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Meteorological, Hydrological and Other Natural Hazards in Site Evaluation for Nuclear Installations

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DRAFT SAFETY GUIDE

Revised Safety Guide No. SSG-18

CONTENTS

1. INTRODUCTION

BACKGROUND

1.1. Requirements for site evaluation for nuclear installations are established in IAEA Safety Standards Series No. SSR-1, Site Evaluation for Nuclear Installations [1]. This Safety Guide provides recommendations on meeting these requirements in relation to the evaluation of meteorological (Requirements 18 and 19), hydrological (Requirement 20), and selected other natural hazards (Requirement 23) as well other general requirements in SSR-1.

1.2. Meteorological hazards are associated with extreme meteorological conditions and with rarely occurring[1] hazardous meteorological events. Hydrological hazards are associated with external flooding events, as well as low water level conditions. Other natural hazards selected for this safety guide (e.g. wildfire, drought, ice impacts, debris[2], biological phenomena) can also potentially affect nuclear installation sites.

1.3. This Safety Guide complements IAEA Safety Standards Series Nos: SSG-9 (Rev. 1), Seismic Hazards in Site Evaluation for Nuclear Installations [2]; SSG-21, Volcanic Hazards in Site Evaluation for Nuclear Installations [3]; SSG-79, Hazards Associated with Human Induced External Events in Site Evaluation for Nuclear Installations [4]; and NS-G-3.6, Geotechnical Aspects of Site Evaluation and Foundations for Nuclear Power Plants [5], which collectively establish recommendations on hazard evaluation. This Safety Guide also provides prerequisites for IAEA Safety Standards Series Nos SSG-35, Site Survey and Site Selection for Nuclear Installations [6] and NS-G-3.2, Dispersion of Radioactive Material in Air and Water and Consideration of Population Distribution in Site Evaluation for Nuclear Power Plants [7].

1.4. Since publication of the previous version of this Safety Guide, significant new knowledge and experience has been gained in relation to evaluation of meteorological and hydrological hazards. The modifications incorporated into this Safety Guide consider the following:

(a) Occurrences of extreme meteorological and hydrological events;
(b) Lessons learned from the 2011 Fukushima Daiichi tsunami and from subsequent hazard re-evaluations;
(c) Recent experience in the application of IAEA safety standards;
(d) Upgrading of existing nuclear installations and experience from recent extreme natural events;
(e) The potential impacts of climate change on siting and design of nuclear installations, and on estimates of hazard parameters;
(f) Natural hazards not previously addressed in IAEA Safety Guides, such as wildfire, drought, biological phenomena, ice impacts, debris, space weather, meteoroids and meteorites;
(g) Specific hazards associated with new types of siting such as offshore locations and transportable reactors;
(h) Considerations for developing beyond design basis hazard parameters;

[1] Rarely occurring meteorological phenomena is defined in para. 3.20 of this Safety Guide.
[2] For the purposes of this Safety Guide, debris represents any material, organic or inorganic, that is advected through the air and/or water. This does not include debris avalanche, referred to in SSR-1 [1]

(i) A graded approach to site evaluation for new types of nuclear installation with relatively low risks;
(j) The impact of meteorological and hydrological events to safety measures and emergency response around the site.

1.5. Additionally, this Safety Guide clarifies the distinction between the process for assessing site specific meteorological, hydrological and other natural hazards and the process for defining the relevant design basis and beyond design basis parameters for nuclear installations. As a result, it fills in gaps and avoids undue overlapping of the two processes, which are performed at various stages during the lifetime of nuclear installation.

1.6. This Safety Guide supersedes IAEA Safety Standards Series No. SSG-18, Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations[3].

OBJECTIVE

1.7. The objective of this Safety Guide is to provide recommendations on how to comply with the safety requirements established in SSR-1 [1] on assessing hazards associated with meteorological, hydrological, and selected other natural phenomena. This Safety Guide includes considerations for determining the corresponding design bases and beyond design bases for these natural hazards and measures for protection of the site against hazards of this type.

1.8. This Safety Guide is intended for use by regulatory bodies responsible for establishing regulatory requirements, designers of nuclear installations, consultants, advisory bodies, technical support organizations and operating organizations directly responsible for the evaluation of meteorological, hydrological, and other external natural hazards at a nuclear installation site.

1.9. For definitions and explanations of the terms used, see the IAEA Safety and Security Glossary [8]. Explanations of terms specific to this Safety Guide are provided in footnotes.

SCOPE

1.10. This Safety Guide addresses all types of new and existing nuclear installation as described in para. 1.7 of SSR-1 [1], as follows:

(a) Nuclear power plants;
(b) Research reactors (including subcritical and critical assemblies) and any adjoining radioisotope production facilities;
(c) Storage facilities for spent fuel;
(d) Facilities for the enrichment of uranium;
(e) Nuclear fuel fabrication facilities;
(f) Conversion facilities;

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, WORLD METEOROLOGICAL ORGANIZATION, Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations, IAEA Safety Standards Series No. SSG-18, IAEA, Vienna (2011).

(g) Facilities for the reprocessing of spent fuel;
(h) Facilities for the predisposal management of radioactive waste arising from nuclear fuel cycle facilities;
(i) Nuclear fuel cycle related research and development facilities.

Facilities for mining or processing of uranium or thorium ores and disposal facilities for radioactive waste are not considered in this Safety Guide[4].

1.11. This Safety Guide provides recommendations on the evaluation of external hazards associated with meteorological, hydrological, and selected other natural phenomena for nuclear installation sites. External hazard evaluations are needed over the entire lifetime of the nuclear installation project, from site survey, through the site evaluation process (i.e. site selection and site characterization stages from which the design bases are derived, up until the end of the operational period).

1.12. The meteorological, hydrological, and selected other natural hazards considered in this Safety Guide are those caused by external events. The concept of external events is intended to include more than those occurring in the external zone[5], since in addition to the area immediately surrounding the site area, the site area itself may contain features that pose a hazard to the installation, such as a water reservoir.

1.13. The transport of radioactive material by the atmosphere and in surface water and groundwater and its dispersion in the environment is considered in NS-G-3.2 [7] and is out of the scope of this Safety Guide. Hazards related to geotechnical, seismic, and volcanic phenomena are addressed in NS-G-3.6 [5], SSG-9 (Rev.1) [2], and SSG-21 [3], respectively. These are also out of scope of this Safety Guide.

1.14. Recommendations for applying a graded approach to hazard evaluation for nuclear installation sites are provided in this Safety Guide. A graded approach means that the evaluation can be customized in accordance with the severity of the potential radiological consequences of failure when subjected to loading conditions associated with meteorological, hydrological, or other natural phenomena.

1.15. This Safety Guide is mainly focused on site characterization for new nuclear installation sites. However, the recommendations are also applicable to the re-evaluation of existing installations[6] and to the periodic safety reviews described in IAEA Safety Standards Series No. SSG-25, Periodic Safety Review for Nuclear Power Plants [9].

1.16. The meteorological, hydrological, and other natural hazards addressed in this Safety Guide may need to be determined independently of the characteristics of the nuclear installation

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[4] While not within the scope of this safety guide, the recommendations provided may be helpful for the evaluation of meteorological and hydrological hazards for radioactive waste management and disposal facilities, particularly during their operational phase.

[5] The external zone is the area immediately surrounding a proposed site area in which population distribution and density, and land and water uses, are considered with respect to their effects on the possible implementation of emergency measures. This is the area that would be the emergency zones if the facility were in place [8].

[6] For the purpose of this Safety Guide, existing nuclear installations are those installations that are either (a) at a pre-operational stage for which the construction of structures, the manufacturing, installation and/or assembly of components and systems, and commissioning activities are significantly advanced or fully completed; or (b) at the operational stage (including temporary and extended shutdown periods). The construction and operation of additional facilities has occurred at many existing nuclear installation sites. The re-evaluation of an existing site could identify differences between the design bases for an existing facility and those for a new facility to be built on the site. These differences may indicate a need to assess the safety of existing facilities on the re-evaluated site for modified or newly determined external hazards.

that is to be installed. For example, some hazard evaluations may be performed at the site selection and/or site characterization stages, possibly prior to the availability of information on the design of the nuclear installation. Recommendations on the determination of the appropriate basis for the design and evaluation of a nuclear installation through the use and application of appropriate criteria are provided in IAEA Safety Standards Series No. SSG-68, Design of Nuclear Installations Against External Events Excluding Earthquakes [10].

STRUCTURE

1.17. Section 2 provides recommendations on the evaluation of hazards associated with meteorological and hydrological phenomena for nuclear installation sites. Section 3 provides recommendations on data requirements (for data collection and for investigations). Section 4 provides recommendations for the evaluation of meteorological hazards. Section 5 provides recommendations on the evaluation of hydrological hazards. Section 6 provides recommendations on other selected natural hazards (non-seismic, non-geotechnical, non-volcanic). Section 7 provides recommendations on developing design basis and beyond design basis parameters. Section 8 provides recommendations on measures to protect sites. Section 9 provides recommendations on changes in hazards over time, including climate change. Section 10 provides recommendations on monitoring and warnings for the protection of the nuclear installation site. Section 11 provides recommendations on applying a graded approach to the evaluation of nuclear installation sites. Section 12 provides recommendations on the management system to be established for the performance of hazard evaluation. Annex I provides examples of criteria for characterizing meteorological and hydrological variables. Annex II presents an evaluation of tsunami hazards. Annex III outlines tsunami warning systems. Annex IV details climate change parameters relevant to site evaluation for nuclear installations. Annex V describes combinations of extreme events used to determine design basis events and beyond design basis events for coastal sites, based on member state experience. Annex VI presents probable maximum precipitation.

2. GENERAL CONSIDERATIONS FOR THE EVALUATION OF HAZARDS DUE TO METEOROLOGICAL, HYDROLOGICAL, AND OTHER NATURAL PHENOMENA

CHARACTERISTICS OF METEOROLOGICAL, HYDROLOGICAL AND OTHER NATURAL PHENOMENA

2.1. The hazards considered in this Safety Guide are grouped into meteorological hazards, hydrological hazards, and other natural hazards: see Sections 4–6, respectively. These hazards could affect the safety functions of a nuclear installation in multiple ways. For example, the ability of the ultimate heat sink to perform its function adequately could be affected by extreme water temperature associated with heatwaves, severe drought in the region, obstruction of channels, loss of water source due to dam failure, downstream failure of water control structures, and anthropogenic effects such as the pumping of groundwater. In other cases, the ultimate heat sink may be impacted by a drawdown of the sea level resulting from a surge, seiche or tsunami.

2.2. The hazards considered in this Safety Guide may simultaneously affect multiple units, modules or structures, systems and components (SSCs) important to safety at a nuclear installation site (e.g. electrical power supply systems, decay heat removal systems, other vital systems), introducing the potential for common cause failure. Defence in depth (i.e. providing adequate diversity as well as redundancy and physical separation) is vital in design against common cause failure. Recommendations on the design of nuclear installations against external events, including consideration of common cause failures, are provided in IAEA Safety Standards Series Nos SSG-67, Seismic Design for Nuclear Installations [11] and SSG-68 [10].

2.3. Meteorological, hydrological and other natural hazards could also impact infrastructure around the site area of a nuclear installation (e.g. roads, electrical supply, communications). These impacts could jeopardize the implementation of safety measures and/or hinder emergency response[7]. The feasibility of safety measures and emergency response under the impact of the meteorological, hydrological and other natural hazards is required to be evaluated (see Requirement 13 of SSR-1 [1]). This evaluation should be reviewed throughout the lifetime of nuclear installation.

2.4. Changes in hazards over time, including due to climate change, are important considerations for the development of hazard parameters in the site evaluation process. Re-evaluation of hazards on regular basis should be performed, e.g. during the periodic safety review of a nuclear installation. Periodic safety review is discussed in more detail in SSG-25 [X].

Meteorological hazards

2.5. Although Requirements 18 and 19 of SSR-1 [1] separate meteorological hazards into extreme meteorological hazards, and rare meteorological events, this Safety Guide groups meteorological aspects of external hazards together by hazard type (e.g. wind hazards, precipitation) to facilitate efficient hazard evaluation. The following types of meteorological hazards are addressed in this Safety Guide, and, where applicable, should be considered in site evaluation for a nuclear installation:

(a) Air temperature and moisture.
(b) High intensity winds:
    (i) Tornadoes;
    (ii) Cyclones (tropical cyclones, typhoons, and hurricanes).
    (iii) Other extreme wind events (e.g., extratropical cyclones, downbursts, squall lines, katabatic winds)
(c) Precipitation (liquid equivalent):
    (i) Local intense precipitation;
    (ii) Watershed-scale precipitation.
(d) Snowpack.
(e) Lightning.
(f) Waterspouts.
(g) Dust storms and sandstorms.
(h) Hail.
(i) Freezing precipitation and frost related phenomena.

[7] For example, a flood that affects the road network around a nuclear installation site could hinder the implementation of temporary flood protection measures and/or operator shift turnover. High intensity winds, wind-borne material, lightning and precipitation could also impede emergency response by slowing down measures for evacuation or relocation and/or by interfering with communications.

2.6. The hazard types listed in para. 2.5 should be assessed individually or as combined hazards where appropriate. This consideration applies to both phenomena combination, and consequences initiated by a single hazard (i.e., direct and indirect effects). For example, high intensity winds may have direct effects (e.g., wind forces) and may lead to other initiating events that are to be included in the safety analysis for the installation (indirect effects such as flying debris and projectiles). . Storm surge associated with tropical cyclones may also cause flooding at the site. Extreme precipitation may lead to large loads on structures (e.g. roofs) as well as cause flooding. High intensity wind combined with freezing precipitation or snow could block the emergency diesel generator air intake structures and simultaneously cause loss of offsite power.

Hydrological hazards

2.7. Hydrological phenomena that are generated at relevant bodies of water and which may cause flooding or low water conditions are considered in this Safety Guide. Relevant bodies of water include oceans, seas, estuaries, lakes, reservoirs, rivers, streams, and canals that may produce or affect flooding on or adjacent to a nuclear installation site. The most important phenomena that should be considered, where applicable, in site evaluation include:

(a) Storm surge;
(b) Wind generated waves;
(c) Tsunamis;
(d) Seiches;
(e) Flooding due to extreme precipitation;
(f) Sudden releases of impounded water from natural or artificial storage;
(g) Backwater effects due to downstream blockages or impoundments
(h) Channel migration or diversion
(i) Credible combined events.

2.8. Other hydrological phenomena that could cause hazards to a nuclear installation site, and which should also be considered, where applicable, in site evaluation, include:

(a) Water level rising upstream or falling downstream caused by, for example, obstruction of a river channel by landslides or by jams caused by ice, logs, debris or volcanic materials;
(b) Landslides or avalanches into water bodies;
(c) Low water flow or water level that challenges the ultimate heat sink;
(d) Loss of a water source due to events such as dam failure;
(e) Waterspouts;
(f) Deterioration or failure of facilities on the site or near site facilities (e.g. canals, water retaining structures or pipes);
(g) Deficiencies or blockages in site drainage systems;
(h) Swelling of water in a channel due to a sudden change in the flow rate; the origin may be natural, for example a tidal bore, or artificial, as in the case of closure of a hydroelectrical plant;
(i) Variation of groundwater levels.

