river. The duration of RFSs is determined from the variations in sea level caused by the tide.

2.3.6.2. River influences

The RFSs defined in paragraph 2.3.4 are characterised with the following adaptations.

For the "large watershed flooding" RFS, the reference situation is characterised without applying the 15% increase specified in paragraph 2.3.4.1, and considering a maximum level of the theoretical tide*.

For the "failure of a water-retaining structure" RFS, the reference situation is characterised considering an average high sea level (tidal coefficient of 70).

For the "local wind waves" RFS, the reference situation is characterised considering an average high sea level (tidal coefficient of 70).

The tidal bore* phenomenon which can occur in estuaries is covered by the high reference levels. Furthermore, the conditions of occurrence of tidal bores justify not combining them with high sea levels.

3. CHARACTERISING THE REFERENCE FLOOD SITUATIONS (RFS)

3.1. Introduction

The RFSs are characterised on the basis of the observed data for the site in question, adopting a reasonably conservative approach. The reasons for this are to allow for limitations in the quantity and reliability of available data, uncertainties inherent to the current state of knowledge (modelling, etc.) and future climate and environmental changes. Therefore the approach shall include unfavorable hypotheses and margins.

For each RFS the "influencing factors" specified in the remainder of the guide shall be monitored. These factors have been defined in view of the significant impact of their variation on the RFS. Moreover, the licensee shall analyse any exceptional flood situation whose characteristics near the site exceed the one-hundred-year return period values, or the highest previously observed values. The occurrence of such a situation or a significant change in one of these influencing factors can make it necessary to reassess the RFS before the next periodic safety review of the installation.

The way uncertainties are taken into consideration is developed in section 3.2.

RFS characterisation is achieved in particular using the parameters and methods defined for each RFS in sections 3.3 to 3.14.

It may be necessary to study several scenarios for each RFS to characterise the envelope values to use for the design of the installation protection provisions.

In the RFS study, all the levels are presented using the same geographical reference datum, the choice of which is clearly specified.

3.2. Taking uncertainties into consideration

The RFSs are characterised first and foremost from an expert appraisal. This appraisal takes into consideration the identified uncertainties in the current state of knowledge. The aim of the recommendations concerning the consideration of combinations of events, initial states, or more broadly all the uncertainties, is to introduce conservative measures.

Given the lack of reliable uncertainty propagation models, the uncertainties relating to each parameter shall be examined.

In the paragraphs specific to each RFS, the guide proposes a method for taking certain particular uncertainties into account. When no information is provided, the uncertainties shall be addressed applying the principles developed below.

The uncertainties can be grouped into different types:

1) to assess the probabilities of exceedance associated with the rare events:
   a) the uncertainties in the statistical analysis input data;
   b) the uncertainties relating to the choice of statistical model;
   c) the uncertainties relating to the size of the statistical sample available;
   d) the uncertainties relating to representativeness of that sample

2) to assess the hydraulic values of parameters relative to the rare events considered for the design of the installations:
   e) the uncertainties relating to lack of knowledge (also known as epistemic or systemic uncertainties);

f) the uncertainties relating to the variability of the possible initial states (also known as aleatoric or statistical uncertainties).

Uncertainties of types a, b, e and f are difficult to quantify statistically because they result from the choice of hypotheses and the calculation methods, or from the interpretation of certain data. Consequently, it is accepted that experts' appraisals enable these best choices to be made, without it being necessary to add a safety margin to the estimate to cover these uncertainties. "Best" means that the experts' choice is justified either by the existing scientific consensus in the area considered, or by sensitivity analysis concerning certain hypotheses proving the conservative nature of the result.

The sensitivity analysis of the result for the hypotheses can, for example, be conducted by identifying the influencing parameters, then adopting unfavorable values for these influencing parameters. The number of sensitivity studies can be limited by identifying the most influencing parameter and taking the most unfavourable value for the characterisation of the RFSs so as to cover the uncertainties for a whole set of parameters. This approach is particularly appropriate with regard to hydraulic flood propagation.

With regard to type-a uncertainties, it is essential to have the data critically reviewed by an expert to check their reliability. The expert also checks that the data are representative for the site.

The other two sources of uncertainty come from the size and representativeness of the statistical sample (types c and d).

Once available information has been collected that is detailed enough to ensure its exhaustiveness, any statistical sample available shall be used to determine the probability of exceedance curve for the rare events. Any historical data reported prior to the existence of the observation stations and their regular data recordings shall also be taken into account.

Given the fact that all these data represent only a limited amount of information, and generally only concern a relatively short period of time (type-c uncertainty), the confidence interval of the calculated mean value shall be evaluated. To cover the uncertainties relating to sampling, the chosen extrapolated value shall be the upper bound of the recommended confidence interval for each RFS. In practice, the 70% confidence interval generally displays an amplitude that is considered "appropriate". For some RFSs, adopting a more unfavorable confidence interval (e.g. 95%) is a way of covering type-b uncertainties.

Evaluating the uncertainties (type d) relating to the representativeness of the statistical sample available at the time of the calculation, is highly complex. These uncertainties result from the fact that the available sample and the statistical model calibrated on the data from that sample can display different characteristics to those that could appear during the life of the structure (dependency on successive annual events, succession of high-occurrence and low-occurrence periods, etc.). More specifically, the type-d uncertainties encompass uncertainties due to the hypothesis of stationarity* of the data, which constitutes a strong hypothesis for the hazards influenced by climatic or anthropological changes; methods of correcting these changes can be applied to certain RFSs. However, on condition that the statistical sample used for the calculation is as exhaustive as possible, the uncertainties on the representativeness of the sample can be considered to be taken into account by both a suitable choice of the extrapolation model used (type-b uncertainties) and the calculation of the associated confidence interval (type-c uncertainties).

3.3. Local rainfall

3.3.1 Characterising the reference rainfall events

The reference rainfall events are quantified from a statistical study of the rainfall data recorded at a weather station that is representative of the conditions of the site. They are defined for all the durations necessary for the development of one or more conservative rainfall scenarios for the areas of the site with equipment or rooms that require protecting. The Montana formula* is an acceptable method for characterising the intensity of the reference rainfall events.

The biases due to the use of "non-centred" rainfall data* are corrected. For the 6-minute "non-centred" rainfall data, the correction given by the Weiss coefficient (1.14) is acceptable with the current state of knowledge.

The validity of the one-hundred-year return period reference rainfall value shall be justified notably by examining the values measured in representative stations other than the chosen station, or by comparison with the values calculated using a regionalised approach*.

3.3.2 Quantification of runoff flow rates

The runoff flow rates are quantified by a rainfall-runoff transformation method.

It is recommended to perform detailed numerical modelling of the watersheds for this purpose. The rainfall events are modelled by design rainfall events* (Keiffer or double-triangle rainfall patterns are considered appropriate, given the current state of knowledge) and are associated with one or more periods of intense rainfall, with a view to obtaining unfavourable rainfall event scenarios for the areas of the site with equipment or rooms that require protecting. The values of the infiltration losses take into account the behaviour of the ground during extreme rainfall events.

However, in some simple cases, other methods such as the rational method* can be used.

3.3.3 Study of the behaviour of the stormwater drainage system[5]

The model of the installation's stormwater drainage system should be integrated into a aggregate model of the site stormwater drainage system to cover the interactions between the different sections of the site system.

The friction coefficients used for the system shall be representative of the wear and state of maintenance of the pipes. The values are justified by taking the drainage system maintenance programmes into consideration; failing this, increased overflow values are used.

The continuous flow rate discharged into the stormwater drainage system in normal operation, and of significant levels with regard to its capacity, are taken into consideration when characterising the flow rate to be discharged by the system.

If the drainage system discharges into the sea, the levels established by the competent administrative department serve as the reference for quantifying the 10-year return period high sea level at the outlet.

As a general rule, the unfavorable nature of the drainage system behaviour model is justified by setting the model parameters to increase the overflows, or – when possible – by calibration* using measured flow rates.

The drains installed in the low areas near access points shall be identified, and the potential for reaching maximum capacity and overflow shall be examined in all cases.