2.9. The hydrological phenomena listed in paras 2.7 and 2.8 might have multiple impacts on a nuclear installation site. For example, water pressure on walls and foundations may challenge their structural integrity. Groundwater pore pressure may affect the stability of soil or backfill.

Also, water may affect the criticality of fissile materials in some nuclear installations. Such multiple impacts should be considered in both the hazard evaluation and the design of the nuclear installation.

2.10. The dynamic effects of water can be damaging to the structures and foundations of a nuclear installation as well as to the many systems and components located on the site, and this should be considered in the hazard evaluation. Flooding may cause erosion at river or coastal margins, scouring around structures or internal erosion of backfill due to the effects of groundwater. Flooding may transport sediment and debris of all types (including ice floes in very cold weather) that could physically damage structures, obstruct water intakes or damage the water drainage system. Flooding may also contribute to the dispersion of radioactive materials. Recommendations relating to the dispersion of radioactive materials in air, surface water and groundwater are provided in NS-G-3.2 [7].

2.11. Recommendations relating to flood related phenomena such as earthquakes and volcanoes are also provided in SSG-9 (Rev. 1) [2] and SSG-21 [3], respectively.

Other natural hazards

2.12. Other natural phenomena that can occur — and that are not already considered in other Safety Guides — might also have the potential to affect the safety of nuclear installation sites (e.g. other meteorological and hydrological phenomena, space weather). Where applicable, these other natural hazards should be identified and assessed. The other natural hazards considered in this Safety Guide include:

(a) Wildfire;
(b) Drought;
(c) Biological phenomena and debris;
(d) Ice (frazil ice and ice floes);
(e) Icebergs;
(f) Salt spray;
(g) Space weather;
(h) Meteoroids and meteorites.

Changes in hazards with time

2.13. Over the lifetime of a nuclear installation, it is possible that the types of hazard, or their nature or intensity will undergo significant changes. Foreseeable changes in hazards with time should be considered at the site evaluation stage. This includes a consideration of:

(a) Changes in hazards with time caused by changes in land use or land cover, primarily due to human activities (e.g. deforestation, urbanization, river regulation, coastline changes, offshore construction);
(b) Climatic variability and climate change, which may have effects on the occurrence and/or intensity of extreme meteorological and hydrological conditions;
(c) Geological or geomorphological processes, which may also lead to changes in hazards over time (e.g. uplift or subsidence, sediment transport).

Combination of External Events

2.14. In addition to assessing individual hazards, combined events and cascading effects should be systematically identified. This can be achieved, for example, by developing a matrix that maps potential combinations between meteorological, hydrological, and other natural phenomena, along with their possible amplification effects. Advanced statistical and probabilistic techniques may be needed to perform assessment of combined hazards (e.g. joint probability of hurricane and flooding).

Methods for the evaluation of hazards

2.15. Methods for the evaluation of hazards are often divided into deterministic methods, statistical methods and probabilistic methods.

2.16. The evaluation of hazards should include treatment of the uncertainties in the process. Many aspects of the identification, analysis and characterization of the phenomena under consideration and the evaluation of the corresponding hazards and related parameters may involve subjective interpretation by experts. This should be taken into consideration, to ensure that such interpretations are treated in a consistent manner. However, expert judgment should not be used as a substitute for acquiring new or site-specific data where it is feasible to do so.

2.17. It should be ensured that the evaluation provides for a suitable representation of current thinking in the subject that avoids bias in the interpretations and permits the evaluation of all viable hypotheses and models using the collected data.

Deterministic methods

2.18. Deterministic methods are based on the use of physical or empirical models to characterize the hazard. For a given single input value or a set of input values, including initial conditions and boundary conditions, the model will typically generate a single value or a set of values to describe the final state of the system. In this case, there is no explicit account of any annual frequency of exceedance. Appropriate extreme or conservative values (e.g. physical limits) of the input parameters should be used to take into account uncertainties or to provide conservative estimates.

Statistical methods

2.19. When a statistical analysis is performed, it is typically based on time series of observations. The data series available for the region of the site should be analysed to check their quality, representativeness, homogeneity, and completeness. Gaps, missing data, outliers, trends, and break points in the available data set should be investigated and adequately taken into account. The time series should also be examined to verify compatibility with the underlying assumptions of the statistical analysis methods used.

2.20. A typical challenge encountered in statistical hazard evaluations is records that only extend over a short period of time. Efforts should be made to extend or enrich a limited time series, for example by either: (a) increasing the observation time frame using data provided by historical accounts or paleo-information (see Section 3); or (b) taking advantage of statistical homogeneities at a regional scale to build regional samples. These approaches may also be combined. The following should also be considered:

2.21. Historical and paleo-information has different formats than data provided by continuous measurements. For example, the information provided is often that a parameter either exceeded or did not exceed a given perception threshold over some time period. The use of statistical analysis methods that can combine this interval information with the continuous measurements should be considered as a means of effectively extending the period of record.

(a) Another possible option to increase the size of the datasets is regional frequency analysis, which consists of merging the observations available at different sites with similar characteristics to build statistically homogeneous regional datasets. In the simplest version of regional frequency analyses, it is hypothesized that, in a homogeneous region, the local distributions are the same provided that the local values are scaled by a local constant factor. Frequency analysis methods have been also developed to transfer data from the region surrounding the site to enrich the dataset available at the site of interest (to increase its size and fill gaps) based on statistical homogeneity.

(b) Spatial interpolation methods can also be used to enrich a limited time series by estimating values of parameters at a specific location from data measured at other locations.

2.22. Statistical hazard evaluation approaches often focus on analysis of extremes. There are two commonly used methods to develop a time series of extreme values from the available record: block maximum and peak-over-threshold. Threshold selection should be performed carefully to ensure the selection of an appropriate number of peaks and that the peaks are statistically independent and identically distributed. Sensitivity analysis should be performed to ensure that small changes in the threshold (or perhaps change in the block size) does not lead to large changes in analysis results. For both block maximum and peak-over-threshold approaches, different probability distribution functions should be tested (e.g., goodness of fit) to identify the distribution most appropriate to the data sets under study. When using these methods, the extreme values corresponding to various frequencies of exceedance and the associated confidence intervals should be derived from these data.

2.23. The non-stationary characteristics of data sets[8] due to long term variation of variables (e.g. due to climate change) should be addressed, either using simple approaches (e.g. detrending), or using more complex approaches that allow one or more parameters of the selected distribution (e.g. location parameter, shape parameter) to vary over time.

2.24. In addition to traditional frequency analysis approaches, the use of Bayesian methods (i.e. which focus on consistently incorporating prior knowledge into the statistical model) offer a useful framework and should be considered. This framework replaces confidence intervals by credibility intervals and point estimates of statistical parameters by their posterior distributions.

2.25. Care should be taken in extrapolating frequency analyses to return periods well beyond the length of the available records (such as for return periods greater than four times the record length). In particular, fitting an extreme value distribution to a data set representing only a few years of records should be avoided. One approach that should be considered is to add margin;

[8] A common assumption in many time series techniques is that the data are stationary. A stationary process is a stochastic process whose joint probability distribution does not change when shifted in time or space. Such a process has the property that parameters such as the mean and variance do not change over time or position. Stationarity in general terms means that there is a flat looking time series, without a trend, with constant variance over time, a constant autocorrelation structure over time and no periodic fluctuations.

for example, extrapolate to an appropriate return period and then choose a higher percentile instead of the mean or best estimate (see Section 7). Where a physical limit exists, the use of deterministic methods to provide rational limits to the statistical extrapolation by means of an upper limit on the variable of interest (e.g. flooding level, wind velocity) irrespective of the frequency of occurrence, should be considered.

Probabilistic methods

2.26. Probabilistic hazard assessment aims to combine the strengths of deterministic and statistical approaches. The probabilistic approach generally uses the same mechanistic models used in deterministic approaches but treats model structure and model parameters as epistemic uncertainties[9] represented by probability distributions or quantified by logic trees. Aleatory uncertainties [10] are also represented by probability distributions. Propagation of these uncertainties to quantify their contribution to the final results (e.g. hazard parameters) should be addressed. This is generally accomplished via a logic tree approach or two-staged nested Monte Carlo simulation approach. The logic tree approach represents the epistemic uncertainties using a set of branches for alternative models and parameter values, and the mean or percentile hazard curves (i.e., magnitude-frequency curves) can be calculated from a suite of hazard curves generated for the individual logic tree branches. In the Monte Carlo simulation approach, the epistemic parameters are sampled in the outer loop, while the aleatory variables are sampled in the inner loop. Execution of the inner loop for a single realization produces a magnitude vs frequency curve for hazard parameters of interest. Repeating this process for a large number of realizations produces a family of magnitude-frequency curves from which mean values and other percentiles of the hazard parameters can be derived. In this way frequency of exceedance for hazard parameters can be estimated while explicitly and systematically accounting for aleatory and epistemic uncertainties in the modelling process. The number of inner and outer loop simulations should be large enough to ensure statistical stability in the percentile(s) of interest[11].

GENERAL APPROACH TO THE EVALUATION OF METEOROLOGICAL AND HYDROLOGICAL HAZARDS

2.27. As established in SSR-1 [1], the following Safety Requirements are applicable to meteorological and hydrological hazards:

— Requirement 6 states that "**Potential external hazards associated with natural phenomena, human induced events and human activities that could affect the region shall be identified through a screening process.**"
— Requirement 7 states that "**The impact of natural and human induced external hazards on the safety of the nuclear installation shall be evaluated over the lifetime of the nuclear installation.**"

[9] Epistemic uncertainty, also known as knowledge uncertainty or reducible uncertainty, is uncertainty that results from a lack of knowledge. It can be caused by several factors such as: incomplete knowledge of a phenomenon, incomplete understanding of processes, a model that neglects certain processes, imprecise or inaccurate measurements or evaluations. In theory, epistemic uncertainty could be reduced by gaining more knowledge (e.g. collecting more data).

[10] Aleatoric uncertainty, also known as aleatory variability or irreducible uncertainty, is the inherent randomness in a process or data. Unlike epistemic uncertainty, aleatory uncertainty cannot be reduced by gathering more data or gaining knowledge.

[11] The probabilistic methods with random sampling may require a large number of simulations. This issue can be addressed by using surrogate models (e.g. reduced order model, lower fidelity mechanistic model) or by using a stratified sampling technique (e.g. Latin Hypercube sampling).

- Requirement 8 states that "**If the projected design of the nuclear installation is not able to safely withstand the impact of natural and human induced external hazards, the need for site protection measures shall be evaluated.**"
- Requirement 10 states that "**The external hazards and the site characteristics shall be assessed in terms of their potential for changing over time and the potential impact of these changes shall be evaluated.**"
- Requirement 11 states that "**The evaluation of site specific natural and human induced external hazards for nuclear installations that require an ultimate heat sink shall consider hazards that could affect the availability and reliability of the ultimate heat sink.**"
- Requirement 14 states that "**The data necessary to perform an assessment of natural and human induced external hazards and to assess both the impact of the environment on the safety of the nuclear installation and the impact of the nuclear installation on people and the environment shall be collected.**"
- Requirement 18 states that "**Extreme meteorological hazards and their possible combinations that have the potential to affect the safety of the nuclear installation shall be evaluated.**"
- Requirement 19 states that (footnote omitted) "**The potential for the occurrence of rare meteorological events such as lightning, tornadoes and cyclones, including information on their severity and frequency, shall be evaluated.**"
- Requirement 20 states that "**Hazards due to flooding, considering natural and human induced events including their possible combinations, shall be evaluated.**"
- Requirement 23 states that "**Other natural phenomena that are specific to the region and which have the potential to affect the safety of the nuclear installation shall be investigated.**"
- Requirement 28 states that "**All natural and human induced external hazards and site conditions that are relevant to the licensing and safe operation of the nuclear installation shall be monitored over the lifetime of the nuclear installation.**"
- Requirement 29 states that "**All natural and human induced external hazards and site conditions shall be periodically reviewed by the operating organization as part of the periodic safety review and as appropriate throughout the lifetime of the nuclear installation, with due account taken of operating experience and new safety related information.**"

2.28. The meteorological, hydrological, and other characteristics of the region around the site of the installation should be investigated. The size of the region to be investigated, the type of information to be collected, and the scope and detail of the investigations should be determined on the basis of the nature and complexity of the environment of the area in which the site is located, regardless of national or other administrative borders. In all cases, the scope and detail of the information to be collected and the investigations to be undertaken should be sufficient to evaluate the hazards (see also para. 4.14 of SSR-1 [1]). With regard to tsunami related phenomena, special considerations as to the size of the region to be investigated are provided in Sections 3 and 5 of this Safety Guide.

2.29. The general approach to meteorological, hydrological, and other natural hazard evaluations should be directed towards reducing the uncertainties at various stages of the evaluation process so as to obtain reliable results driven by data. The most effective way of achieving this is to collect a sufficient amount of reliable and relevant data. There is generally a trade-off between the time and effort necessary to compile a detailed, reliable and relevant database, and the degree of uncertainty that the analyst should take into consideration at each step of the process. Both regional and site specific data should be collected to improve the confidence in the site characterization and hazard evaluations.

2.30. In all cases, whether a deterministic, statistical or probabilistic approach is used, uncertainties in the results of the hazard evaluation should be estimated. Engineering judgement should be exercised with regard to the choice of the approach and the relevant parameters to be used, and in defining the numerical values associated with the parameters. The results of the hazard analysis should be compared with results of previous studies, observations, and historical or paleorecords, and adapted if necessary.

2.31. In the deterministic approach, uncertainties should be estimated by conducting a sensitivity study. This can be done, for example, by evaluating the uncertainty in the data used by the models, and by testing the degree to which the predictions of hazards are affected by varying the values of relevant input parameters over their possible ranges. In the deterministic approach, the uncertainties should be considered by using a conservative process at key steps of the evaluation. The conservatism built into the deterministic process should be such that uncertainties are duly accounted for.

2.32. In the statistical approach, uncertainty estimates (e.g. confidence intervals) should be produced as part of the analysis. Uncertainty can also be investigated by fitting different distributions to the data.

2.33. In probabilistic hazard analysis, the consideration of uncertainties should be explicitly included in the procedure. The overall uncertainty will involve both aleatory as well as epistemic uncertainties that arise owing to differences in the interpretation of the data, choice of models, and distributions for input parameters by experts participating in the hazard evaluation process.

2.34. Climate change is adding further uncertainty to meteorological, hydrological, and other natural hazard evaluations. Uncertainties in climate change modelling that should be considered include assumptions with regard to future emissions of greenhouse gases relating to different socioeconomic scenarios, and discrepancies between different global and regional climate models (see Section 9).

3. SITE INVESTIGATIONS AND DATA COLLECTION FOR THE EVALUATION OF METEOROLOGICAL, HYDROLOGICAL, AND OTHER NATURAL HAZARDS

3.1. Site investigation and data collection should be undertaken with care to include all necessary information for characterizing and evaluating regional and site specific meteorological, hydrological, and other natural hazard parameters values. The size of the region to be investigated, the scope and detail of the information to be collected, and the investigations to be undertaken should be sufficient to determine the design bases for protection of the nuclear installation against relevant hazards. The spatial and temporal resolution of the collected data should be appropriate to the specific hazard assessment objectives. Persons collecting data for hazard evaluation should collaborate with the national meteorological service to access their archived datasets and their expertise and standards for observational data collection and processing. Information collected should be compiled in site specific catalogues or databases for each of the hazards under consideration. If it has been conclusively shown in the preliminary investigation that a hazard may be excluded from further consideration, the reasons for doing so should be documented.

3.2. The structure databases containing information for hazard evaluation should be standardized to permit reproducible analyses by a third party and to permit the development of scalable databases over the lifetime of the nuclear installation. The effects of climate change or other changes in hazards over time may necessitate revised evaluations in future years, which may need to be compared with the original evaluation.

3.3. Data collected by site monitoring systems that have been in operation since the preliminary phase of the site evaluation — although obtained over a short period of time — should be used to assess whether the data obtained from regional networks used to estimate the hazards at the site are representative of the specific characteristics in the vicinity of the site. One method to assess representativeness of regional data can be performing a correlation analysis between on-site and off-site data. Collection of data and information should be continued throughout the lifetime of the nuclear installation to support updates of the safety case (e.g. as determined by periodic safety reviews).

3.4. Data should include the location and date/time at which it was measured/acquired. Data should be presented clearly, using maps of an appropriate scale, graphs and tables. In general, geographic information systems are very useful for organizing spatial data collected during the site evaluation stage. Such systems can be used to implement a digitized system for all site related data, including a digital elevation model extended to the appropriate region surrounding the site area as necessary for assessing the hazards.

3.5. The record used to evaluate extreme values of meteorological, hydrological, and other variables (i.e. the combined instrumental observations, historical record, and paleo-information) should cover a period commensurate with the targeted return period of the extreme values[12]. Information regarding extreme events observed in the region are especially valuable for model calibration, in addition to developing an understanding of hazard potential. Therefore, data on extreme hazard conditions for the region should be collected and assessed for each hazard. In some cases, where the existing network for collecting data in the region is inadequate, supplementary observation stations should be set up and operated as early as practicable during the initial stages of the site evaluation process. Although the time available for collecting supplementary data is usually relatively short, the information obtained is often valuable.

3.6. Historical and anecdotal accounts should be sought; these often provide important information not captured in instrumental records, which may be useful for improving the comprehensiveness and the reliability of hazard evaluations. Such accounts should be obtained by means of a thorough search of information sources such as, historical archives, newspapers, catalogues of occurrences, personal narratives, field investigation reports, and film or video records. Care should be taken to verify such information, with emphasis given to primary sources.

[12] For instance, for an annual frequency of occurrence of a hazard of 10^{-2}, typically adopted to determine the extreme parameters in meteorology, the minimum period of continuous observation should be at least 30 years, since the uncertainty often becomes large for return periods more than three to four times the length of the sample period.

3.7. Instrumental records and historical information should be supplemented with paleo-information, where available (e.g. geologic or dendrochronological information). For example, tree ring data can be used to extend temperature and precipitation records, and geologic evidence can be used to extend the useful record for riverine and coastal flooding. It should be noted that the absence of geological evidence for floods does not prove that there were no floods in the past.

METEOROLOGICAL DATA

3.8. For assessing the extreme values of meteorological variables and rarely occurring hazardous meteorological phenomena, specific and detailed information should be collected. In this regard, the following should be taken into consideration:

(a) Normal and extreme values of climate parameters (e.g. air pressure, ambient air temperature and humidity, wind speed and direction) characterize the meteorological environment. These are measured routinely by national meteorological services and, in some cases, by international and regional organizations and centres, and by private organizations. Measurements made, collected, archived and made available by national meteorological services are often available worldwide and facilitated by the World Meteorological Organization through different tools and programmes[13]. The World Meteorological Organization maintains standards and best practices for instruments and for their siting and measurements. All these data, standards and practices may be used, in consultation with the national meteorological services, taking into consideration the specific nuclear safety objectives and the criteria and methodologies for evaluating hazards for nuclear installation sites. The meteorological data collected are typically used to derive the following:
   (i) Extreme values of wind speed, precipitation (liquid equivalent), and snowpack, to develop design loads for SSCs important to safety.
   (ii) Extreme or threshold air temperature and humidity conditions (e.g. the number of hours certain wet bulb temperature[14] values are exceeded each year) to establish loads for the design of heat sink systems, systems for the removal of containment heat following an accident, and nuclear installation heating, ventilation and air conditioning systems.

(b) Rarely occurring hazardous meteorological phenomena should be assessed on the basis of regional meteorological data and information sources. In some cases, the information will not be captured by direct measurement. Instead, the intensity of such phenomena should be derived from the severity or the nature of the impact or damage (e.g. wind speed estimates for tornadoes are derived from damage assessments).

[13] For example, the WMO Observing Systems Capability Analysis and Review tool (OSCAR), accessible at https://space.oscar.wmo.int/, facilitates the inventory, assessment, and monitoring of global observing systems used for weather, climate, water, and related environmental observations. Some local site information might not be accessible via the OSCAR platform: therefore, consulting with the national meteorological service is crucial to ensure access to all available and archives of observational data.

[14] Wet bulb temperature, dew point temperature and relative humidity are indicators of atmospheric moisture. Wet bulb temperature refers to the lowest temperature that can be obtained by evaporating water into the air. The dew point is the temperature to which air must be cooled in order to reach saturation, assuming air pressure and moisture content are constant. Relative humidity is the ratio of the amount of atmospheric moisture present relative to the amount that would be present if the air were saturated.

3.9. Climatological statistics, including extreme values, should — to the extent possible — be determined from records of observations made under standard conditions and by following standard procedures. In this regard, the specifications for measurements — including standards and best practices for instruments, instrument siting, observations, data management, the quality management system and homogenization — are available in publications of the World Meteorological Organization or national nuclear safety guides and standards. National meteorological services should be engaged to provide the needed support and expertise.

3.10. Relevant meteorological data and information may also be available through regional climate centres or from local or regional development projects (e.g. coastal protection projects, other power generation installations), and should be collected where available. This data may include historical observational data, meteorological reanalysis data, and local historical records on extreme events.

Off-site sources of meteorological data and information

3.11. For evaluating the extreme values of meteorological variables, the dataset should be as continuous and long as is feasible. Available meteorological data should be identified from stations installed in the region and operated by the national meteorological service, or other entities. Data providers should be consulted as early as possible to ensure data reliability.

3.12. The size of the region to be investigated should be determined based on the specific characteristics of the meteorological and geographical environment of the area in which the site is located. Long term data sets from stations most representative of site conditions for the parameters concerned or, alternatively, the records of neighbouring meteorological stations belonging to the same climatic zone should be processed to provide more robust estimates of the necessary parameters. Data representativeness can be shown by making comparisons with similar data obtained in an on-site meteorological data collection programme.

3.13. Where possible, the beginning date for the time interval (e.g. yearly or seasonal) for data analysis should be chosen to be at a time when the meteorological variable concerned is not at the peak or valley of a cycle (e.g. water year for hydrological data).

3.14. Most national meteorological services publish listings of the specific meteorological and climatic data that they have collected. Most national meteorological services also publish or make available the data in digital form together with some basic analyses for monthly and annual climatological statistics, including extreme values. Users of these data should be aware that while national meteorological services generally follow standards for measurement that are established by the World Meteorological Organization, field measurements made by different organizations do not necessarily follow the same standards. For example:

(a) The standard 10 m height and instrument exposure for measuring wind speed and direction might not be observed owing to the logistics of instrument installation.

(b) Measurement techniques for recording maximum wind speed vary from State to State. The general tendency is to record average values for a given constant duration, such as 3 s gusts, 10 s gusts, 60 s averages, or 10 min averages. The averaging time used for the collected wind data should be recorded. Appropriate conversion factors should be applied consistent with the application for which the data will be used (e.g. structural design, atmospheric dispersion). Data from stations with discontinuous measurements (e.g. only maximum wind gusts) should be treated with caution and only used for appropriate tasks.

(c) Air temperatures (such as dry bulb and dew point temperatures) are recorded continuously at some recording stations and at frequent intervals at other stations. At some secondary locations, only the daily maximum and minimum air temperatures are recorded.

(d) Data that are routinely collected and used for analyses of extreme maximum precipitation generally include the maximum 24 h precipitation depth. Records based on shorter averaging times contain more information and should under certain circumstances be preferred[15].

These variations should be carefully evaluated and, if necessary, the data should be adjusted before processing. Information on adjustments and data processing methods should be documented.

3.15. Documentation of meteorological analyses should include a description of each meteorological station (e.g. geographical location, altitude, exposure, instrument types and placement) and the monitoring programme (e.g. variables measured, measurement frequency, calibration history), data record period (s) and data quality.

3.16. Numerical mesoscale models with spatial resolution adequate to resolve the regional and local topographic features of the site are useful for simulating the atmospheric circulation and other local meteorological parameters at regional and local scales. If such models are available, validated and adequately supported, they should be used as part of the meteorological evaluation of the site, including for improving the understanding of the meteorological conditions at the site in relation to those of the region. Such data may be accessible through national meteorological services, regional climate centres, other national and regional relevant institutions, and the private sector.

On-site meteorological observation programme

3.17. An on-site meteorological observation programme should be established as early as possible after selecting a candidate site for a nuclear installation. The implementation of such a programme should be coordinated with the national meteorological service or regulatory authority to ensure that the relevant standards and best practices for instrumentation, data collection and monitoring, as well as for exchanging of data sets are observed[16].

3.18. The on-site meteorological observation programme should be used as part of an on-site surface-based programme for vertical profile monitoring for evaluating the atmospheric dispersion at the site in accordance with para. 6.2 of SSR-1 [1]. The meteorological parameters monitored should include at least air pressure, air temperature, humidity, wind speed and wind

[15] Note that for short averaging periods very intense precipitation can occasionally be observed from weather systems, which would be smoothed out if a 24 h averaging period were used. This may be the case when considering precipitation events from thunderstorms.

[16] Some States have issued their own guidance and criteria for on-site meteorological monitoring programmes at nuclear installation sites.

direction, and precipitation[17] (see also paras 2.12–2.14 of NS-G-3.2 [7]). All parameters should be measured at standard heights and exposures[18].

3.19. There may be indirect evidence that long term measurements made at nearby meteorological stations can be considered representative of the site. Nevertheless, on-site data obtained during the short period of record of the site evaluation should be the basis for assessing the repressiveness of nearby station data, since deviations from regional to local meteorological conditions may be caused by local topography, nearby bodies of water, or other unique site characteristics.

Rare meteorological phenomena

3.20. Events characterized as rare meteorological events (see Requirement 19 of SSR-1 [1]) are unlikely to be recorded at any single location or by a standard instrumented network owing to their low frequency of occurrence or owing to the event damaging instruments or causing unreliable measurements (e.g. phenomena that produce extreme wind speeds). Therefore, data from the surrounding region should be collected to assess the likelihood and intensity of such phenomena. The size of the region to be investigated is required be determined based on the specific meteorological and geographical characteristics of the area in which the site is located and the hazard under consideration (e.g. tornadoes, cyclones, lightning): see para. 4.14 of SSR-1 [1].

3.21. Two types of data on rare meteorological phenomena, which are generally available from national meteorological services or other entities, should be collected: historical information; and data and information that has been systematically collected, processed, and analysed in recent years. Recent datasets may include more occurrences of events of lower intensity and may be more representative of intensity distributions than historical information. Combining both types of information should be considered in order to provide a more comprehensive evaluation of the hazard.

3.22. Occasionally, a comprehensive collection of data and information obtained soon after the occurrence of a rare meteorological event may be available. This could include measured values of variables, eyewitness accounts, photographs, descriptions of damage and other qualitative information. Such detailed studies of rare meteorological events should be used in constructing a model for their occurrence and should contribute, in conjunction with a known climatology for a particular region, to the evaluation of the hazard for that region. Often the area affected by some rare meteorological phenomenon (e.g. tornadoes) is comparatively small, which may make the collection of relevant and adequate data difficult to achieve.

3.23. Following the collection of data on rare meteorological phenomena, a specific catalogue should be compiled.

Remote sensing

3.24. In many States, there are weather radar networks and arrangements for acquiring aerial or space-based observations of surface meteorological parameters. Some of these data sets may be of a sufficiently long period of record, and could include estimates of surface wind speeds,

[17] The precipitation can be measured on an almost continuous basis using an appropriate instrument (e.g. weighing gauge, tipping bucket gauge)

[18] Exposure refers to the placement of the instrument such that measurement accuracy and bias are not compromised.

air temperature, precipitation, or other variables. Remotely sensed data is often collected for condition or damage assessment for both rare and extreme meteorological events. Where available, remotely sensed data should be considered and used in conjunction with conventionally measured data. Adequacy and accuracy of the remotely sensed data should be confirmed, to the extent possible, using ground-based records.

Climate models

3.25. Observational, historical or paleo information records might not fully capture future climate and extreme event conditions due to climate change. Therefore, these records should be supplemented or extended by using outputs from climate models.In particular, climate prediction models (ranging from days to multi-annual prediction based on current and past climate data), and/or climate projections (multi-annual to multi-decadal simulations of future climates under various greenhouse gas emission scenarios) could be used to supplement the observational records. In such climate projections, accurate hazard evaluation is constrained by uncertainties in the simulation models as well as possible deviation between simulated scenarios and local conditions (e.g. local land use/land cover changes not captured in global or regional climate simulations). Appropriate use should be made of climate model data. For additional information on climate prediction and projections datasets, see Annex IV. For additional information on land use/land cover changes see Section 9.

Reanalysis models

3.26. Reanalysis datasets providing hourly values for many atmospheric, land-surface and sea-state parameters together with estimates of uncertainty are available, covering several decades (some as far back as the late 19th century). Reanalysis datasets, where available, should be used for hazard evaluations. For example, in areas with sparse rain gauge density, reanalysis datasets can be a convenient source of precipitation data for flood simulations.

HYDROLOGICAL DATA

3.27. Persons collecting data for hazard evaluation should collaborate with national hydrological services to access their archived observational hydrological data, as well as standards and procedures for data collection, data processing, and for the installation and operation of instruments.

3.28. Hydrological data should include the following, as applicable for the site:

(a) The hydrological characteristics of all relevant surface water bodies in the site vicinity (e.g. river, lake, sea);
(b) The locations of and descriptions of existing and proposed water control structures, both upstream and downstream of the site, which might influence site conditions;
(c) Hydrogeological conditions relating to groundwater in the region and at the site.

3.29. The tidal water level range should be determined for sites located in coastal areas affected by tides. The tidal range can vary greatly from place to place, and astronomical tides fluctuate on a time scale of hours to years. Tide predictions, as well as tide data obtained at coastal gauge stations in the site region should, where possible, be obtained from the national authorities. Data should cover a period that includes all the cyclical phenomena producing the tide (i.e. approximately 19 years).