If the RFS study is carried out in steady flow rate conditions (Quacot's formula, rational method), the behaviour of the stormwater drainage system sections whose under-capacity could cause overflows in the areas of the site containing equipment or rooms that require protecting, shall be verified.

On completion of the site development work, an on-site verification shall be carried out to validate the hypotheses used in the studies (of the functioning of the drainage system and the runoff scenario) for the description of the watersheds and the stormwater drainage system. This verification can be supported by topographical surveys, as-built drawings, runoff and drainage tests corresponding to normal rainfall situations.

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[5] The term stormwater drainage system is used in a general sense. In practice, an installation can have several distinct drainage systems.

3.3.4 Influencing factors to be monitored

The chosen influencing factors to be monitored are:

- ☐ the functioning of the stormwater drainage system,
- ☐ the characteristics of the drained watersheds.

The rainfall data measured on the site are kept in a usable database.

3.4. Small watershed flooding

3.4.1 General

The instantaneous peak flow rate is determined from an average flow rate resulting from an extrapolation multiplied by a shape factor. This shape factor is the average of the ratios of the peak instantaneous flood flow rate to the mean flow rate associated with this peak flow rate for a selection of floods measured with a sufficiently small time step.

The method is based on simulations using a hydrological model if flow rate data are available. Otherwise, the shape factor and the estimated flow rate beyond which runoff is considered to be total are deduced from regional approaches (Caquot's formula, rational method, etc.).

When using the method indicated in the third paragraph of section 2.3.3.2 for watersheds with a surface area of less than 100 km^2, the recommendations of sections 3.3.1 and 3.3.2 apply. Runoff modelling takes into account the behaviour of the ground during extreme rainfall events (more particularly, the water saturation of soils in rural watersheds shall be taken into account).

If characterising the water level from the reference flow rate requires the use of a local flood propagation model, the recommendations relative to flood propagation on large watersheds apply (see section 3.8).

3.4.2 Influencing factors to be monitored

The influencing factors to be monitored are the characteristics of the drained watersheds.

3.5. Deterioration or malfunctioning of structures, circuits or equipment

3.5.1 General

A conventional break failure is postulated for each structure, circuit and item equipment, unless:

- ☐ a break can be excluded due to the design requirements and the operational monitoring of the structure, circuit or item of equipment concerned,
- ☐ there is no malfunction, intrinsic failure or hazard that could lead to a break.

In the case where breaking is excluded, the possibilities of deterioration or malfunction are nevertheless studied: overtopping of structures or equipment, increased percolation in dykes, etc.

The parameter to be evaluated to characterise the RFS is usually the discharge volume resulting from the break. In the case of circuits or equipment items in wich a flow passes, the discharged volume can be assessed on the basis of this flow rate and the time necessary to isolate the leak.

To assess the effect of the discharged volume, it is usually necessary to characterise the potential resulting water height. The volumes of water that could enter the rooms to be protected are quantified on the basis of this water height.

The unfavorable nature of the breaks considered is evaluated according to:

- ☐ the volumes involved,
- ☐ the location of the breaks with respect to the installation's important safety equipment,
- ☐ the possibilities of detecting and isolating the leaks.

3.5.2 Characterising simple breaks

The conventional break is characterised in several stages:

- ☐ identification of the structures, circuits and equipment item whose failure would represent a conservative scenario,
- ☐ defining of the chosen conventional break,
- ☐ characterising of the volume discharged.

When identifying the most unfavorable structures, circuits and equipment and defining the conventional break, experience feedback is always taken into consideration.

Depending on the characteristics of the structures, circuits and equipment, the break shall be located at the point that could lead to the most severe potential consequences in accordance with the three criteria of section 3.5.1.

The duration of the leak depends on the type of break and the time necessary to detect and isolate the leak.

The leakage rate of circuits is characterised from the characteristics of the circuit and of the break. The pipe break is considered to be total. Less severe failure hypotheses can be applied if the licensee can justify them on the basis of the characteristics of the equipment concerned (for example if possible movements of the pipe are limited by its supporting elements), and the associated requirements and operational monitoring.

In the case of an "open" circuit on a water source of "infinite" volume, such as a watercourse, a canal or the sea, and which is not provided with devices for isolating a leak, the upstream level to be considered is a frequently observed level.

The discharged volume is the sum of the volume in the circuit that can flow out by gravity and, where applicable, the volume that flows out while the circuit is still being supplied before it is isolated.

For the breaks in structures such as basins or tanks, the structures are assumed to be at the maximum filling level authorized in operation.

3.5.3 Characterising multiple breaks

It shall be verified that the various hazards[6] taken into consideration in the safety demonstration (such as an earthquake, strong winds, explosion, fire, etc.) would not lead to a flood caused by multiple breaks in structures, circuits or equipment situated on or near the site. If this cannot be verified, then the cumulative consequences of the failures of these structures, circuits and equipment shall be assessed. Damage being caused to circuits and equipment by other items of equipment or structures rendered unstable by the hazard in question is also considered. When characterising the multiple breaks of structures, circuits and equipment, experience feedback is always taken into consideration.

The structures, circuits and equipment to be considered, depending on their location, in an earthquake situation, are:

- ☐ tanks not designed to withstand earthquakes,
- ☐ pipes not designed to withstand earthquakes,
- ☐ special features (compensators) on pipes, which are not designed to withstand earthquakes,
- ☐ the structures or items of equipment that can be harmed by other items not designed to withstand earthquakes,

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[6] Hazards originating outside the structures or buildings containing the equipment to protect,

- ❑ dykes on canals and watercourses not designed to withstand earthquakes,

The following hypotheses are to be considered for the earthquake:

- ❑ for tanks: the complete and simultaneous emptying of all the tanks not designed to withstand earthquakes and situated on the platform is considered. The protective role of a retention area can be put forward only where its performance is ensured in the occurrence of an earthquake. All the tanks are assumed to be filled to the maximum filling level authorized in operation.
- ❑ for the ponds: emptying of the volumes of the ponds situated above the level of the platform is considered. The ponds are assumed to be filled to the maximum level planned for in operation, except for the stormwater ponds, which are assumed to be filled to a frequently observed level.
- ❑ for pipes: the break of a pipe not designed to withstand an earthquake and producing an unfavorable effect (see 3.5.1) is considered, The pipe break is considered to be total. Less severe failure hypotheses can be applied if the licensee can justify them on the basis of the characteristics of the equipment concerned (for example if possible movements of the pipe are limited by its supporting elements), and the associated requirements and operational monitoring.
- ❑ for the special features: the simultaneous rupture of all the compensators situated on pipes not designed to withstand an earthquake are considered. Total rupture of the compensator is considered. Less severe failure hypotheses can be applied if the licensee can justify them on the basis of the characteristics of the equipment concerned (for example if possible movements of the pipe are limited by its supporting elements), and the associated requirements and operational monitoring.

3.6. Mechanically induced wave – malfunctioning of hydraulic structures

3.6.1 Identification of mechanically induced wave scenarios

The study of the possible causes of mechanically induced wave concerns the structures internal to the site (pumping stations, discharge structures, etc.) and the external structures (other pumping stations, hydroelectric plants, etc.), including those belonging to other hydraulic structure operators. In this second case, the structures situated at a distance from the site shall not be ruled out without prior analysis.

The maximum level reached as a result of the mechanically induced wave is closely related to the water levels and initial flow rates. It is necessary to seek the worst-case scenario, taking into account the structure operating instructions.

3.6.2 Quantification of the mechanically induced wave

For channels with simple geometry, the formula [7] $h=cV/g$ is sufficient to quantify the mechanically induced wave. In more complex cases it may be necessary to use mathematical models (1D or 2D), or even a physical model.

It may be necessary to take into account phenomena such as Favre waves*, or the edge effects accompanying the main wave, if necessary using three-dimensional models.

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[7] Where h is the height of the mechanically induced wave (m); c is the speed of propagation of the mechanically induced wave (m/s); V is the average speed of flow before flow cutoff (m/s)

3.6.3 Change in the water level in a reach through water storage (or drainage)

When the flow recovery systems are passive (weirs, etc.), it is sufficient to check that they are adequately sized for the most critical situation. When the flow is recovered by active systems such as sluice gates, it is necessary to demonstrate that the actuating components are sufficiently reliable and to guarantee their operational state.