3.30. The water level range for non-tidal phenomena should be obtained, subject to the following considerations:

(a) Water level records should be obtained for all relevant bodies of water at the site and/or at all gauge stations that are representative[19] of the site conditions for the possible phenomena. Water level records should be as complete and extensive as possible. Attention should be paid to the frequency of data collection to ensure that water level measurement results over an appropriate time scale are collected.
(b) Wind wave characteristics (direction, amplitude (typically significant wave height), period, and duration) should be collected. Coastal and offshore wave measurements can be obtained using ultrasonic altimeters, wave buoys, and/or from satellite derived data.
(c) Comprehensive historical information and instrumental records on past tsunamis — as far back in time as possible — should be collected.
(d) Information obtained from tsunami deposits should be collected to improve the accuracy of estimating the magnitude and recurrence period of giant tsunamis. However, tsunami deposits are subject to many epistemic uncertainties; therefore, the interpretations of multiple scientists should be taken into account.
(e) Available documentation from any field surveys performed following significant inundation events should be reviewed. This may provide information such as highwater marks for riverine flooding or storm surge. For tsunami events, this may include the tsunami source, data on tsunami height, runup, drawdown and the horizontal inundation, period and duration. In addition, the impact of the tsunami inundation event on the region (e.g. 50 km radius) should be obtained together with the date, location and information on structures affected (e.g. ports, buildings).
(f) Water levels for significant historical events near to the site should be obtained, if available. This includes historical flood marks, tsunami runup heights and historical low water levels during periods of drought. In addition to water levels, other parameters of the inundation (horizontal distance, period), the date of occurrence and the accuracy of the measurements should be reported.

3.31. For rivers and streams, measurements of water discharge and related information should be obtained, including the following:

(a) Water discharge records for all relevant bodies of water near the site and/or at all gauge stations that are representative of site conditions.
(b) Rating curves and numerical models, which relate water level to water discharge. Attention should be paid to the date on which the rating curve was developed, since anthropogenic and bathymetric and/or topographic changes may dramatically alter the relationship between the stage and the water discharge.
(c) Where available, peak water levels (e.g. high water marks) from past flood events should be obtained.

3.32. Hydrogeological data derived from geological media and backfill, such as data on permeability and porosity, should be collected at the site and its vicinity. Groundwater measurements should be obtained as follows:

[19] A hydrological model can be used to construct synthetic hydrological data for a site using available data from another site.

(a) Piezometers should be installed at the site to monitor the groundwater levels and pressures in the appropriate aquifers. The number and location of the piezometers should cover a sufficiently large area, generally extending beyond the site boundaries, to enable the local conditions and variability of the groundwater table to be analysed. The data collection period should be of sufficient length to capture both seasonal and yearly fluctuations. High frequency datasets are useful to observe the effects of storm events, especially for aquifers composed of fractured rock, aquifers in karst environments, or aquifers with direct connection to surface water.
(b) Information should be obtained on anthropogenic influences on groundwater levels, such as changes in the site layout (e.g. backfill), the locations and magnitudes of groundwater extraction, or artificial recharge.
(c) Information should be obtained on the extent and degree of hydraulic connections between groundwater and bodies of surface water. For example, groundwater level rises often result from local precipitations or flooding events on linked bodies of surface water. Then data on precipitations and water levels in linked bodies of surface water should be acquired at a frequency that permit an analysis of the correlation with high groundwater level.
(d) Long term groundwater level records should be obtained for the region and in comparable hydrogeological situations to allow estimation of the effects of extreme meteorological conditions on groundwater levels, and to examine long term trends such as those due to large scale groundwater extraction.

3.33. In certain locations, the following information may be important and, if so, it should be collected:

(a) The historical occurrence of ice floes and ice jams and the extent, thickness and duration of ice coverage at and near the site. Special attention should be paid to the potential for frazil ice conditions to occur near the site.
(b) Measurements of near-shore and along-shore currents induced by tides or winds.

Geophysical, geological and seismological data

3.34. Two different sets of geophysical and geological data should be considered: (a) specific site geology; and (b) nearfield and far field sources of the tsunami phenomena, if appropriate to the site. The specific geological data in the vicinity of the site that should be collected include the following:

— Stability and erodibility of streambanks and shorelines;
— Sediment characteristics that influence sediment transport, such as grain size distribution, density, and chemical composition, especially near the water intake structures of a nuclear installation;
— Hydrogeological characteristics such as permeability and porosity;
— The potential for landslides;

Tsunamigenic sources include seismogenic structures, submarine and subaerial landslides and volcanic activity.

3.35. Evidence of tsunamis that have occurred in the region surrounding the site should be considered and compiled in a tsunami catalogue specific to the site. All historical information and geological evidence (e.g. tsunami deposits) of past tsunamis in the region should be considered in this catalogue.

3.36. The tsunami source parameters and data on the tsunamigenic potential should be collected for the relevant body of water where the nuclear installation site is located. Some States also collect information on national and international tsunamis to take into account similarities in the mechanism and tectonic background of tsunami generation (see Annex II). The following geophysical, geological and seismological data should be collected for use in determining the source characteristics of potential severe tsunami generators, both local and distant, together with their estimated annual frequency of occurrence:

(a) For earthquake induced tsunamis: the earthquake date and origin time, epicentre location, depth, magnitude, seismic moment, focal mechanism (strike, dip and rake angles of the fault plane) and rupture zone parameters (width, length, slip, rigidity, rupture velocity, rising time)[20]. Seismic reflection data should be acquired to identify and characterize faults, especially blind underwater faults near subduction zones.
(b) For subaerial and submarine landslide-induced tsunamis, landslide and cliff characteristics, including location, type and rheology of geological layers, and geometry (e.g. slope, size, volume).
(c) For tsunamis induced by volcanic phenomena, the characteristics of volcanoes that may induce tsunamis, as specified in paras 6.47 and 6.48 of SSG-21 [3].
(d) Tsunami associated with ice shelf, iceberg, or glacier calving.

Topographic and bathymetric data

3.37. The following topographic data should be collected:

(a) The reference vertical datum and horizontal datum. Special attention should be paid to the possibility that surveys made at different times may have been made using different survey grids or datum. The grid or datum used in each data set should be explicitly stated.
(b) General topography of the watershed containing the site and detailed topography of the site area and the area immediately surrounding the site that could be flooded (including any changes due to construction of the facility). The resolution and accuracy of topographic data should be appropriate to the scale and purpose of the analysis being performed (e.g. hydrologic modelling of the watershed vs. detailed hydraulic modelling of flood levels and water velocities on or near the site, or water control structures affecting the site).
(c) Boundaries of the watershed.
(d) Flood plain characteristics, including the extent of the impervious surface, and roughness associated with land use and vegetation.
(e) Historical phenomena of channel migration, including cut-offs, subsidence and uplift. Regional topographical data should be checked to assess the possibility for future channel diversions.
(f) Elevations and descriptions of levees and other bank protection structures in the vicinity of the site.
(g) Recent modifications of the topography due, for example, to subsidence, or a large earthquake.

[20] Note that for megathrust earthquakes of Mw 9-class, the tsunami cannot be numerically simulated accurately unless non-uniform slip is considered.

3.38. Bathymetric data to be assembled for the nuclear installation site should include:

(a) The reference vertical datum and horizontal datum. Special attention should be paid to the possibility that surveys made at different times may have been made using different survey grids or datum. The grid or datum used in each data set should be explicitly stated. Special attention should be paid when matching topographic and bathymetric datasets.
(b) Bathymetry of the relevant water bodies, including detailed bathymetry along the shoreline near the installation site. For coastal sites where tsunami or storm surge modelling is proposed, bathymetric data should be assembled for an area extending offshore (e.g. to a water depth of approximately 100 m or greater, with a spatial resolution of 10 m or less).
(c) Detailed bathymetric survey of submarine canyons, if they are present near the coast. Near field tsunamis can be induced by canyon slope landslides, and canyon geometry can also modify the propagation of a far field tsunami.
(d) Drainage networks, including canals and drainage features (both artificial and natural), should be described, including the side slope, width and depth of the main channel and the bottom roughness.
(e) Data on long term and short term erosion and/or deposition (from sources such as old surveys, maps, aerial photographs, lidar, and satellite imagery).
(f) Recent modification of the bathymetry due, for instance, to subsidence, or a large earthquake.

Data on anthropogenic activities

3.39. Along the coast, the impact of offshore and near-shore structures (e.g. harbours, breakwaters, sea walls and water gates) and land use (e.g. industry, housing, forestry, farming), both existing and planned, should be considered. All permanent and temporary structures that could significantly affect local currents and bathymetry should be considered. For structures, the dates of construction, general dimensions and/or construction plans and responsibility for administrative and/or operational control should be obtained. Coastal land use types and areal coverage should be obtained.

3.40. In a river basin, anthropogenic activities modify hydrological processes primarily owing to: (a) changes in land use; and (b) modifications in existing channels and watersheds with existing or new hydraulic structures. All permanent and temporary structures that could significantly affect local flows and bathymetry should be considered. Information should be collected on relevant past and probable future human activities, including:

(a) Modification in land use, especially vegetation type and coverage, farmed areas and agricultural practices, logging areas and practices (e.g. deforestation), urbanized areas (e.g. roughness and impervious cover), storm drainage arrangements, transport networks and characteristics, mining and quarrying activities and their associated deposits.
(b) Modifications in the watershed associated with structures such as dams and reservoirs, weirs and locks, levees and other flood protection structures along rivers, diversions into or out of the basin, flood ways, channel improvements and modifications (e.g. dredging), bridges and transport embankments, and water-related developments (e.g. aquaculture).

3.41. For relevant water control structures, the following information should be collected[21]:

(a) Dates of construction, commissioning and commencement of operation;
(b) The nature and type of the main structures and significant appurtenances (e.g. gates, outlets, main and emergency spillways);
(c) Storage characteristics, data on flood design, and safety factors considered in the evaluation of the maximum, normal and average pool elevation and storage volume;
(d) Dates and nature of significant modifications (e.g. spillway modifications);
(e) Responsibility for administrative and operational control;
(f) Operational history, especially any incidents or failures;
(g) Planned operations in normal and extreme river flows (e.g. flood control);
(h) Hydrographs for design inflows;
(i) Seismic design bases;
(j) The size and location of protected areas;
(k) The effects of the structure on river erosion or sedimentation, debris, and ice effects.

4. EVALUATION OF METEOROLOGICAL HAZARDS IN SITE EVALUATION FOR NUCLEAR INSTALLATIONS

INTRODUCTION

4.1. Nuclear installations are expected to be designed to withstand hazards associated with extreme meteorological conditions and with rarely occurring hazardous meteorological phenomena. The design and continued operation of a nuclear installation should consider the inclusion of parameters for rare and extreme meteorological events, as described in SSR-1 [1]. Meteorological hazards that could affect the safety of nuclear installations are required to be considered throughout the lifetime of the facility (see Requirement 7 of SSR-1 [1]).

4.2. SSR-1 [1] divides meteorological phenomena into extreme meteorological hazards (i.e. identified by extreme values of meteorological parameters derived by analysis from meteorological station data) and rare meteorological events (i.e. a meteorological event that is unlikely to be measured at any specific location because of its very low frequency of occurrence at any single place). These phenomena are unlikely to have their maximum intensity recorded at a given place and might not be observed by a fixed instrument network.

4.3. Extrapolation of observational meteorological data should be used to assess extreme events. However, the extrapolations are limited by the quantity and quality of historical observational data available. Additionally, historical data alone might not fully represent future climate and extreme event conditions due to climate change. For sites that have a limited historical dataset, observational records should be supplemented or extended using climate model outputs or reanalysis data. Recommendations on the use of climate projection data are provided in Section 9.

4.4. Exploratory data analysis should be used to identify the possible non-stationary behaviour of the stochastic process under consideration, which may reflect climatic variability and climate

[21] This information may not be publicly available or obtainable from the operating organization. This may force the use of conservative or bounding assumptions regarding the hazard posed by the water control structure.

change, among other natural phenomena. Criteria for design purposes should describe this possible non-stationary behaviour. Further recommendations are provided in Section 9.

4.5. A description of each meteorological station from which data are obtained and its geographical setting should be included in the report on the analysis performed for evaluating the hazard. This should include a description of the meteorological variables collected and how the data is processed.

4.6. Many of the hazards described in this section might prevent access to the site due to extreme conditions or damage in the surrounding area. Consideration should be given to ensuring both access to the site and access within the for operational personnel and for implementing emergency response actions. Loss of off-site power, along with the loss of communication are possible under certain circumstances. Recommendations on site protection measures and procedures are provided in Section 8.

AIR TEMPERATURE AND HUMIDITY

4.7. Extreme air temperatures and high atmospheric moisture content (resulting in increased enthalpy) could impair the performance of heating, ventilation, and air conditioning systems that maintain environmental conditions of rooms housing items important to safety (especially electronic devices), and could also affect the availability of the ultimate heat sink. (see para. 4.36 of SSR-1 [1]).

Hazard evaluation

4.8. A comparison between the site specific data collected by the on-site measurement programme and data from existing off-site meteorological stations in the region should be performed (see paras 3.8–3.26 for further recommendations on data sources). Such a comparison is helpful to identify stations with long term records for which the meteorological conditions are similar to those for the site. These data should form the basis of the hazard evaluation that is used to determine the design basis temperature(s) and humidity values for the site.

4.9. If a statistical approach is followed, a dataset of daily maximum and minimum air temperatures (representing the extreme recorded temperatures each day) should be collected. This dataset can be used to derive either annual maximum and minimum values (i.e. block maxima method) or temperature values exceeding specified thresholds (i.e. peak-over-threshold method). These data provide the foundation for the statistical analysis Where available, sub-daily air temperature should also be collected. (see paras 2.19– 2.24).

4.10. An analysis of the atmospheric dry bulb and humidity values (e.g. as wet bulb temperature) should be performed for design basis purposes. One method that should be considered is to identify various annual percentile values of dry bulb and wet bulb temperatures[22] that are exceeded on average by the indicated percentage of a year.[23] These annual percentile values may be used for the design of heating, ventilation, air conditioning and dehumidification equipment. Estimates of the duration for which the ambient dry bulb and wet bulb temperatures remain above or below given values (i.e. the persistence) may also be necessary and should be considered in the data analysis.

4.11. For nuclear installations that utilize evaporation-based designs for the ultimate heat sink (e.g. mechanical draft cooling towers), the data set of ambient dry bulb and wet bulb temperature values collected should be used to identify meteorological conditions representing (a) the maximum evaporation potential and (b) the minimum water cooling (e.g. cooling capacity of the cooling tower).

Values of parameters deriving from the hazard evaluation

4.12. The results of a hazard evaluation for extreme air temperature and humidity should include: (a) high dry bulb temperatures and high coincident wet bulb temperatures; (b) high non-coincident wet bulb temperatures, and (c) low dry bulb temperatures. The appropriate extreme temperatures should be derived using statistical, deterministic, or probabilistic methods and if appropriate should be characterized by the annual frequency of exceedance of given thresholds with an associated confidence interval. The duration or persistence of very high or very low temperature and humidity remaining above or below given values should also be considered.

HIGH INTENSITY WINDS

4.13. High intensity winds may be caused by several different meteorological phenomena, such as extended pressure systems[24], certain cumulonimbus cloud formations (thunderstorms and associated downbursts), frontal passage and squall lines, blizzards, foehn wind, tornadoes, air flows induced by gravity (e.g. katabatic winds), regional monsoon winds, and other local phenomena. Some of those phenomena (e.g. tropical cyclones) can produce high intensity winds and torrential rain, as well as high waves and storm surges. Requirements 19 of SSR-1 [1] classifies wind resulting from tornadoes and cyclones as a rare meteorological event, whereas other sources of wind, as discussed in this paragraph, are considered to be extreme meteorological hazards. For many locations, winds resulting from tornadoes or cyclones are the bounding wind speed scenarios. Some locations may have local conditions where the bounding wind speeds result from phenomena other than tornadoes or cyclones. In these instances, these hazards should be considered and described in detail.

Hazard evaluation

4.14. A comparison between the site specific data collected by the on-site measurement programme and data from existing off-site meteorological stations in the region should be performed (see Section 3 for more details on data sources). Such a comparison is helpful to

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[22] Wet bulb temperatures can be calculated from concurrent measurements of dry bulb temperatures, dew point temperature (or relative humidity) and air pressure.

[23] For example, 1.0% and 2.0% values that are exceeded on average for 88 and 175 hours per year for the period of record analysed are typical design conditions. Similarly, 98% and 99% values are cold weather parameters for which the corresponding weather element is lower than the design condition for 175 and 88 hours.

[24] Depending on sources and on national practice or convention, extended pressure systems may also be designated as storms, depressions, cyclones or hurricanes.

identify stations with long term records for which the meteorological conditions are similar to those for the site. These data should form the basis of the hazard evaluation that is used to determine the design basis wind speed value for the site.

4.15. Processing of the data for the evaluation of extreme wind statistics should be standardized for the location of the nuclear installation in terms of: (a) uniform averaging time periods defined in relevant engineering standards, (b) uniform heights and soil surface roughness, and (c) corrections for local topographical effects. If wind data are not measured at the standard height of 10 meters above the ground, then the data should be normalized to this standard height usin g profiles with an adjustable coefficient suited to the local roughness.

4.16. If a statistical analysis is used, the data set of wind speed values should be collected and used to identify the extreme annual values (i.e. block maxima) or values above a certain threshold (i.e. peak over threshold). These data form the basis for the statistical analysis (see paras 2.19– 2.24).

Values of parameters deriving from the hazard evaluation

4.17. Values of parameters deriving from the hazard evaluation are usually necessary for nuclear installation design purposes (e.g. for structural analysis of wind loading SSCs). As necessary, the wind direction coincident with the extreme wind speed values should also be determined. The characteristics from wind-borne missiles should be derived consistent with the estimated wind speeds.

CYCLONES

4.18. For the purposes of this Safety Guide, cyclones include tropical cyclones (cyclones, hurricanes, and typhoons) and extra-tropical cyclones[25]. Requirements 19 of SSR-1 [1] identifies cyclones as a rare meteorological event, which reflects the fact that the most destructive effects are unlikely to be measured at any specific location.

4.19. Paragraphs 4.20–4.31 provide recommendations on the development of a characteristic cyclone wind speed for a nuclear installation site for design basis purposes. Recommendations on the storm surge and the distribution of heavy rains in cyclones are provided in Section 5.

Hazard evaluation

4.20. If the site is subject to the effects of tropical cyclones, a combination of statistical and deterministic approaches should be considered to develop the site parameter wind speeds. In such an approach, the statistical properties of tropical cyclones should be combined with deterministic numerical models to generate thousands of storm track simulations to determine

[25] A tropical cyclone is a warm core, large scale circulation of winds around a central region of low atmospheric pressure. Typhoons are tropical cyclones occurring in the western Pacific Ocean; hurricanes are tropical cyclones occurring in the Atlantic Ocean, the Caribbean Sea, the Gulf of Mexico and the eastern Pacific Ocean. Tropical cyclones can produce extremely powerful winds and torrential rain, as well as storm surge and high wind-driven waves. Extra-tropical cyclones are produced outside of tropical regions and are formed when cold air masses interact with warm air masses on land or sea. In the Northern hemisphere the winds of these cyclone systems deflect to the right, the opposite is true in the Southern hemisphere. An extratropical cyclone can have winds as weak as a tropical depression, or as strong as a hurricane. Examples of extratropical cyclones include blizzards, Nor'easters, and the ordinary low-pressure systems that give the continents at mid-latitudes much of their precipitation.

the wind speed probability distribution for a particular location. The methods for evaluating the parameters for tropical cyclones depend on the results of studies on the structure of cyclones and combine large amounts of data from synoptic networks, satellites and aircraft as well as data obtained from modelling.

4.21. The characteristics of the movement of tropical cyclones and their effects on land and sea are well known. However, it should be taken into account that meteorological measurements at the surface and in the upper air in tropical cyclones are still inadequate in several regions in terms of either area coverage or record period. When a tropical cyclone moves over land, it is usually in a weakening stage, and observations even from a relatively dense land observation network might not be representative of the characteristics of the intense stage of a tropical cyclone as it crosses the coastline. This should be appropriately accounted for and corrected when land-based observations are used.

4.22. High resolution imaging from orbiting and geostationary meteorological satellites should be used, where available from national meteorological services. These images should be used for the detection and tracking of tropical disturbances, the estimation of their intensity and the derivation of the wind field at cloud level.

4.23. Reports from reconnaissance aircraft should be used, where available. Such reports provide important additional information about cyclones. Data from such reports have been used extensively, in conjunction with conventional synoptic data, to help explain the three-dimensional structure of the core regions of tropical cyclones.

4.24. The following data on the storm parameters for tropical cyclones should be collected whenever available:

(a) Minimum central pressure;
(b) Maximum wind speed;
(c) Horizontal surface wind profile;
(d) Shape and size of the eye;
(e) Vertical temperature and humidity profiles within the eye;
(f) Characteristics of the tropopause over the eye;
(g) Positions of the tropical cyclone at regular (preferably six hourly) intervals;
(h) Sea surface temperature.

4.25. For the determination of the 'extreme' values of some variables, the 'highest' or 'lowest' values (depending on the variable) that have been recorded should be ascertained. Since synoptic observations are made at discrete time intervals, some of these values should be determined by the use of special weather reports from land-based locations or ships at sea or additional information derived from synoptic maps. When determining the extreme values for a specific location, consideration should be given to the averaging period by which the data was collected, if applicable.

4.26. Most of the data used for evaluating tropical cyclone parameters are associated with storms over open water and, as such, should only be considered applicable to open coastal sites. For inland locations, the effects of topography and ground friction should be examined and quantified. It should also be taken into account that poleward moving storms generally lose their quasi-symmetrical tropical characteristics and evolve towards the structure of extended pressure systems with well-marked thermal contrasts. In considering the site evaluation for nuclear installations at higher latitudes, modifications should be made to the criteria developed for sites at lower latitudes.

4.27. Despite the availability of aircraft reconnaissance data accumulated over recent decades, certain pertinent tropical cyclones parameters might not be fully measured in each storm. Uncertainty in tropical cyclone parameters should be considered in the hazard assessment.

4.28. In order to determine the applicability of a model for a particular nuclear installation site, the local conditions, the specific characteristics of the site, and the historical data should be carefully evaluated. Whenever possible, case studies should be made to determine the characteristics of tropical cyclones that have traversed the vicinity. Consultation with the national meteorological and hydrological services should be performed to identify the relevant region of study, as well as historical storm paths, based on the climatological record in the site region.

4.29. For extra-tropical cyclones, there are several approaches to hazard evaluation. Wherever densely distributed meteorological stations exist, recorded time-series of windspeeds should be used as the basis for a statistical hazard evaluation at the site. The region to be considered and hence the number of used time series from different meteorological stations depends on factors such as topography, climatology, surface roughness and length of time series. The length of time series for certain meteorological stations should be extended with regional information (e.g. from disbanded meteorological stations) if available and reliably transferable to existing meteorological stations with methods such as kriging. Transfer of the hazard evaluation results from off-site meteorological stations to the site should be performed by wind field calculations.

4.30. If densely distributed meteorological stations do not exist, or as an alternative way to review the results of this kind of analysis, weather models developed for the region under consideration should be used to produce a large number of physically possible weather realizations and thus create a synthetic time series for further assessment. If available, other methods may be employed, but verification and validation of the model(s) and the results should be undertaken, regardless of which method is chosen.

Values of parameters deriving from the hazard evaluation

4.31. The hazard evaluation for tropical cyclones, hurricanes or typhoons should result in an extreme wind speed for a given averaging period and corresponding to an established annual frequency of exceedance. Other features of interest for design, such as the vertical profile of the wind velocity, the duration of the wind intensity above specified levels and wind-borne projectiles should also be described. Cyclone generated projectiles should be specified in terms of their dimension, mass, and velocity.

TORNADOES

4.32. Tornadoes are generally described as violently rotating columns of air, usually associated with a thunderstorm. If tornadoes strike a nuclear installation, damage to structures or equipment may be caused by the following:

(a) The battering effect of very high intensity winds;
(b) The sudden pressure drop that accompanies the passage of the centre of a tornado;

(c) The impact of tornado generated missiles on installation structures and equipment.
(d) The rainfall from tornadic storms may induce local floods and consequently may be the cause of additional indirect damage (see discussion of local intense precipitation in paras 4.44-4.47).

Hazard evaluation

4.33. Tornadoes, which are classified as a rare meteorological event in Requirement 19 of SSR-1 [1], have been documented around the world. Information over as long a period of time as possible should be collected to determine the potential occurrence of tornadoes in the region of the nuclear installation.

4.34. Since the possibility that tornadoes may occur in any region that experiences extreme thunderstorms, a more detailed investigation should be performed to obtain suitable data to assess the tornado hazard, as described in paras 4.37–4.40.

4.35. An intensity classification scheme suitable for the site region should be used (e.g. the Fujita–Pearson, enhanced Fujita scale, the TORRO scale). For most tornado scales, the classification for each tornado is based on the type and extent of damage. Descriptions and photographs of areas of damage provide additional guidance for the classification of the tornado. Consultation with the national meteorological and hydrological services, or other relevant entities, should be performed to access the historical tornado record and to identify the applicable classification scheme.

4.36. The annual frequency of exceedance at which a particular nuclear installation site will experience tornado wind speeds in excess of a specified value should be derived from a study of the tornado inventory. A meteorologically homogeneous region centred at the site[26] should be considered for developing the tornado inventory.

Values of parameters deriving from the hazard evaluation

4.37. The results of a hazard evaluation for tornadoes should be the annual frequency of exceedance at which a particular site may experience tornado wind speeds in excess of a specified value. In the analysis, additional weighting may be given to the most severe tornadoes that have occurred within a smaller area surrounding the site (e.g. within a 50 km distance).

4.38. After determination of the tornado wind speed, a tornado model should be selected to develop the maximum expected pressure drop and the maximum rate of pressure drop. Additional parameters, such as the translational speed, maximum rotational speed, and radius of maximum rotational wind speed, should be considered; these parameters may be important for the structural analysis of the nuclear installation.

4.39. Tornado generated projectiles should be specified in terms of their dimension, mass, and velocity. This can be a standard spectrum from available regulatory guidance, or a site-specific spectrum derived from a site-specific analysis. To protect against the effects of tornado missiles, a spectrum of missiles (ranging from a massive missile that deforms on impact to a rigid penetrating missile) should be considered, thereby providing assurance that the necessary structures and equipment will be available to mitigate the potential effects of a tornado on the

[26] Generally, an area of about 100 000 km^2 is acceptable. However, certain locations may need a larger area of inspection.

safety of the nuclear installation. Tornadoes have a very low frequency at any site; consequently, to be credible, the representative missiles should be common items around the nuclear installation site and should have a reasonable probability of becoming airborne within the tornado wind field.

4.40. Tornado missiles aerodynamics and the resulting impacts on SSCs should be estimated using computational codes[27] designed to analyse these specific phenomena, or alternative methods (e.g., structural/experimental testing, comparison with other load cases).

PRECIPITATION (LIQUID EQUIVALENT)

4.41. Paragraphs 4.42–4.67 provide recommendations on precipitation in the liquid phase, or the liquid equivalent of solid precipitation, and do not discriminate between the solid and liquid phases.

4.42. An extreme precipitation event is a weather occurrence characterized by heavy rainfall, snowfall or other forms of precipitation within a specific period and geographical area. A distinction should be made between extreme precipitation directly over the site (local intense precipitation) and larger watershed rainfall events: flooding at the site may result from either of these scenarios independently or from their combination. Additional details on both flooding scenarios, and the methods used to calculate flood elevations at the site can be found in Section 5.

4.43. Hazard evaluation should be based on long term precipitation data from stations in the site region. An assessment of the regional precipitation regime should be made to identify meteorological stations that have climatological conditions similar to the site and to select those stations most appropriate to provide long term data series for analysis. The selection process should at least include a consideration of micrometeorological characteristics, mesoscale systems and topographic influences. Data from stations equipped with a continuously recording rain gauge suitable for resolving the temporal resolution of rainfall needed for the analysis (e.g. sub-hourly rainfall data is typically needed for site-scale local intense precipitation) should be used, where available. These data should be complemented by weather radar data, where available. Results from long re-analysis model simulations can also supplement local rain gauge data. The complete set of precipitation data should be used to derive extreme values. Consideration should be given to any precipitation data collected in an on-site measurement programme. Precipitation datasets compiled by the national meteorological service are available in some States. The most up to date dataset available should be used, and where necessary, adjusted to include effects of any major storms that have occurred since the datasets were produced.

Hazard evaluation

Local intense precipitation

4.44. External flooding hazards due to a local intense precipitation event occur at the immediate site, regardless of the site's grade elevation or physical proximity to a nearby water body. Local intense precipitation estimates should represent extreme precipitation that could reasonably occur over the site, as opposed to large area precipitation over the watershed in which the site

[27] Examples of existing codes are TORMIS and TONBOS.

is located. These extreme values should be used to inform the design of the nuclear installation (e.g. for the site drainage system and protection from flash floods).

4.45. When local intense precipitation datasets compiled by the national meteorological services or other entities are not available for the occurrence frequencies used in nuclear installation design, extreme values should be obtained from the application of statistical analysis (see paras 2.18– 2.23)[28].

4.46. In cases where there is no continuously recording network in the site vicinity, but where precipitation totals for fixed intervals exist for stations that are climatologically similar to the site, similarity concepts should be considered. For example, 24 hour rainfall totals can be de-aggregated into shorter intervals based on the depth–duration relationship of a nearby gauge. It should be taken into account that de-aggregation to very short time intervals (e.g. less than a few hours) can introduce large uncertainty.

4.47. When the results of the local intense precipitation analyses are reported, a description of the meteorological stations and the climatological and topographical setting should be included. The analysis method applied, along with any adjustment to the data should be reported in conjunction with the results of the analyses. If estimates or datasets from the national meteorological service or other entity were used, this should be documented.