3.6.4 Influencing factors to be monitored

The influencing factors to be monitored are the equipment and structures that could cause mechanically induced wave (structural modification or construction of a new structure).

3.7. High groundwater level

3.7.1 Hydrogeological data

Knowledge of the local hydrogeology shall be based on the acquisition of descriptive data relative to the site and its surroundings (geology, groundwater levels, hydrodynamic data, etc.…). The data collected from public organisations shall be supplemented by the results of in-situ measurements. More specifically, piezometric measurements shall be taken over a continuous period that shall never be less than 1 year and shall preferably exceed 3 years, with a sufficiently small time step to characterise the amplitude and speed of fluctuations in groundwater level. The number and location of the piezometers shall enable the local functioning of the groundwater table to be analysed by covering a sufficiently large area, generally extending beyond the site boundaries.

If the conditions at the boundaries of the hydrogeological system are linked to a body of water (sea, lake, etc.) or a watercourse, it is recommended to monitor the change in the corresponding water levels at the same time.

An analysis of the groundwater level fluctuations shall be carried out to identify the behavioural particularities of the groundwater table and to characterise water level rise and fall times. This analysis shall allow:

- in application of method 1 described in section 2.3.3.5, the contribution relative to the initiating event to be clearly distinguished from that induced by the initial level considered,
- in application of method 2 described in section 2.3.3.5, a verification of the independence of the analysed events for the statistical analysis of the levels measured or simulated in the event of a high rise.

This analysis is carried out taking the piezometric levels representative of the groundwater table fluctuations and displaying the highest fluctuations or the highest levels, in order to define the behaviour of the groundwater table comprehensively.

3.7.2 Quantification of the groundwater level

It is recommended to use modelling tools. In certain conditions however, the hydrogeological conditions can enable an upper bound of the groundwater rise to be characterised in a simple and conservative manner without modelling being necessary.

A model is generally calibrated on observed high levels, which are not necessarily representative of the levels that could be reached in an extreme situation. In this case, the model is used beyond its calibration range, and it is necessary to justify the unfavourable nature of the hypotheses relative to the representation of the geological layers situated above the aquifer* and which could be reached during an extreme rise in the groundwater level.

In the application of method 2 defined in section 2.3.3.5, it is advisable to adopt a highly unfavorable scenario by ignoring certain factors that significantly limit the rise in the groundwater level, such as the increase in permeability and porosity often observed in the rocky geological layers near the surface, the impermeability of surfaces that limits infiltration, the presence of groundwater drainage features or the artesian flow* of the water table, which constitute outlets for the groundwater.

3.7.3 Influencing factors to be monitored

The influencing factors to be monitored are the hydrogeology of the site and the upstream and downstream conditions.

3.8. Large watershed flooding

3.8.1 Processing the flow rate data

The reference flow rate is quantified from a statistical analysis of the flood flow rates measured at the hydrological station that is representative of the conditions of the site.

The « renouvellement » method is an acceptable method of performing the statistical extrapolation. The representativeness of the main monitoring point for the site can be justified by comparing the size of the watersheds at the station and the site: if the difference is more than a few per cent, it is advisable to correct the data series, by using Myer's formula* for example.

The quality of the flow rate data, which can vary from one monitoring station to the next, is reviewed before the data are analysed. This review requires the collection of information such as the sampling time step, the organisation in charge of the station management, the calibration curves, any changes in the point of measurement, the measuring technique used, and the hydrological regime. It can be based on either the method of cumulative residuals* between stations situated close to one another, or on a check of the consistency of the measured flood volumes with the values obtained in other stations.

If there is a lack of good quality data for the point concerned, it is acceptable to take data from other stations to reconstitute a sample of data representative of the point concerned, but justification shall be provided. Attention shall be paid to, inter alia, the quality of the mathematical law used to reconstitute the sample of data.

When the hydrological regime is significantly modified by hydraulic structures such as water-retaining structures, it may be necessary to correct the impacted measured flow rates:

- ☐ If the difference in area between the watershed upstream of the hydraulic structure and the watershed upstream of the site is 10% or less, and if the reservoirs likely to store large volumes of water are situated in the upper part of the watershed, no correction is necessary;
- ☐ if this is not the case, the question of how to distribute the volumes stocked or released during the floods shall be addressed; this comes down to considering the propagation times of these volumes had they not been retained or released.

If the flow rate sample is significantly heterogeneous, it can be divided into sub-samples, subject to justifications. More specifically, the methods used to characterise the confidence interval shall be presented.

3.8.2 Extrapolation of the flow rates to the extreme flow rates

The choice of the extrapolation law adopted by fitting it to the flow rate sample shall be justified, notably by presenting a visual check and a test on the goodness of fit of the chosen law against the empirical distribution.

One method of obtaining the reference instantaneous peak flow rate consists in extrapolating it from a sample of daily flow rates, then multiplying the flow rate resulting from the extrapolation by a shape factor. This shape factor is the average of the ratios of the peak instantaneous flood flow rate to the mean daily flow rate associated with this peak flow rate for a selection of floods measured with a sufficiently small time step. This selection of floods contains the heaviest floods observed and the floods whose hydrograph shape can be transposed to floods with high return periods.

The consistency of the reference flow rate evaluated in this way is examined in the light of other studies concerning the site sector (previous studies or studies carried out by other organizations), justifying any discrepancies.

3.8.3 Reference water level

3.8.3.1. General

The reference water level can be easily used to characterise a site. It is deduced from the study of the flood plain around the site corresponding to a flood whose maximum flow rate equals the chosen flow rate (the reference flow rate or a lower flow rate if it leads to a higher level).

The reference water level is calculated:

- ❑ in steady flow rate conditions, unless it is proved appropriate to perform the calculation in transient flow rate conditions,
- ❑ by adopting a unfavorable value for the identified influencing parameter(s).

An influencing parameter is a parameter whose variations have a significant impact on the calculation results. It is acceptable to conduct the RFS study by successively increasing each influencing parameter for which there is some uncertainty, insofar as this approach covers the uncertainties for a whole set of parameters. This approach limits the number of sensitivity studies relative to the parameters covered (see 3.2).

3.8.3.2. Modelling the flood plain

The flood plain is preferably defined on the basis of a numerical model* of the site.

The main data required to develop this model are:

- ❑ topographical information – particular attention shall be paid to the main hydraulic elements (structures, dykes, etc.) - and recent bathymetric information,
- ❑ hydraulic information (flood marks*, monitoring station recordings, possibly dynamic, land use, etc.),
- ❑ the geometrical characteristics of the structures (bridges, dykes, plants, dams, etc.),
- ❑ the hydraulic laws of the structures through which the flows pass, in order to model them.

The model shall cover an area that extends laterally to include the entire extent of the extreme flood plain, unless the unfavorable nature of the limits chosen for the hazard assessment can be proved. The longitudinal extension of the model shall be sufficient for the uncertainties associated to the upstream and downstream limit conditions to have a negligible impact on the water levels at the site.

The model grid shall be refined in the zones of hydraulic interest (dykes, structures, particular features such as bridges, sills, dams, plants, weirs, etc.). The particular features can be integrated in the model geometrically or as hydraulic laws, substantiated and adapted to the range of extreme flow rates.

The model is calibrated on the basis of the available data relative to severe floods, paying particular attention to head losses at particular features (bridges, narrow points, etc.): when the study is based on a previously established height – flow rate relationship, the validity of this calibration law on the date of the study shall be verified. When calibration is impossible due to a shortage of data, particularly concerning the flood plain, the values of the parameter(s) of the model which cannot be adjusted, such as the Strickler coefficient*, can be characterised by appraisal. The model shall be validated in transient flow rate conditions if the calculations are carried out for transient flow rate conditions. The results shall confirm the hypothesis concerning the initial distribution of the modelled flows between the different parts of the river bed (river bed and flood plain).

When the RFS study uses a one-dimension numerical model, it shall, where necessary, define compartments* that are physically consistent with the terrain. The hydraulic connections associated with the compartment system shall be sufficiently accurate to represent the phenomena of overflow (overtopping)* and bypassing of dykes, and adapted to the simulated range of flow rates. The levels calculated in the outside bends of meanders shall be corrected whenever necessary.

When the RFS study uses a two-dimensional model, the roughness coefficient is adjusted by zone on the basis of field observations to reflect the land use, for the zones that cannot be calibrated.

The characterising of the flood plain can depend on the behaviour of dykes that could be eroded during the flood. In this case, the behaviour scenario adopted for these structures (breach or resist) is justified on the basis of its unfavorable nature or by a specific study taking into consideration the water rise times and the water velocities associated with the extreme flow rates. Likewise, the potential for jams resulting from an accumulation of debris or from icing and, where applicable, their impact on the water levels at the site, are analysed.

The consistency of the reference levels evaluated in this way is examined in the light of other studies concerning the site sector (previous studies or studies carried out by other organizations), justifying any discrepancies.

3.8.4 Particular case of confluences

When a confluence has to be taken into account to evaluate the flood plain in the vicinity of the site, the used flow rates are characterised for each of the three branches (two upstream and one downstream). For the downstream branch, the downstream flow rate Q is the reference flow rate, such as it is defined in section 2.3.4.1. The flow rate adopted for the upstream branches is the distribution of the worst-case flow rates, without exceeding the reference flow rate in each branch, and ensuring that the sum of the two flow rates equals the downstream flow rate Q.

The calculation of the water levels in the vicinity of the site is preferably based on two-dimensional modelling when the extreme flood leads to a significant overflow in the confluence zone. In some cases, the difference between the flow rate distribution scenarios is such that the most unfavorable scenario can in principle be characterised; if not, various configurations are studied and the one leading to the highest water levels in the vicinity of the site is adopted.

3.8.5 Influencing factors to be monitored

The influencing factors to be monitored are:

- ☐ the morphology and the land use in the river bed of the watercourse,
- ☐ the structures such as bridges and dykes (state of repair, modification of a structure or creation of a new one),
- ☐ the flood control management rules.

3.9. Failure of a water-retaining structure

3.9.1 General

The choice of the structure representing the highest potential hazard shall be justified by an expert opinion, enlightened wherever necessary by flood wave propagation calculations for several structures.

The method of assessing the RFS can be based on a two-step calculation: firstly, calculation of flood wave propagation from the dam to immediately upstream of the site, and secondly, calculation of the water levels around the site by means of a local model.

The aim of studying the flood wave is to determine the flow characteristics in the area surrounding the site as a function of time (time for the wave to arrive, speed and flow rate, duration of the flood) and to quantify the RFS (flood plain and reference level).

The flood plain and the reference level are preferably characterised by numerical modelling of the area around the site.

3.9.2 Hypotheses associated with the failure

Failure of the structure inducing a flood wave is postulated; it is considered that the failure leads to complete emptying of the reservoir.

The reservoir is assumed to be filled to the maximum level at the time of failure, which corresponds to the design-basis flood for the structure, called the "highest water level" (HWL), or the normal operating level (also known as the full supply level) in the case of reservoirs for which the regulations applicable to water-retaining structures do not define a HWL. The function of the water-retaining structure whose failure is envisaged can oblige taking a higher initial water level in this reservoir. The failure of a flood retention structure shall thus be examined postulating that the water is at the overtopping level of this structure.

For concrete or masonry structures, the failure is considered to occur as an instantaneous and total destruction.

For rock or earth-fill structures, failure is gradual (piping*, or overtopping if applicable). In the event of failure by piping, the RFS study shall indicate the initial moment used as the reference for the flood wave; this is the moment when the initiating leak is detectable; it is acceptable to take it as being the moment the flow rate reaches about 1 $m^3.s^{-1}$,

3.9.3 Propagation of the flood wave

The flood wave propagation study distinguishes two zones:

- ❑ the "upstream" zone in which the level reached by the wave propagated on a dry bottom exceeds that of the worst known flood, or the one-hundred-year return period flood if the latter is higher;
- ❑ the "downstream" zone, which ends when the level reached by the wave is lower that of the ten-year return period flood.

In the "upstream" zone the flood wave is propagated on a dry bed; in the "downstream" zone it is propagated on the mean interannual flow rate* of the watercourse. The function of the retaining structure (e.g. a flood retention structure) can make it necessary to use a different initial flow rate.

For the entire path of the wave, the following hypotheses are adopted:

- ❑ the water-retaining structures crossed by the wave are assumed to be filled to the HWL, or the normal operating level in the case of structures for which the regulations do not define an HWL; they fail when the peak of the wave hits the structure, unless it can be demonstrated that they resist and behave as a weir. It shall nevertheless be verified that the resistance, even if partial, of a structure downstream of the site is not likely to create an additional rise in the water level upstream of the structure. In certain duly justified cases, the possibility of preventively lowering certain downstream retention structures can be adopted; this requires the lowering times, in all circumstances, to be much shorter than time it takes for the wave to reach the structures.
- ❑ the numerical simulation is adapted to the nature of the simulated flow (wave front propagation, torrential flow, etc.). The propagation model is appropriate for the flow rates reached.

3.9.4 Reference level

The flood plain is calculated at the site from the flood wave hydrograph, obtained after propagation up to the numerical model input point used to represent the site and the surrounding area (local model) and increased by 15%. The initial flow rate in the local model is the mean interannual flow rate of the watercourse. The function of the retaining structure (e.g. a flood retention structure) can however make it necessary to use a higher initial flow rate.

The analyses of the modelling of the flood plain around the site are carried out in accordance with the recommendations of section 3.8.3.2, taking into account the following specific recommendations:

- the reference level and the levels associated with the flood wave are defined by adopting a unfavorable value for the identified influencing parameter(s). This unfavorable value aims at covering the calculation uncertainties. An influencing parameter is a parameter whose variations have a significant impact on the calculation results. It is acceptable to conduct the RFS study by successively adopting a more unfavorable value for each influencing parameter for which there is some uncertainty, insofar as this approach covers the uncertainties for a set of parameters. This approach limits the number of sensitivity analysis relative to the parameters covered (see 3.2) ;
- The times for the wave to reach the points of interest and the times taken to reach the maximum levels are reduced by 13%.

3.9.5 Particular case of confluences

When evaluating flood wave propagation, it is acceptable to consider, for each branch of the confluence, the flow rate conditions defined in section 3.9.3 according to the location of each branch in the upstream or downstream zone.

It may be necessary to consider the impact of the rise of the wave in each affluent of a confluence when characterising the flood plain for the site: the calculation of the water levels in the vicinity of the site in this case will preferably be based on two-dimensional modelling when the RFS leads to significant overflow in the confluence zone.

3.9.6 Influencing factors to be monitored

The influencing factors to be monitored are:

- the influencing factors to be monitored mentioned in section 3.8.5,
- the establishment of a new retaining structure,
- the conditions of operation of a water-retaining structure upstream of the site if the modifications can lead to more serious consequences than those of the break failure postulated in the RFS study.

3.10. Local wind waves

3.10.1 Characteristics of the reference wind

The wind speed used to characterise the RFS is an average wind speed over 10 minutes measured at a height of 10 metres. It is calculated from a statistical study of the extreme wind events irrespective of their direction, and is not associated with a prevailing direction. Unfavorable values are used for the local parameters that can influence the wind flow at the site (site topography, surface roughness).

3.10.2 Generation and propagation of the local wind waves

The zones in which local wind waves can develop are determined from the geometry of the body of water around the site, taking all the zones displaying a sufficient length (fetch*) for significant local wind waves to be generated. It is assumed that the mean wind speed* over a hundred-year return period generates local wind waves on each fetch.

If calculating the local wind waves using an empirical method, at least two recognised formulae shall be used, checking that they are applied in their ranges of validity and that their results are mutually consistent. If this is not the case, the most unfavourable result is used.

The local wind waves are considered to be established for the duration of the RFS.

The action of the sea current on propagation of local wind waves is examined. If the current could increase or decrease the local wind waves, its effects are taken into account.