Watershed scale precipitation

4.48. External flooding hazards may be caused by precipitation occurring over the watershed (or a portion of the watershed) in which the site is located (i.e. flooding on streams and rivers). The precipitation may occur upstream of the site or downstream (e.g. backwater effects). Watershed precipitation estimates should be derived using extreme but realistic precipitation estimates that could occur over the catchment area upstream of the site and a sufficient region downstream that takes into account potential backwater effects. Variation in the temporal and spatial distribution of precipitation over the watershed can lead to significant variation in the magnitude and timing of flooding at the site. Precipitation data collected for the watershed should be the basis for the design storm (i.e. precipitation model) used to assess the hydrologic hazard (see paras. 5.87- 5.121).

4.49. The hazard evaluation should use data from stations equipped with a continuously recording rain gauge suitable for resolving the temporal resolution of rainfall needed for the analysis and the watershed under consideration (e.g. hourly to daily rainfall data is typically needed for watershed scale precipitation). These data should be complemented by weather radar data, where available. The complete set of precipitation data should be used to derive extreme values.

4.50. In some watersheds, snowmelt can be a significant contributor to flooding at a nuclear installation site. Data on extreme snowpack in the upstream basins should be collected: this may be available from the national meteorological service or other entities. Data on seasonal accumulation of snow and melt sequences (i.e. impacts of temperature, wind, rain) should be

[28] In some States, extreme precipitation values are defined through the use of existing probable maximum precipitation characteristics that have been generated by the national meteorological service, or other entities, by means of a deterministic approach.

collected. Consideration should be given to the combination of snowmelt and rainfall, which may generate larger floods than either phenomenon alone.

4.51. For large watersheds, sub-basins within the main watershed should be identified (e.g. based on the local meteorological, topographic, and hydrological characteristics), as well as the number and location of stream gauges. Each of these sub-basins may include their own meteorological observation stations, which should be used, in part, to determine the precipitation values for that sub-basin. The observation station selection process should consider all the relevant observation stations that provide precipitation data for the watershed. In practice, meteorologists and hydrologists should collaborate to select the optimal set of sub-basins for a given watershed.

Values of parameters deriving from the hazard evaluation of local intense precipitation

4.52. The local intense precipitation flooding assessment should be based on local intense precipitation estimates (magnitude, duration, and temporal distribution), with the form depending on the type of analysis (i.e. deterministic, statistical or probabilistic). Local intense precipitation estimates typically should have sub-hourly temporal resolution, with durations ranging from several hours to a day (sometimes more). The durations needed will depend upon the site size and topography and should be selected in consultation with the hydrologist performing the flooding assessment.

Deterministic characterization

4.53. For deterministic local intense precipitation flooding assessment, the precipitation input in the form of depth-area-duration or intensity- duration-frequency tables or curves should be provided, from which the hydrologist should develop credible extreme rainfall events (i.e. discrete combinations of magnitude, duration, and temporal distribution that will maximize site-scale flooding).

Statistical characterization

4.54. For statistical local intense precipitation flooding assessment, the precipitation input should be provided in the form of depth-duration-frequency or intensity- duration-frequency curves, from which the hydrologist should develop design rainfall events corresponding to the return period(s) of interest. Depth-duration frequency curves for point rainfall can be constructed by performing a regional frequency analysis of point precipitation observations from a meteorologically homogeneous region surrounding the site.

Probabilistic characterization

4.55. Probabilistic modelling of local intense precipitation flooding should be based on point precipitation frequency curves for durations ranging from 5 minutes to several hours, as well as a set of temporal distribution profiles that can be sampled. Depending on the site configuration, these periods of time typically ranging from 5 minutes up to several hours, and in some cases up to several days.

Values of parameters deriving from the hazard evaluation of watershed scale precipitation

4.56. Watershed scale flooding models should be based on distributed rainfall estimates (rainfall rates or accumulations) over the watershed at regular time steps over the duration of the storm(s). These are typically provided on a gridded basis (i.e. maps covering the watershed), or hyetographs for each sub-basin.

Deterministic characterization

4.57. For deterministic watershed scale flood modelling, the largest credible rainstorm for a watershed of interest (often referred to as the probable maximum precipitation: see Annex VI), should be estimated and used as input for a hydrologic model of the watershed

4.58. The duration and area size of the probable maximum precipitation used should be selected in consultation with hydrologists. For example, the rise time of the flood hydrograph to peak (time of the arrival of the peak flow) from storms over different parts of the basin will inform the selection of probable maximum precipitation duration. In addition, for large watersheds, it should be considered whether it is also necessary to estimate the probable maximum precipitation for sub-watersheds. The selection of sub-watersheds will be determined by the physical characteristics and stream-gauging station locations. For regions where storm characteristics and flooding vary significantly with season, probable maximum precipitation estimates for each season should be considered (e.g. warm vs cold season, rainy vs dry season, hurricane vs non-hurricane season).

4.59. There are two main approaches that should be considered for developing probable maximum precipitation estimates (a generalized or indirect approach and a basin specific or direct approach) with several variations of each approach. The details of these two approaches, including considerations for tropical regions and orographic influences are given in Annex VI.

Statistical characterization

4.60. For very small watersheds, the direct application of point precipitation frequency estimates should be considered as a simple, conservative approach. For larger watersheds, areal reduction factors should be applied to the point rainfall estimates from stations distributed in the watershed to obtain estimates of watershed-averaged precipitation frequency. In general, areal reduction factor relations should be developed for the specific region of interest, and care should be taken with regard to the scale at which they are applied (e.g. for most current areal reduction factor methods, uncertainties grow rapidly with watershed size).

Probabilistic characterization

4.61. Watershed-scale precipitation should be modelled probabilistically via stochastic storm transposition or continuous weather simulation. Stochastic storm transposition is based on a catalogue of storms that have occurred in or near the region of interest. Continuous weather simulation generates synthetic precipitation fields based on seasonal and long term weather forecasts, or regional precipitation statistics.

4.62. In stochastic storm transposition, a catalogue of storms that have occurred within a transposition domain (i.e. meteorologically homogenous region) that includes the site should be developed. The transposition domain should be constructed based on considerations such as the types of precipitation that can occur (e.g. tropical storm rainfall, synoptic scale frontal rainfall, thunderstorms), relative frequency, seasonality, topographic influences, moisture sources). Stochastic storm transposition should then be used to generate watershed-averaged precipitation frequency curves by randomly selecting storms from the catalogue and transposing them to random locations within the transposition domain. The number of random storm events to be generated will be a function of the desired annual exceedance frequency.

4.63. Statistical continuous weather simulation (also known as a weather generator) generates a time series of daily or sub-daily weather variables, including precipitation such that regional statistical properties (derived from observations) such as mean, variance, persistence, and extreme events are preserved. Continuous weather simulation based on ensembles of seasonal and long term weather forecasts have been used to overcome the restraints from short observed time series and expand rainfall time series for further analysis. For usage of such synthetically generated time series it should be confirmed that: (a) the generated data are statistically independent, and (b) the data are representative for the area under investigation.

SNOWPACK

4.64. Snowpack can be defined as the total amount of snow and ice on the ground (including both fresh and old snow) that has accumulated over time at a particular site. The load due to snowpack will depend on both snow depth and packing density. These two parameters can be combined to express snow depth in terms of a water equivalent depth and converted to a load or weight.

Hazard evaluation

4.65. If significant snowfall occurs in the region, an assessment should be made of the snowfall distribution. Remote sensing data taken after snowstorms at the site may be helpful in this task. The variables that should be considered include precipitation rate and snow depth, packing density, and snow cover. Depending on the location of the nuclear installation site, maps depicting the estimated snow load may be available in building codes and standards. This load case should be adapted to nuclear safety practice (e.g. in terms of appropriate exceedance frequency).

4.66. In cold regions where snow on the ground may persist for long periods, caution should be exercised in estimating the design basis snowpack since snow depth and compaction will vary from location to location. The meteorological station selected should be one that has a comparable topographical position to that of the nuclear installation site (e.g. data from a meteorological station on a south facing slope should not be used in considering the siting of a nuclear installation on a north facing slope).

4.67. In mountainous regions where the density of a meteorological network is such that the values measured at a regional meteorological station may differ significantly from the values at the site, a site specific evaluation should be performed. Nuclear installation sites should be evaluated individually, with considerations included for any local factors (such as neighbouring structures and topography) that may have an influence on the snow load.

Values of parameters deriving from the hazard evaluation

4.68. The results of a hazard evaluation for extreme snowpack should include the determination of the water equivalent and the annual frequency of exceedance when relevant. Some locations that rarely experience snowfall events may use a conservative assumption of a snow load based on the regional specific conditions and nuclear installation design.

4.69. Another factor that should be considered in the hazard evaluation for extreme snowpack is the additional weight of the rain on an antecedent snowpack; the water equivalent weight of the snowpack should therefore be supplemented by a rainfall level corresponding to a low frequency of exceedance.

LIGHTNING

4.70. Lightning is a visible electrical discharge most commonly produced in thunderstorms and is classified as a rare meteorological event in Requirement 19 of SSR-1 [1]. Lightning discharges can be positive or negative[29]. Lightning strikes consist of an initial shock and are often followed by long-lasting lightning discharges and/or subsequent shocks. Lightning transients exhibit extremely high voltages, currents and current rise rates.

4.71. Various types of lightning impact should be considered, for example physical damage, live hazard and failure of systems. The potential effects that should be considered include thermal effects (Joule effects), ignition, sparking, insulation breakdown effects (e.g. potential surge effect), mechanical effects (e.g. envelope breakage, mechanical deformation), electrical and electromagnetic effects (e.g. overvoltages, overcurrents), electrochemical effects, acoustic effects and/or visual effects (e.g. flash). The extreme electric field created under certain circumstances produces point discharges and can cause breakdown (a conductive path) in all but the most robust of insulators. Once a path has been established for the return stroke, currents of tens to hundreds of kiloamperes can flow.

4.72. While it is not currently possible to predict the exact time and location that lightning will strike, statistical information should be used to provide an indication of the areas prone to lightning activity as well as the seasons and times of day when such activity is most likely to occur. It should be taken into account that lightning is an unpredictable transient phenomenon with characteristics that vary widely from flash to flash and whose measurement is difficult.

Hazard evaluation

4.73. The lightning strike frequency should be determined, which is the product of the equivalent collection area of the structure or object[30] and the flash density per unit time in the area where the structure is located. In several States, the frequency and severity of lightning strikes evaluated for the site vicinity are provided by lightning detection networks. Additionally, an indication of lightning activity can be obtained from satellite observations of lightning optical transients. Optical transient density data (with sufficient averaging) should be used to as they provide better estimates of ground flash density than thunder observations, which might not accurately capture the relationship between flash density and thunderstorm

[29] Positive lightning is more dangerous than negative lightning because it originates from the tops of thunderstorms and can strike up to 40 km away, making it unpredictable and potentially deadly. It often hits areas far from the storm centre. Negative lightning, while still hazardous, comes from the lower levels of thunderstorms and usually strikes directly beneath the storm in the rain shaft. Its shorter, more direct path makes it more predictable compared to positive lightning. Positive discharges are typically less frequent than negative discharges.

[30] The equivalent collection area for lightning is the hypothetical surface area around a structure or object within which a lightning strike is likely to be intercepted, based on its height, geometry, and surrounding conditions.

hours or days. There are also regional variations in the ratio of cloud-to-ground flashes to total flashes.

4.74. Damage caused by lightning can be extensive; therefore, a sufficiently large area should be considered in the hazard evaluation so that the different effects of lightning on the nuclear installation may be assessed.

4.75. Lightning standards identify different types of natural lightning impulse. For the purposes of site characterization, the following types of impulse should be documented:

(a) First positive;
(b) First negative;
(c) Subsequent lightning strike;
(d) Long term current (charge and duration).

4.76. Lightning can cause various failure modes in the event of a strike on a nuclear installation. Therefore, the following lightning properties should also be documented:

(a) Peak current;
(b) Current rising time;
(c) Time of half value;
(d) Impulse charge (first positive strike);
(e) Specific energy (first positive strike).

4.77. The hazard evaluation for lightning should result in an estimated annual frequency of exceedance for lightning strike[31] for the nuclear installation as well as details on the lightning characteristics listed above.

WATERSPOUTS

4.78. Waterspouts, like tornadoes, can be considered as a rare event because they are unlikely to be measured at any specific location. Waterspouts are generally divided into two categories: tornadic waterspouts and fair-weather waterspouts[32]. Waterspouts can transfer large amounts of water to the land from nearby water bodies.

Hazard evaluation

4.79. The likelihood of occurrence of waterspouts at the site should be assessed. In many States, the national meteorological services, or other entities, identify and record waterspouts to document their intensity and other fundamental characteristics. The national meteorological services are usually informed of waterspouts by a variety of sources such as ships, aircraft,

[31] Some Member states use deterministic methods to define lightning strike parameters. This type of analysis is often used in engineering, safety planning, and in designing lightning protection systems rather than defining the frequency of lightning strikes.

[32] Tornadic waterspouts form over water or move from land to water and have the same characteristics as a land tornado. They are associated with severe thunderstorms, and often accompanied by high intensity winds and waves, large hail and frequent dangerous lightning. Fair-weather waterspouts are generally more prevalent and less intense: they form most in the summer in calm weather. They typically move slowly, if at all, since the cloud they are attached to is static. While many waterspouts form in the tropics, locations farther north (or south) within temperate zones also report waterspouts.

weather observers, the coast guard and the general public. This phenomenon, like many others, can be underreported if there is an insufficient monitoring network.

Values of parameters deriving from the hazard evaluation

4.80. If there is a history of waterspouts in the region, the hazard evaluation for waterspouts should be used to determine the annual frequency of exceedance and the range of intensities. The associated precipitation should be taken into account in the design of the drainage system for the nuclear installation site.

DUST STORMS AND SANDSTORMS

4.81. Dust storms and sandstorms should be considered, where appropriate. They are common in arid and semi-arid regions but can also occur in other regions under drought conditions. The term 'dust storm' is most often used when fine particles are blown long distances[33], whereas the term 'sandstorm' is more likely to be used when, in addition to fine particles obscuring visibility, a considerable amount of larger sand particles become airborne and are blown closer to the surface.

Hazard evaluation

4.82. The likelihood of occurrence of dust storms and sandstorms at the site should be assessed. The frequency of dust storms and sandstorms should be compiled on the basis of hourly weather observations when visibility is 10 kilometres or less, the wind speed exceeds a threshold value (e.g. 5.8 m/s), and relative humidity is below a threshold value (e.g. less than 70%)[34]. Appropriate values of dust or sand concentration (in mg/m^3 air) should be computed on the basis of empirical relationships using visibility observations, empirical correlations of (mean) windspeeds and particle mass, or validated models for mass transport calculations by wind. Where applicable, the combination of dust with other hazards should be considered[35].

Values of parameters deriving from the hazard evaluation

4.83. If relevant to the site, the results of a hazard evaluation for dust storms and sandstorms should be the total dust or sand loading ($mg \cdot h/m^3$), duration (h), and average dust or sand loading (mg/m^3) for the historic dust storm or sandstorm that had the largest calculated time integrated dust or sand loading. In addition, considerations for the possible combination of the expected sand and/or dust loads along with the design basis wind speeds should be performed.