If the steepness of the waves is such that the conditions of wave breaking are reached or exceeded, the reference local wind waves is defined by the local wind waves whose characteristics are at the limit of breaking.

3.10.3 Overtopping

When the RFS causes the overtopping of protective structures, the overtopping water volumes shall be estimated. The overtopping volumes are estimated for each fetch, taking wind direction into account. The choice of formulae or methods used for the overtopping calculation shall be justified (scope of validity, unfavorable nature of the result, etc.).

The method used to take account of the effect of wind on the overtopping flow rates shall also be justified (for example, application of a multiplication factor to an overtopping flow rate when the latter is estimated by an empirical formula that does not take the effect of the wind into account).

3.10.4 Influencing factors to be monitored

The influencing factor to be monitored is the creation or modification of structure(s) that could significantly modify the fetches defining the RFS.

3.11. Sea level

The reference sea level is defined with respect to the chart datum and in the legal altimetric system of the site.

3.11.1 Theoretical tide

If the theoretical tide level is not evaluated from results obtained in a monitoring station at the site, it is permissible to use the theoretical tide value calculated for a regional monitoring station: a correction factor may then have to be applied to allow for the difference in the maximum theoretical tide between the studied site and the regional monitoring station.

3.11.2 Storm surge

The extreme storm surges are characterised from data on the sea high water storm surges, using a statistical study on the local or regional scale.

The series of observations used for this study are selected taking into account the duration (the longest possible), the reliability of the values (particularly for the highest storm surges) and the representativeness for the site. The possible existence of a bias linked to the change of the sea level in the series of storm surges is examined. The decision to either apply a correction factor or not when developing the sample of observed storm surges shall be explained.

The values of historical storm surge events are recorded and taken into consideration in the statistical study.

The calculation of thousand-year return period storm surges on a local scale using the conventional extrapolation laws is at present unable to take satisfactory account of exceptional events (outliers) observed at several monitoring stations. An additional increase in reference sea level of 1 m is applied to allow for this.

Another approach - based on a regional analysis for example - can be used to calculate the thousand-year return period storm surge, subject to demonstration of the suitability of the statistical extrapolation model used and its relevance for the outliers observed by various monitoring stations. In this case there is no need to apply an additional margin.

3.11.3 Influencing factors to be monitored

The influencing factor to be monitored is the conducting of major port development works near the site.

3.12. Ocean waves

3.12.1 Ocean wave characteristics

The reference ocean waves "off shore" are defined for a distance sufficiently far from the coast to be completely unaffected by the physical phenomena that occur in shallow water when waves are propagated near the coasts, and wave breaking in particular.

3.12.2 Propagation

The propagation of waves from the open sea up to the site is characterised by modelling, including wherever necessary the entry of the waves into port docks or water intake or discharge channels, and the interactions of the waves with coastal structures. Wave propagation is simulated for stationary conditions and considering constant unfavourable boundary conditions.

The appropriateness of the propagation models used is justified either by a numerical model simulating the dominant physical phenomena involved in wave propagation in coastal zones, and in the presence of coastal or port structures, or by a physical model.

One or more unfavorable off-shore wave directions shall be adopted to determine the potential for overtopping the various site protection elements (external sea walls, internal structures in channels, etc.). The search for these unfavorable directions can be limited to a few angular sectors on condition that the relevance of the chosen sectors is justified.

If the steepness of the waves is such that the conditions of wave breaking are reached or exceeded, the reference ocean waves shall be defined by the waves whose characteristics are at the limit of breaking.

3.12.3 Overtopping

When the RFS causes the overtopping of protective structures, the overtopping water volumes shall be estimated. The choice of formulae or methods used to calculate the flow rates of structure overtopping by the waves shall be justified (scope of validity, unfavorable nature of the result, etc.).

The method used to take account of the effect of wind on the overtopping flow rates shall also be justified (for example, application of a multiplication factor to an overtopping flow rate when the latter is estimated by an empirical formula that does not take the effect of the wind into account).

3.12.4 Influencing factors to be monitored

The influencing factors to be monitored are:

- ☐ major port works being carried out near the site,
- ☐ undermining of dyke foundations by the action of the water, particularly in the early life of the structure.

3.13. Seiches

3.13.1 General

The annual seiche height is characterised by an empirical or statistical estimate, depending on the available data. It is based on experience feedback or measurements made over a period of at least one year.

The measurements taken at sea serve to determine whether low-frequency oscillation phenomena are likely to cause coastal seiches. If necessary, these oscillations shall be quantified, notably in terms of frequencies concentrating the most energy, and their propagation in the hydraulic facilities shall be studied.

3.13.2 Influencing factors to be monitored

The influencing factors to be monitored are:

- ❑ major port works being carried out near the site,
- ❑ the creation or modification of the coastal structures of the site.

3.14. Particularities of estuary sites

The estuary shall be subject to overall hydrodynamic numerical modelling to estimate the high levels.

The effects of water overflow and spreading in the areas adjacent to the estuary are determined if they have a significant influence on the flood plains around the site. The flood plain in this case is characterised following the recommendations of section 3.8.3.2.

The meteorological effects on the whole area, and the effects linked to the propagation of the storm surge in the estuary, are taken into account in the simulation, considering a hundred-year return period wind scenario (upper bound of the 70% confidence interval) defined following the recommendations given in section 3.10.1. This scenario is maintained for a period that takes account of the tidal dynamics and taking into account a wind direction whose unfavorable nature is confirmed.

The river flow rate is represented in steady flow rate or transient flow rate conditions. In this latter case, the hydrograph shall be such that the maximum river flow rate is reached at the moment when the influence of the high tide at the site is maximal.

4. PROTECTION AGAINST FLOODING

Two types of recommendations are given below:

- ❑ some concern the licensee's organisation and the operating provisions that would warrant being implemented to anticipate and manage the hazards associated with external flooding;
- ❑ some concern the design of the installation. These recommendations have been developed from the perspective of a new installation design. For an existing installation whose design does not integrate these recommendations, it shall be determined whether, after making certain improvements if necessary, it is possible to obtain an adequate level of protection of the interests mentioned in article L.593-1 of the Environment Code.

4.1. Specific aspects of a flood

Flood can concern several or even all the installations on a site. It can also affect several lines of defence simultaneously.

Flood can also affect the site's environment: depending on the extent and duration of the phenomena that cause it, flood can lead to the isolation of the site and loss of support functions (off-site electrical power supplies, telecommunications, off-site emergency resources, discharge facilities, etc.).

The action of the water can be static or dynamic, or a combination of the two. The dynamic effects can for example be the erosion of embankments, watercourse banks or dykes, a change in water turbidity, effects of debris jams or floating bodies. This can affect the availability of certain equipment items.

Flood can moreover be accompanied by other phenomena (lightning, wind, etc.).

Nevertheless, depending on the causal phenomena, flood can sometimes be predicted by implementing warning systems, and the site configuration can also be adapted in a preventive manner.

4.2. Protection principles

For each RFS considered, means of protection are to be put in place to preserve the safety functions that could be affected.

The material and organisational provisions for protecting:

- ❑ the sites,
- ❑ the buildings containing important protection elements[8] associated with nuclear safety in the situation in question,
- ❑ the rooms containing the important protection elements within these buildings,
- ❑ the systems or components themselves within these rooms,

provide several lines of defence.

The independence of these lines of defence is sought wherever necessary.

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[8] As defined in article 1.3 of the order of 7 February 2012, that is to say all the "elements important for the protection of the interests mentioned in article L. 593-1 of the environment code (public security, health and safety, protection of nature and the environment), that is to say structure, equipment, system (programmed or not), hardware, component or software present in a basic nuclear installation or placed under the responsibility of the licensee, fulfilling a function necessary for the demonstration mentioned in the second paragraph of article L. 593-7 of the environment code, or checking that this function is ensured"

The specific aspects of floods, particularly those mentioned in section 4.1, are taken into account when defining and designing these provisions. The level of protection is appropriate for the risks presented by the installation. Depending on the phenomena causing the flood and the nature of the means of protection, an event of greater intensity that the RFS may lead to a cliff-edge effect. A **cliff-edge effect** occurs when, starting from the RFS, a slight aggravation of the flood situation (for example, a water level that overtops a dyke) leads to a significant deterioration in the safety functions. Each RFS shall be examined to detect and analyse any possible cliff-edge effects.

With regard to the safety functions which shall be preserved in the event of flooding, the installation sizing is made on the basis of the defined RFSs. Furthermore, the design and sizing of the protection elements take into account:

- ❑ objectives for protection of the interests mentioned in article L. L.593-1 of the environment code with regard to the nuclear safety of the installation,
- ❑ results of the cliff-edge effects analysis,
- ❑ predictable climate changes over the conceivable life time of the installation considered[9].

The implemented protection approach takes account of the possibilities of hazards or effects (fire, mechanical shocks, etc.) induced by the situation considered.

4.3. Material protection measures

4.3.1 General

The structures contributing to the protection are designed, operated and maintained to obtain the performance indicated in the nuclear safety demonstration.

The general layout of the site and the installation takes the flooding hazard .

The installation is preferably designed and operated such that the chosen RFSs do not lead to the ingress of water into the rooms containing important protection elements associated with nuclear safety. Moreover, any deterioration - on account of the RFSs - in the quality of the water used by the facility shall not call into question the preservation of the installation's safety functions. In the particular case of equipment installed in the open air (storage areas, etc.), these equipment are designed and installed such that they can fulfil the safety functions in the case where water is present on the ground.

The site layout allows performance of the necessary actions to maintain the nuclear safety of the facilities and manage the situation in the case of flooding (access to the facilities, movement on the site, etc.).

Measures that require neither human intervention nor energy supplies should be preferred. The choice and dimensioning of measures requiring human intervention or energy inputs take into account the possibilities of anticipating the feared events and their kinetics.

The material measures necessary to control the RFS consequences are subject to predetermined requirements, within the meaning of article 1.3 of the abovementioned order of 7 February 2012, adapted in order to guarantee their reliability and effectiveness under the conditions in which they could be implemented. The same goes for the material measures whose functioning or performance is taken into consideration in the characterising of the RFSs.

Changes in the installation environment, and notably climatic change, may require the licensee to reassess the characteristics of the potential flood situations throughout the life of the installation. For this reason, it is advisable to favour material measures that lend themselves to future adaptation.

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[9] At the time of writing this guide, this latter point concerns the RFS's that depend on the sea level.

4.3.2 Site characteristics monitoring

In the installation safety reports mentioned in articles 8, 20, 37 and 43 of the abovementioned decree of 2 November 2007, the licensee presents its strategy for acquiring qualitative and quantitative data enabling it to determine the major characteristics of the site concerning the flooding hazard.

The acquisition of data continues during operation of the installation in order to consolidate the characteristics of the various situations (data, modelling) and observe the changes that can result, for example, from modifications in the site environment or climatic changes, particularly for the "influencing factors to be monitored" mentioned in chapter 3.

When an event that could cause a flood occurs during the life of the installation, the licensee shall take all the necessary measures to collect and analyse the information concerning the said event that is relevant for the site (hydrograph, flooded zones, observed levels, debris jams, etc.). This information is used to enhance knowledge of the site and improve future studies, by helping to improve the calibration of a model, for example.

4.3.3 Passive material measures

4.3.3.1. Site protection structures

Protection of the site against flooding can be based on protective structures external to the site (dykes, drainage systems, dams whose operation can be modified in the event of a flood, etc.). In this case, the licensee examines the behaviour of these structures when filing the BNI creation authorisation application, and during the periodic safety reviews.

The licensee justifies this behaviour and its preservation, including when the licensee is not the operator of these structures. This justification is based on the regulatory requirements to be met by these structures, or, if necessary, on agreements made with their operators.

With regard to the on-site protection provisions, the licensee shall be particularly attentive to the bypass possibilities (passageways in dykes, etc.).

4.3.3.2. Platform and stormwater drainage systems

Setting the installation platform at a level above the maximum water level evaluated for the area covered by the installation, considering all the relevant RFSs, is a robust measure that shall be favoured.

The layout of the site, and of the platform in particular (slopes, retention systems, stormwater drainage systems, road development, etc.), can prevent water from flowing towards the rooms to be protected.

Gravity drainage systems shall be favoured to allow for the possibility of loss of off-site electrical power supplies. The licensee deals with the particular points of the system that present a potential for debris jams, through appropriate maintenance measures or by planning contingency actions.

The stormwater drainage system is designed on the basis of reference rainfall events. The above-ground retention areas that can be used to reduce the flows to discharge shall be clearly defined and justified.

The stormwater ponds are not necessarily sized on this basis insofar as their behaviour in case of reference rainfall events does not call into question the preservation of the safety functions.

4.3.3.3. Hydraulic structures

Whenever possible, tanks, ponds and external pipes are designed and located so as to mitigate the consequences of their accidental rupture or overflow.

The ponds and channels are designed so as to limit any dynamic oscillations and avoid a specific amplification of the hydraulic waves in the corresponding frequency range (seiche, mechanical induced wave, etc.).

Tunnels that could contribute to the flood hazard are identified: they are designed so as to limit the possibilities of transferring water towards equipment or rooms that require protecting.

When tunnels house important protection elements associated with nuclear safety, they are designed such that the important protection elements cannot be reached by the water or, failing this, that they can continue to fulfil their role in the presence of water in accordance with II of article 2.5.1 of the abovementioned order of 7 February 2012.

4.3.3.4. Raising thresholds

To limit the ingress of water into rooms housing important protection elements associated with nuclear safety, it is a good practice to place thresholds at building access points. The flooding hazards linked to the impact of prevailing winds on water run-off are examined. The anticipated settlements are taken into account and checked periodically in situ.

4.3.3.5. Drainage of rainfalls from roofs

The overall layout of the devices for draining rainfalls runoff from roofs takes into account the potential for water ingress into buildings in the event of system overflow, particularly through the location of the water downpipes and overflows.

The water drainage devices are preferably situated outside the buildings. They are designed to limit the potential for blockage. Open-air drainages shall be favoured wherever possible.

The potential for water accumulating on the roofs shall be examined; rapid drainage of the collected water shall be favoured. The capacity of the roofs to cope with reference rainfall events lasting 6 minutes shall be verified. In the case of insufficient water drainage, the build-up of water on roofs for a unfavorable rainfall duration shall be examined.

4.3.3.6. Watertight volume

Particular attention is paid, both at the design stage and during operation, to all openings (passageways, pipes, spaces between buildings, etc.) that could allow water to enter buildings.

The watertight volume extends from the lowest level of the infrastructures to a high level defined according to the site RFSs and the installation's safety objectives.

In addition, water entry channels situated below the platform setting level are closed off as required so that in a flood situation the water cannot reach the rooms housing important protection elements associated with nuclear safety. The design of the sealing material shall take into account the hydraulic pressure associated with the potential presence of water outside the watertight volume*. Passive measures shall be favoured, so that there is no need for human intervention to close these water entry pathways (closing of valves, etc.) in the event of flooding of the site.

4.3.4 Other provisions

4.3.4.1. Warning systems

When the protection of the installations with respect to a RFS is based on provisions that require human intervention - whether this takes place in advance of the actual flood or not – the licensee shall provide a suitable warning system.

The warning system implemented by the licensee shall provide sufficient advance warning to allow all the necessary protection measure to be implemented, including if this system relies on off-site resources.

Justification can be based on the regulatory requirements that the competent monitoring organisations shall satisfy and, if applicable, on the agreements made with these organisations.

The monitoring means associated with the warning system can also be used for situation tracking.

4.3.4.2. Monitoring the installations

On account of the detection of deviations and the watch provided for in articles 2.6.1 and 3.10 respectively of the abovementioned order of 7 February 2012, the licensee shall provide means for monitoring the installations and rooms that can detect any abnormal presence of water and monitor the development of a flood situation.

4.3.4.3. Support functions

The risks associated with the loss of a support function due to flooding (immersion of equipment, risks associated with water turbidity, debris jams) or correlated phenomena (risks associated with lightning and wind) shall be studied at the design phase. This examination takes account of the conceivable duration of loss of a support function and the reliability of the equipment involved in maintaining the safety functions in this situation.