WIND IMPACTS ON HYDROLOGICAL HAZARDS

4.84. For flooding hazards such as storm surge, the dominant forcing mechanism is the marine surface boundary layer wind field. This wind field forcing generates surge, waves, coastal currents, and other storm associated phenomena. Thus, for evaluation of flooding hazards such

[33] Dust from the Sahara Desert in North Africa is periodically observed in European, North American, and Caribbean regions.

[34] The United Nations Office of Disaster Risk Reduction provides the following thresholds to define the intensity of sand or dust storms. 'Light' is defined as having visibility less than 3000m and wind gusts greater than or equal to 20 knots. 'Moderate' is defined as having visibility less than 1500m and wind gusts greater than or equal to 30 knots. 'Heavy' is defined as having visibility less than 500m and wind gusts greater than or equal to 40 knots.

[35] The combination of clay dust with high humidity may impact electrical or electronic systems.

as storm surge (see paras 5.3–5.30), time-dependent two-dimensional wind fields should be used as inputs to a hydrodynamic (i.e. surge and current) model as well as an offshore wave model (in most cases). Wind fields should be developed using a planetary boundary layer model, a reanalysis model or hindcast models (i.e. wind fields developed via analysis of observed storms).

4.85. To estimate other flooding hazards such as riverine flooding or tsunami, coincident wind wave effects should be determined (see paras 5.26–5.44). Coincident wind waves (wind waves coincident with the main flood generating process) should be estimated at the site based on the longest fetch length using a wind speed with an appropriate return period and duration. Thus, data on wind speeds and durations, wind fetch, and orientation near the site should be collected for use in calculations of wind wave effects.

HAIL

4.86. Hail is a form of precipitation consisting of irregular spheres of ice (hailstones) 5–150 mm in diameter. Hailstones consist mostly of water ice. The velocity at which hail falls when it strikes the ground varies with the diameter of the hailstones, the friction with the air and the ambient wind speed. Hail has been known to damage automobiles, structures, and to down trees, potentially resulting in the loss of off-site power to a nuclear installation. Hail also has the potential to block drainage systems and is commonly accompanied by heavy rainfall. Large quantities of hail could potentially clog water intakes and cause damage to exposed SSCs.

Hazard evaluation

4.87. The likelihood of occurrence of hail at the nuclear installation site should be assessed. The frequency of hail events, the size of the largest hailstones, and if available the depth of hail resulting from the event in the site region should be obtained from data records maintained by the national meteorological service or other entities.

4.88. Consideration should be given to the accumulated weight on structures in areas prone to intense hailstorms.

Values of parameters deriving from the hazard evaluation

4.89. If relevant to the site, the results of a hazard evaluation for hail should include the following on the basis of historical records:

(a) An estimate of the maximum hail size;
(b) The depth of hail;
(c) An estimate of the velocity at which hail falls when it strikes the ground.

FREEZING PRECIPITATION AND FROST RELATED PHENOMENA

4.90. Freezing precipitation is a precipitation that falls when the temperature on and above surfaces is below freezing and can occur due to freezing rain, snow, rime and in-cloud icing. The drops freeze upon impact with a surface, resulting in a layer of ice, the effects of which should be considered. These effects include increases in the dead loads and the response of structures, and significant increases in the static and dynamic response to wind action for conductors in transmission lines. Similar, but usually less pronounced, effects occur frequently in steel trusses under winter conditions. In addition, the formation of ice in cooling systems may affect their efficiency.

4.91. The potential for freezing precipitation to cause widespread power outages and a loss of off-site power at the nuclear installation should be considered. There is also the potential that freezing precipitation may led to hazardous conditions at the site, such as slippery or unpassable surfaces, doors becoming frozen in place, or blockages in the air intakes for the ventilation system.

Hazard evaluation

4.92. the likelihood of occurrence of freezing precipitation and frost related phenomena at the nuclear installation site should be assessed. Local records and experience should be considered when establishing the design basis ice thickness and concurrent wind speed; however, very few sources of direct information or observations of naturally occurring ice accretions might be available. Wind, when combined with frozen precipitation, may lead to the accumulation of ice on surfaces that would otherwise be protected. In some States, railway, electric power and telephone company associations have published reports compiling information on the occurrence of ice on utility wires. Other States may have industry standards containing recommendations regarding atmospheric ice loads to be considered in the design of ice sensitive structures.

4.93. In determining the equivalent radial ice thickness from historical weather data, the quality, completeness and accuracy of the data should be considered, together with the robustness of the accretion algorithms.

Values of parameters deriving from the hazard evaluation

4.94. If relevant to the site, the results of a hazard evaluation for freezing precipitation and frost related phenomena should include a nominal ice thickness and a concurrent wind speed.

5. EVALUATION OF HYDROLOGICAL HAZARDS IN SITE EVALUATION FOR NUCLEAR INSTALLATIONS

INTRODUCTION

5.1. Nuclear installations are expected to be designed to withstand the effects of hydrological hazards without loss of capability to perform their safety functions. One or more hydrological hazards and their appropriate combinations may need to be considered depending upon the location of the site (e.g. open coast, estuary, inland near river or lake, inland far from water bodies).

5.2. Recommendations on the meteorological inputs that are needed to address hydrological hazards are provided in Section 4. Recommendations on combinations of hydrological hazards and combinations of hydrological hazards with other types of hazard are provided in Section 7.

STORM SURGE

5.3. Storm surge is the rise of still water surface elevation in near-shore areas of water bodies induced by high intensity winds together with an atmospheric pressure reduction that occurs in conjunction with a severe meteorological disturbance. The hazard evaluation is generally split into three typologies: open coastal area, semi-enclosed body of water, and enclosed body of water. In an open coastal area, the water level rise should be represented by a single peak surge hydrograph that corresponds to the meteorological disturbance that passed over the point under study. In an enclosed or semi-enclosed body of water, such as a bay, lake or harbour, the meteorological disturbance might cause oscillation of the water surface, and a multi-peak surge hydrograph might result. This long period oscillation of the water body is often called a seiche; recommendations on seiches are provided in paras 5.91–5.97.

5.4. When evaluating storm surge hazard, a reference water level, such as tidal cycle (e.g. spring tide or king tide) or high lake level, should be assumed to occur coincidently with the storm surge. In addition, interactions with other concurrent phenomena such as heavy precipitation, river flooding, and wave set-up should be considered, as these combinations may amplify the overall hazard at the site..

5.5. The potential for storm surge at a site should be assessed on the basis of meteorological and hydrological information (both historical and instrumental). If a site has a potential for storm surge, a preliminary assessment should be made. Historical records should be consulted to obtain information such as water levels for storms occurring before the instrumental record period. For the instrumental record period, case studies of severe storms observed in the region should be used to identify the characteristics of the critical storm that would produce surge at the site with a given (sufficiently low) frequency of exceedance, as follows:

(a) Minimum central pressure and associated peripheral pressure (for tropical cyclones);
(b) Minimum pressure (for extra-tropical storms);
(c) Maximum sustained wind speed and its direction;
(d) Wind fetch[36];
(e) Duration of storm and associated winds;
(f) Direction and speed of movement of the storm;
(g) The storm track, and in particular the point at which the storm track is closest to or crosses the coast;
(h) Antecedent water levels (tidal and nontidal).

Hazard evaluation

5.6. For regions subject only to extra-tropical storms, statistical analysis using observed water levels should normally be used for storm surge hazard evaluation. This is because extra-tropical storms can be very extensive and complex, and they are difficult to characterize with a small number of parameters. Conversely, tropical cyclones can be characterized using a small number of parameters and should be assessed using probabilistic or deterministic modelling approaches to estimate water levels at the nuclear installation site.

[36] In relation to wind generated waves, the wind fetch is the maximum unobstructed distance that wind can travel over a water body in a constant direction.

Statistical methods

5.7. To apply statistical methods it should be ensured that reliable storm surge data (for the difference between the predicted tide level and the observed water level) are available covering a sufficiently long period of time and from an adequate number of gauge stations in the region. When calculating the storm surge data, the effect of long term sea level variations in the region should be excluded. The surge data should be available as still water levels, excluding the influence of high frequency waves and astronomical tides. This is normally the case when instrumental surge data for a certain region are available.

5.8. Time series from several locations should be correlated, providing a basis for developing a synthetic time series that is valid over a longer interval than the time span of the local observations. The use of time series from other representative hydrometric stations should be used to broaden the basis of the analysis and make it more reliable.

5.9. Sea or surge levels documented by historical records, if available, should be used: these can significantly extend the data set, even though the uncertainties associated with these data are usually greater. The statistical analysis should then be based on the data from the 'instrumental period' (that usually cover tens of years to one hundred years) and the 'historical period'. The principal information that should be sought for the historical period is the number of events when sea or surge levels exceeded a hight threshold. In some region, the completeness of this data over hundreds of years could be established. Historical data should be used to broaden the basis of the analysis and make it more reliable.

5.10. By working with actual sea or surge levels as basic parameters, the different factors relating to the intensity, path and duration of storms are implicitly taken into account if the records cover sufficiently long periods of time. This approach has advantages and should be applied to the maximum extent possible, especially for regions subject to extra-tropical storms (i.e. which can be very extensive and complex, and difficult to model in a form suitable for the deterministic method).

Probabilistic methods

5.11. Probabilistic storm surge hazard evaluation should be used to construct a relationship between the surge levels and their corresponding annual exceedance probability. The joint probability method[37] is the probabilistic approach most widely applied to storm surge. There are several variants of this method, which mainly differ in how the joint probability method characteristics are modelled, and how the joint probability method integral is evaluated.

5.12. The joint probability method integral should be used to develop joint probability method surge (storm response) hazard curves. This integral encompasses all possible values of the storm parameters via their distributions, instead of using only discrete storm events in the record. So it is valid for extremes, although necessarily dependent on the accuracy of the parameter distributions.

[37] The joint probability method approach assumes a parametric storm description involving five or six TC descriptors. Foreach of the storm parameters, (potentially dependent) probability distributions are developed via studies of historical storms and the regional storm climatology. These distributions are each discretized and sampled parameter combinations (each defining a synthetic storm) are simulated with a high-resolution hydrodynamic model using the bathymetry, topography, and land cover of the study site to simulate the storm surge response.

5.13. The tropical cyclone forcing for hydrodynamic modelling should be defined by the wind field at the sea–air interface and the inner-core sea level pressure and gradient. The wind field is typically represented by the 10 m elevation speed and direction at 30 minute time intervals. Storm surge typically increases with storm size, with the effect typically enhanced on gradual ocean bottom slopes. The probability analysis should be used to determine the marginal or conditional distributions of storm parameters, based on analysis of historical tropical cyclones. The small sample size typically associated with tropical cyclones in most coastal regions increases the uncertainty associated with fitting distribution to the parameters; consequently, bootstrap resampling methods should be applied to develop the values of the distribution parameters.

5.14. The most commonly applied distributions for central pressure are the Gumbel extreme value distribution and the truncated Weibull distribution. The storm translational speed is typically fitted with lognormal or normal distributions. Some studies have modelled a dependence between forward speed and intensity, fitting different distributions to high- and low-intensity storms.

5.15. Variant joint probability methods use different methods to discretize and sample from the probability distributions. Uniform discretization with Monte Carlo sampling should be considered: it is the most straightforward approach, but it can be computationally expensive. As a result, joint probability method optimal sampling methods have been developed to minimize the number of storm simulations needed.

Deterministic methods

5.16. The use of deterministic methods should also be considered to estimate the maximum water elevation for the hazard evaluation for storm surge. To compute the maximum storm surge elevation using a deterministic method, a set of credible maximized hypothetical storms should be constructed taking into account the information, knowledge and results from the evaluation of meteorological hazards. These maximized hypothetical storms should be placed at locations such that they produce maximum high-water effects on the proposed site. The application of a deterministic method is not a unique process but is a combination of procedures of transposition, maximization and estimation in which the hydrologist and the meteorologist should apply their expert judgement. This procedure is readily applicable to tropical cyclones but might present some difficulties in its application to extra-tropical storms. The procedure should include the selection of the probable maximum storm to be used for evaluation of the surge and an evaluation of surges for open coastal regions as well as for semi-enclosed and enclosed bodies of water.

5.17. The analysis should consist of selecting appropriate storm parameters and other relevant parameters (e.g. maximum wind velocity, atmospheric pressure differential, bottom friction and wind stress coefficients) to be used as inputs to a one-dimensional or two-dimensional storm surge model that maximizes the flooding potential. All parameters should be conservatively evaluated and should be justified.

5.18. The storm surge analysis should provide the following as outputs:

(a) Over-water wind field and pressure gradients for the initial position of each storm and for specified later times;

(b) Summary of storm surge calculations, including the total increase in water depth at each specified traverse depth, starting with ‘deep water’[38] and continuing to shore at the initial time and at specified later times;
(c) Summary tables and plots of the total storm surge hydrographs for specified locations.

Deterministic method - open coastal regions

5.19. An appropriate validated hydrodynamic model should be selected for calculating the storm surge elevation. A two-dimensional model should be used (with the possible exception of long narrow geometries such as surge propagation in a tidal river). The outcome of the meteorological analysis should be an extreme wind field and pressure gradient. This should then be transposed along various tracks with an optimum forward speed for surge generation to determine the most extreme surge for a particular location.

5.20. It is possible that the cyclone or extra-tropical storm generating the peak water level for the storm surge elevation might not represent the critical conditions for design. Other cyclones or storms may generate lower peak surges but may cause high water levels of longer duration or may produce higher wind speeds and waves. The wave activity associated with these cyclones or storms could conceivably produce higher design basis water levels. Also, for nuclear installation sites located within a bay, cyclones or storms that would generate peak surges that are lower but of longer duration on an open coast could generate higher peak surges and more severe wave conditions within the bay, resulting in higher design water levels. Hence cyclones or storms other than those generating the peak open coast surge, but that could produce effects such as those just described, should be considered.

Deterministic method - semi-enclosed bodies of water

5.21. For analysing storm surges in semi-enclosed bodies of water, the open coast surge should be evaluated first, and then routed through the entrance and up the bay or river to the nuclear installation site using a numerical model. The combination of parameters generating the highest open coast surge does not necessarily generate the highest surge at a site located on a bay or estuary; however, there exists a critical set of parameters, particularly the direction of the storm and its translational speed as it travels up the bay or river, which will generate the surge elevation at the site. For evaluating the water movement in a semi-enclosed basin, a two-dimensional transient hydrodynamic analysis should be used to capture bathymetric variations and wave reflections within the basin. The parameters selected for use in the numerical models should be conservatively selected or evaluated.

5.22. For sites located on bays with low beach berms and low marshes, overtopping of the beach berms together with flooding is possible. Open coast surges with longer duration, but lower than maximum peaks, may generate the highest surge elevations at such sites. The erosion of beach berms and bay entrances, which might worsen flood conditions, should also be taken into consideration for semi-enclosed bodies of water.

5.23. The results of the surge analysis for a semi-enclosed body of water should include the calculated time histories of the associated open coast surges, discharges of water through the

[38] ‘Deep water’ is water of a depth greater than L/2, where L is the wavelength of the surface wave under consideration.

entrance, surge profiles up the bay or river, contributions of wave setup[39] due to cross winds and, if applicable, contributions due to runoff and river flow.