This can lead to specific provisions concerning, for example, the protection of electricity substations near the site.

4.3.4.4. Mobile resources

If the maintaining of the safety functions during an RFS requires the use of mobile resources (electric power generators, pumping equipment, etc.), the licensee shall justify that they can be deployed sufficiently rapidly for the considered RFS. The layout and organisation of the site shall enable these mobile resources to be routed to the required location and deployed in the considered RFS.

4.3.4.5. Common resources

If the preservation of the safety functions during an RFS requires the use of resources common to several installations, the licensee shall justify that these resource are capable of fulfilling the safety functions in the considered RFS.

4.3.4.6. Groundwater level

If it is necessary to lower the groundwater level for a given site, the licensee shall favour gravity drainage rather than pumping.

4.4. Organisational protection measures

Pursuant to section II of article 2.5.1 of the abovementioned order of 7 February 2012, the licensee shall define and implement a monitoring and maintenance policy for all the passive and active material protection measures, and shall prove, in view of this policy, that the operability of the protection measures is preserved. This particularly concerns the rainfall drainage systems, where deposits can build up very quickly.

When the protection measures are actions, these actions are formalised in procedures. The licensee shall implement organisational measures (provisioning of means, periodic verification of their availability, alert procedures, training, etc.) to ensure correct performance of these actions in the planned times. The licensee shall formalise these organisational measures in the general operating rules (RGE) or the on-site emergency plan (PUI).

With regard to the implementation of the alert and situation monitoring system, the licensee shall define the monitored quantities and the associated benchmark values.

The licensee shall take organisational measures to mitigate the consequences of the situation: installation monitoring, emergency organisation, etc.

The licensee shall analyse the potential for site isolation, and if necessary take organisational measures to implement the abovementioned procedures, guarantee the presence of the required personnel and material resources, and the permanence of the communication means necessary for management of the emergency. The licensee shall verify that the conditions of vehicle and personnel movement on the site in the situation in question allow these procedures to be implemented.

4.5. Assessment of the consequences

The licensee shall justify the soundness and the effectiveness of its chosen protection measures with regard to nuclear safety, notably on account of article 3.7 of the abovementioned order of 7 February 2012, on the basis of an assessment of the consequences of the envisaged situations.

In this context, the licensee shall take into consideration the following phenomena:

- possible leaching of areas, rooms or equipment contaminated by radioactive or chemical substances,
- possible appearance of new transfer routes for radioactive or chemical substances due to flooding.

For the assessment of non-radiological risks, the scenarios considered (chosen substances and hypotheses) are appropriate for the potential consequences.

GLOSSARY

The definitions of the terms in this glossary are based on the contributions drawn up by the working group in charge of the tentative "flooding" guide, the report of the Institute of Radiation Protection and Nuclear Safety referenced IRSN/DSR No.149 concerning the Blayais NPP experience feedback method drawn up by EDF, and on the basis of French dictionaries and reference works (French Dictionary of Hydrology, Encyclopaedia of Urban Hydrology and Drainage, etc.).

Artesian flow
Artesian flow is the upward motion of water in wells or bores tapping a captive groundwater table whose piezometric level is above the ground level.

Aquifer
An aquifer is a body (layer, massif) of water-permeable rocks, with a substratum and sometimes covered by less permeable rock, featuring a saturated zone with sufficient hydraulic conductivity to allow significant flow from a groundwater table and the catchment of appreciable quantities of water. It is the whole made up by the solid environment (container) and the water it contains. An aquifer can, depending on its filling level, include an unsaturated zone.

Calibration
The calibration of a numerical hydraulic model (see below) consists in assigning values to the adjustment parameters, chiefly the friction forces of the terrain (Strickler coefficient), that enable the natural observed flows to be best reproduced for a set of hydrological events representative of the various hydraulic regimes of the studied watercourse. It should be noted that the calibration step enables the model to be adjusted for floods of the order of size of the observed floods, therefore significantly lower than the floods envisaged in this guide.

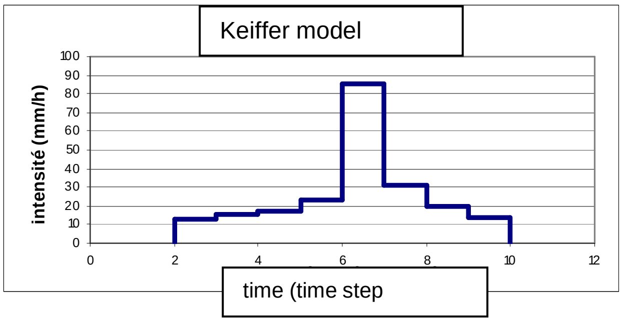
"Centred" and "non-centred" rainfall data
The daily rainfall data which correspond to totals recorded at fixed times are called "non-centred" data. Another possibility, which can only be envisaged with small recording time steps, consists in sliding the origin of the time step until the highest total is found. In this case the term "centred" data is used, which sometimes gives rise to misinterpretations, as the instantaneous peak of the phenomenon does not necessarily coincide with the middle of the time step. ~~One can also talk of "sliding time step data"~~. For rainfall events lasting 24 hours, it is checked experimentally that the maximum centred rainfall events are on average 1.14 times stronger than the non-centred events. The average coefficient of 1.14 is called the Weiss coefficient.

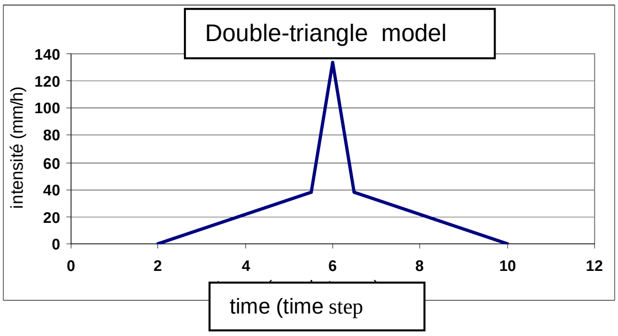
Compartment
To simulate the flow of a watercourse in flood from a one-dimensional (1D) numerical hydraulic model (see below), it may be necessary to supplement the model with compartments in order to represent the flooding of floodable zones beyond the river bed. The compartments are connected to the river bed and to one another by hydraulic connections that represent weirs, siphons, overflows or breaches in the dykes. The flow velocities in the compartments are assumed to be zero.

Debris-jam (or ice-jam) and break-up
These phenomena consist in the formation and disappearance at varying speeds of temporary barriers created by the build-up of floating debris or ice. These obstructions, which form at particular localized features (bridges, culverts, grids, etc.), cause a rise in the water level upstream (during jam build-up) or downstream (during jam break-up).

Design rainfall events (Keiffer or double triangle rainfall patterns)

A design rainfall event is a fictitious rainfall event that is statistically "representative" of the observations from which it is drawn. The construction of a design rainfall event consists in proposing a distribution over time ofg summed rainfall events. The design rainfall events are multidimensional objects to which it is not relevant to assign a return period. Many types of design rainfall events can be found in the literature, including "double-triangle" rainfall patterns made up by a relatively short period of intense rainfall situated within a sequence of long rainfall events, and Keiffer type patterns (rainfall events defined such that their mean intensities over different durations have the same return period). The two figures below show two examples of Keiffer and double-triangle design rainfall events.





Favre waves (undular bores)

When a positive wave travels against a current, the wavefront tends to steepen. Beyond a certain steepness, a series of undulations superimposed on the main wave is observed. These undulations are known as "Favre waves", or undular bores, or secondary waves.

Fetch

A fetch is the length of an extent of water (sea, estuary, lake, watercourse, flood, etc.) on which the action of the wind can create waves.

Flood mark

A flood mark is a mark left by a flood on a structure or other substrate indicating the highest level reached.

Mean interannual flow rate (of a watercourse)

The mean interannual flow rate is the arithmetic mean of the mean annual flow rates calculated over a period of at least 30 consecutive years. The mean annual flow rate is the arithmetic mean of all the flow rates for the year considered.

Mean wind

By convention, the mean wind in meteorology is the wind speed averaged over 10 minutes and measured at a height of 10 metres above the surface.

Mechanically induced wave

A mechanically induced wave is a wave travelling along the open surface of water in a channel, induced by a sudden variation in the speed (flow rate) of the flow. This phenomenon is similar to the "hammering" that can occurs in pipes. One talks of a "positive" mechanically induced wave when there is a sudden reduction in speed, and conversely of a "negative" mechanically induced wave when there is a sudden increase in speed. The mechanically induced wave can be observed during the sudden stopping or starting of the generators of a run-of-river hydroelectric power plant, or of the raw water system pumps in an open circuit water intake channel of a nuclear power plant.

Method of cumulative residuals

The method of cumulative residuals consists in establishing the straight line of regression between two series of data, then in calculating the deviations (residuals) between this straight line of regression and the observed values. It enables the quality of the correlation between these series to be checked. The graph showing the cumulative curve of deviations according to the sequence numbers shows a random distribution of the residuals if the series are well correlated. If the series are poorly correlated, the curve displays non-random deviations around the null value.

Montana (Montana formula)

The Montana formula links the average intensity i, the duration t and the exceedance frequency F of a rainfall event of duration t, as a function of two parameters a and b that depend on the exceedance frequency F considered.

$$i(t,F) = a(F) \cdot t^{b(F)}$$

This model shall be used with caution because a particular pair of parameters a and b does not give a satisfactory fit if the range of rainfall event durations is too great.

Myer (Myer's formula)

Myer's formula relates characteristic flow rates (mean flow rates, ten-year return period flow rates, etc.) to watershed surface areas.

Numerical (hydraulic) model

A numerical hydraulic model enables the flows over a given terrain or structure to be simulated thanks to numerical hydraulic codes which resolve the Navier-Stokes equations governing fluid mechanics, or derivatives of these equations. For the open surface flows, the one-dimension codes (1D - flows along one axis) and two-dimension codes (2D - flows in a plane) thus generally resolve the Barré de Saint-Venant equations. It is then possible, for example, to extract the maximum water levels reached from these equations.

Outlier

In statistics, the term outlier designates an observation whose value deviates significantly from the values of the other observations in the same given sample of data.

Overflow (overtopping)

Overflow, or overtopping, as the terms suggest, is the passing of a mass of water over an obstacle. When a watercourse overtops a dyke, it causes external erosion and rapidly leads to a breach in an embankment structure. This failure mechanism is by far the most frequently cited mechanism of failure of levees, for example with the very high floods that have affected the River Loire in France for the last two centuries. In recent years (from 1993 to 2003), the River Rhône has experienced more breaches by channelling than by overflow.

Piping

Piping is the gradual development of a leak through a dam or a dyke by enlargement of a through-channel. Once the channel has formed, its diameter increases at an exponential rate, and very often results in the collapse of its roof in less than two hours, causing a breach.

Rational method

The rational method is a simplified approach allowing the calculation of the maximum flow rate at the outlet of a watershed subjected to a given amount of precipitation. It assumes firstly the consistent and uniform distribution of the rainfall over the watershed, and secondly the spatial homogeneity of the receiving surfaces, allowing a runoff coefficient to be defined for the watershed.

Among the various formulae that exist, the formula linked to the concept of the site time of concentration is written: $Qp = C \cdot i(Tc) \cdot A$

where Qp, maximum flow rate at the watershed outlet (m^3/s),
C, runoff coefficient (s.u.),
$i(Tc)$, mean intensity of the rainfall event of duration Tc (m/s),
Tc, time of concentration of the watershed,
A, surface area of the watershed (m^2).

Other empirical formulae, such as Caquot's formula, allow the calculation of the maximum flow rate at the outlet of a watershed according to the gradient and surface area of the watershed, the runoff coefficient and functions of the Montana coefficients *a* and *b*.

Reach
A reach is a section of an open channel between two transverse sections.

Regionalised approach
The regionalised approach is based on the use of data from different sites belonging to the same given "hydrological region" (set of sites displaying a certain degree of hydro-meteorological uniformity). This approach provides more abundant information than would be available from the observations of a single monitoring station.

« Renouvellement » method
The “ renouvellement ” method is a statistical method of extrapolating to extreme values. It is based on the use of a sample of observations exceeding a threshold, and the combining of two laws to adjust the observations: adjustment of the annual number of exceedances and adjustment of the observations exceeding the threshold. This method is useful in particular when processing short series in which the samples are enhanced by selecting values exceeding a threshold.

RFS
A "Reference Flood Situation" (RFS) is defined on the basis of an event or a combination of events whose characteristics may be amplified (unfavorable combination or margin to compensate for the limits of current knowledge).

Seiche
A seiche is a stationary wave that can occur in a closed or semi-closed area of water such as a harbour, pond, lake or bay. In a semi-closed maritime dock, seiches are caused by the penetration of long waves coming from the open sea. Seiches usually have a period of between two minutes and a few tens of minutes. If the period of the seiche coincides with the resonance period of the dock, it can be amplified by resonance within the dock. This motion can continue for few minutes, a few hours, or even several days, even when the initiating phenomenon has disappeared.

Significant period (*Ts*)
In a field of waves, the wave heights and periods are variable. The significant period is the average of the wave periods whose heights lie in the upper third of the population of wave heights (sometimes simply written as $T_{1/3}$).

Significant wave height (*Hs*)
In a field of waves, the wave heights (between the peaks and troughs) vary. The significant height is the average of the wave heights whose heights lie in the upper third of the population of wave heights. *

Stationarity
Stationarity is a hypothesis that consists in considering that the properties of the statistical law governing the studied phenomenon do not vary over time. This hypothesis excludes any long-period cyclic variation and any systematic change in the phenomenon over time. The hypothesis of stationarity can be validated, for example, by testing the uniform distribution of occurrence of the events over time.

Storm surge and setdown
The instantaneous storm surge or its opposite, setdown, is defined as the positive or negative difference at a moment *t*, between the sea level effectively observed and the predicted tidal level (theoretical tide). The storm surges and setdowns are essentially induced by the weather conditions (variations in atmospheric pressure accompanying the passage of a meteorological disturbance (depression or anticyclone) and the action of the wind on the surface of the sea creating a drag force).

Strickler coefficient

The Strickler coefficient is a coefficient of friction expressed in $m^{1/3}/s$, which characterises the roughness of a terrain or a hydraulic structure. It expresses the varying degree of the resistance to the passage of the water and is a key parameter in the flow velocity calculation. It is usually used in the numerical models for estimating water levels. It is generally used as a model calibration parameter in the areas where a flood has been observed and quantified.

Theoretical tide

The theoretical tide corresponds to the predictable part of the variations in sea level. Its main component is the astronomical tide, due to the gravitational action of the Moon and the Sun, but it also includes the radiational tide which is the predictable part of the sea level variations of atmospheric origin. The radiational tide is associated with the thermal action of solar radiation on the atmosphere and the ocean. It is low compared with the astronomical tide, but not negligible. By way of example, the amplitude of the radiational tide at Calais is 8.5 cm.

The theoretical tide wave at a given point can be broken down into a sum of waves. Knowing the characteristic harmonic constants of these waves makes it possible to predict the height of the theoretical tide brought down to the mean level at any given moment at the point in question.

Tidal bore

A tidal bore is a set of waves that can appear at the mouth of a river where it flows into the sea under particular conditions: low tide with high tidal coefficient, river with a very high flow rate and very low water level. The rising tide, slowed by the flow of the river, forms a series of positive waves that travel up the estuary at a speed that can vary from a few kilometres per hour to tens of kilometres per hour.

Watershed

A watershed is a delimited region, drained by a watercourse and its tributaries, for which it constitutes the water supply area. Any watershed is defined geometrically, in reference to a given point on a watercourse (its mouth or any other point), by a contour and a surface area.

Watertight volume approach

A protected volume is a volume rendered watertight by closing off the openings in the outer walls of this volume to prevent the entry of water into rooms housing important protection elements associated with nuclear safety.

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