Deterministic method - enclosed bodies of water

5.24. For enclosed bodies of water, the storm surge is generally associated with oscillations of the water surface (i.e. seiche). The methods described in paras 5.86–5.92 should be used to compute both the surge hazard and seiche in enclosed bodies of water.

Values of parameters deriving from the hazard evaluation

5.25. Results from the surge analysis should include estimates of the maximum still water[40] elevation (deterministic methods) or a distribution of still water elevations with a corresponding annual frequency of exceedance (probabilistic methods).

WIND GENERATED WAVES

5.26. Wind over a water body such as ocean, sea, lake, estuary, river or canal develops wind generated surface waves, with typical wave periods of 1–15 s, including swells. These waves can vary in size and shape depending on parameters like wind speed, duration and the fetch (i.e. the distance over which the wind blows). Due to bottom friction, the depth of water has a great influence on wave propagation and wave height when the wave approaches the shore or bank. Waves are referred to as offshore waves, where the water depth is such that the bathymetry does not affect the wave characteristics. Where the water depth is lower, waves are referred to as near-shore wave. When the water depth is less than 5% of the wave length, the waves are called shallow water waves.

5.27. Wind-generated waves can directly impact structures and transport significant volumes of water onto the nuclear installation site (e.g. overtopping, swash, splash). These effects should be appropriately addressed in the hazard evaluation.

5.28. Wind generated waves should be addressed coincidently with high water levels in the considered water body (e.g. due to tides, surge, riverine flooding) since it is not appropriate to superimpose the partial effects linearly.

5.29. It should be taken into account that both the wave height and the period will vary depending on the wind speed, duration, direction, and fetch. If wind wave characteristics are computed from the wind data, the hourly averaged wind speed and direction should be used.

Hazard evaluation

5.30. To determine the wind wave effects near the nuclear installation site, the offshore wave characteristics, such as wave spectra or wave height, period, and direction, should first be determined on the basis of the generating wind field or a statistical study of observed or numerically simulated offshore waves. Next, near-shore wave characteristics, resulting from

[39] The 'wave setup' is the temporary buildup of water level at a beach due to breaking waves, which is to be added to the surge height.

[40] Use of the term 'still water' does not imply that the water is quiescent. Rather, the term is used to define the results of a hazard evaluation before wind–wave or other hazard effects have been combined to produce the design basis parameter for the site (see Section 6).

the transformation of offshore waves, should be evaluated. These wave characteristics, together with the resulting wave forces and overtopping volumes, should then be evaluated for the structures on the site that are important to safety. From wave spectra, the characteristic wave height and period should be estimated. Wave heights referred for designs are generally characterized by the significant wave height and the 1% wave height[41].

5.31. The effects of wind waves at the site that should be considered include both the force associated with the waves as well as any local flooding that may occur. Additionally, the overtopping of berms and/or levees, including by sea spray, should be considered.

Wind field

5.32. To evaluate wind waves, the wind field generating the waves should first be characterized in terms of wind speed, wind direction, duration and fetch.

5.33. The wind speed should be evaluated using deterministic or statistical approaches, as described in Sections 2 and 4. The wind fetch and the appropriate wind orientation should be assessed by studying the regional meteorology and the characteristics of high intensity winds to determine conservative values for the site. For water bodies such as estuary, lake or river, the wind fetch should be assessed considering the extension of the geometry of water body due to the coincident high-water level. If the wave is to be considered jointly with storm surge, a storm similar to the one generating the surge can be regarded as establishing the wind field in order to use consistent storm parameters for the generation of waves and surge.

5.34. When using a deterministic approach to establish the conservative wind field, wind vectors along the selected wind fetch should be calculated for various times during the high intensity winds that might affect the nuclear installation site.

Generation of offshore waves

5.35. The offshore wave characteristics should be deterministically analysed from the wind field selected. In applying simplified methods for such an evaluation, the wind should be assumed to be unidirectional. These methods are based on semi-empirical relationships and use as input the wind fetch, speed and duration. Where these assumptions are not valid, a two-dimensional spectral wave model should be applied. Available historical data (data observed, 'hindcast' (as opposed to forecast) and/or measured, including satellite data) on extreme waves for the region should be reviewed to verify the results of the analysis of offshore wave characteristics.

5.36. Offshore wave characteristics should be statistically evaluated if reliable offshore wave data are available and cover a sufficiently long period of time. Available data from observations (e.g. data from tide buoys, satellite measurements) on the wave characteristics for the region near the nuclear installation site should be incorporated into the analysis. If observation data for a sufficiently long period does not exist, numerical hindcast data or conservative deterministic values can be used alternatively. However, the prediction accuracy of the hindcast data should be carefully checked. An extrapolation should then be performed to compute the significant wave height for the chosen annual frequency of occurrence by using appropriate

[41] The significant wave height H_s is the average height of the upper third of the wave heights in a wave record; the 1% wave height H_1 is the average height of the upper 1% of the wave heights in a wave record. The approximation $H_1 = 1.67\ H_s$ is used in some States.

statistical methods. Since wave heights and wave periods are correlated, an empirical relationship can be used to determine the wave period on the basis of the wave height for the chosen annual frequency of occurrence.

Near-shore waves and interactions with structures

5.37. As the offshore waves travel to the near-shore area of the site, they will undergo dissipation and nonlinear effects owing to changes in water depth, interference from islands and structures and other factors, and the additional input of energy from the wind. The transformation and propagation of these offshore waves to the near-shore area should be assessed. For situations with a regular bathymetry and shoreline, use of semi-empirical models may be warranted. However, for situations with more complex geometry, a two-dimensional numerical model or a physical model should be employed.

5.38. The wave phenomena that should be considered include friction, shoaling, refraction, diffraction, reflection, breaking and regeneration. Wave calculations should also cover local water current structure and local winds.

5.39. The near-shore waves that might have an impact on the design of the nuclear installation should be identified by comparing the histories of various wave heights of incident deep water waves, transition water waves, shallow water waves and limiting breaking waves, with account taken of the still water hydrograph for the storm surge.

5.40. Available historical data on observed extreme waves for the region should be reviewed to verify the results of the analysis of near-shore waves.

5.41. For each SSC important to safety that is potentially exposed to wave action, the characteristics of the design wave in front of the structure should be evaluated. A two dimensional model should be used for the analysis. This evaluation should consist of:

(a) Selection of an appropriate spectrum of incident waves in deep water, the upper wave limit (wave height, period), wave transformations from deep water to the structure, the duration of the waves interacting with the structures, and a sensitivity study of the numerical model parameters including wind and wave direction.
(b) Evaluation of any additional increase in the computed still water level for a storm surge from such effects as wave setup[42]. The extra water setup will further increase the wave heights.

5.42. Wind wave effects that should be considered in the hazard evaluation process include: wave runup along the structures, overtopping of embankments, and sea spray. These effects should be estimated by using semi-empirical methods; however, the applicability of the methods should be verified for the specificities of the site, including the use of physical models.

5.43. The hydrostatic and hydrodynamic loading on structures important to safety should be evaluated. For the given site conditions, the entire range of water elevations that are expected to occur should be evaluated since it is possible that the maximum loading conditions may

[42] The 'wave setup' is the temporary buildup of water level at a beach due to breaking waves, which is to be added to the surge height.

occur at a time other than that of the maximum flooding. The duration of wave loading should also be computed for design considerations.

Values of parameters deriving from the hazard evaluation

5.44. Results from the wind wave analysis should include estimates of the increases in water level due to wind wave activity that are to be superimposed on the still water level. Wave runup height along the beach and/or structure related estimates should be determined as part of the hazard evaluation. Runup height is dependent on the wave characteristics (e.g. wind speed, wind duration, water depth and wave fetch length), offshore bathymetry, geometry and surface roughness of the beach and/or structure. Relevant parameters (e.g. wave kinematics) associated with dynamic effects of the interaction of wind waves with structures should also be considered. Wind waves can lead to the overtopping of protective structures. The overtopping water volumes should be estimated for each fetch, taking wind direction into account. The choice of formulae or methods used for the overtopping calculation should be justified (e.g. scope of validity, unfavourable nature of the result). The method used to take account of the effect of wind on the overtopping flow rates should 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).

TSUNAMI

5.45. A tsunami is a series of travelling waves of long wavelength (e.g. from kilometres to hundreds of kilometres) and period (e.g. several minutes to tens of minutes, and exceptionally hours), generated by deformation of the sea floor (or, in generic terms, underwater floor) or disturbance of the sea surface. Earthquakes, volcanic phenomena, underwater and coastal landslides, rock falls or cliff failures can generate tsunamis. Large meteorites[43] may also impact the ocean and generate a tsunami. It should be taken into account in the hazard evaluation that all oceanic regions and sea basins of the world — and even fjords and large lakes — can be affected by tsunamis.

5.46. Tsunami waves propagate outward from the generating area in all directions, with the main direction of energy propagation determined by the dimensions and orientation of the generating source. The hazard evaluation should take into account the following:

(a) During propagation of the tsunami in deep water, waves proceed as ordinary gravity waves with a velocity depending on the depth of water. In deep ocean, the velocity can exceed 800 km/h, with a tsunami height generally less than a few tens of centimetres and (in the case of earthquake source) with wave lengths often exceeding 100 km.
(b) During the propagation, bathymetry affects the speed and height of the tsunami wave. Refraction, reflection from a sea mount or its chain (archipelago) and diffraction are important factors affecting the propagation of tsunami waves in deep water.
(c) When tsunami waves reach the coastal zone, they produce hazardous effects near and on the shoreline. The wave speed is reduced and the wavelength is shortened when the depth decreases; consequently, waves become steeper and increase in height on approaching shallow water.

[43] For meteorite induced tsunamis, assessments conducted to date do not demonstrate that the frequency of occurrence exceeds the screening level usually adopted.

(d) In the coastal zone, local topography and bathymetry (e.g. a peninsula, submarine canyon) may cause an additional increase in tsunami height. Tsunami height could also be increased by the presence of a bay, estuary, harbour or lagoon as the tsunami moves inland.

(e) Several large waves could be observed; the first one might not be the largest. A recession of the sea has been observed in many cases before the first wave and between each consecutive flooding. A tsunami could cause inland inundation because its wavelength is so long that a huge mass of water follows behind the wave front. Propagation along the rivers towards inland is also common.

5.47. Other hazardous effects of tsunami waves that should be considered are strong currents in harbours and bays, bores in rivers, estuaries and lagoons, and wave forces. Sedimentation phenomena — including deposition and erosion (including scouring) — resulting in effects on water intakes and on the tsunami run-up path to the site, should also be considered. Suspended sediment entrained into seawater might cause the loss of function of cooling water pumps (i.e. if the sediment concentration is higher than the limit of the operating concentration of the pumps). The effects of water-borne debris should also be considered, such as physical damage due to debris collisions, prevention of accident management due to damming of access route, and fire due to oil-mixing debris. Lowering the water level can affect the water intake function.

5.48. Earthquakes are the most frequent source of tsunamis. An earthquake induced tsunami is generated by a seafloor deformation associated with submarine and near-coast earthquakes with shallow depth (e.g., < 50 km), large magnitude (e.g., M > 6.5) and dip–slip mechanism. Strike–slip fault motion produces a small vertical deformation of the sea floor, and consequently the induced tsunamis are usually of smaller height. The potential for tsunamis from both types of seismic event should be considered in site evaluation.

5.49. Tsunamis may be generated by volcanic phenomena when voluminous (e.g. 10^6 to greater than 10^9 m^3) landslides, pyroclastic flows or debris avalanches rapidly enter the sea or large lakes, or by the eruption of underwater volcanoes. Collapse of a volcano edifice triggered by a volcanic eruption or an earthquake may lead to large displacement of the slopes, which in turn can generate tsunamis in proximal bodies of water. Since steep sided volcanoes are unstable structures, any such volcano located near water or underwater should be considered as a potential source of tsunamis.

5.50. Submarine debris avalanches could potentially result in basin wide tsunamis. In addition, even moderate eruptions at island volcanoes have generated tsunamis, although generally it is larger, explosive eruptions that provoke these effects in extreme cases. The most frequent causes of volcanic phenomena induced tsunamis are pyroclastic flows and landslides. The generation mechanism of the most hazardous volcanic phenomena induced tsunamis is the collapse of the caldera. When the caldera collapses, the original volcano up to several hundreds of metres collapses suddenly, causing sudden subsidence of water and a rush of surrounding water into the cavity. The atmospheric pressure wave due to a volcanic eruption can also generate and develop a tsunami. Underwater and coastal (subaerial or subaerial–underwater) landslides, rock falls and cliff failures may also generate tsunamis, some of which are locally more disastrous than earthquake induced tsunamis. These landslides might or might not be triggered by an earthquake or by volcanic activity. All of these phenomena should be considered in terms of their potential to affect the safety of a nuclear installation.

5.51. Meteo-tsunamis generated by meteorological sources such as spatial and temporal change of large-scale atmospheric pressure disturbances should also be taken into account in the hazard evaluation of the site.

5.52. Tsunamis can also be classified as near field tsunamis or far field tsunamis. A tsunami is called a near field tsunami when it affects only the region near its source. Near field tsunamis can be generated by earthquakes, volcanic activity and landslides. Earthquake induced near field tsunamis represent the most frequent type of destructive tsunami. Less frequent, but affecting wider regions, are ocean wide or far field tsunamis that arrive at places remote from their source after travelling across the ocean or sea basins. Massive landslides and volcanic collapses (see para. 5.50), such as those associated with the flanks of growing volcanoes, can also generate far field tsunamis.

Initial assessment

5.53. As an initial assessment, a simplified screening criterion should be applied (see Fig. 1). Using publicly available information (see para. 3.35), evidence of past occurrences of tsunamis should be reviewed for the site region. The evidence should be collected as far back in time as possible. For this purpose, the information collected should be organized and a list of tsunamis relevant to the nuclear installation site should be prepared. No further investigations and studies need to be performed to analyse the tsunami hazard for the site provided that all of the following conditions hold:

(a) The site is located in an area that shows no evidence of past occurrences of tsunamis; and
(b) The site is located more than 20 km from the sea or ocean shoreline[44], or more than 1 km from a lake or fjord shoreline, as appropriate; and
(c) The site is at more than 50 m elevation from the still water level at the sea, the lake or the fjord.

In all other situations, a detailed hazard assessment for tsunamis should be performed as recommended in paras 5.57–5.65.

5.54. Low water level as a result of a tsunami can affect the intake water system for several hours; therefore, the necessary volume of cooling water should be secured in all cases.

Detailed assessment

5.55. The first step in conducting a detailed assessment of the tsunami hazard at a nuclear installation site should be to compile a specific tsunami catalogue and/or database relating to the site. This should be done in accordance with the investigations described in paras 3.34–3.36 to establish whether or not past or recent tsunami events have occurred in the site region, and if so to characterize them (see Fig. 2).

5.56. The potential for both near field and far field tsunamis should be investigated. The occurrence of underwater and near shore seismic or volcanic activity in the site region (about 1000 km distance) should be regarded as an indication of the possible occurrence of near field tsunamis at the site. Also, given that large tsunamis can be generated in remote regions, an evaluation of the potential generation of far field tsunamis should be performed for all

[44] In rivers, tsunamis can propagate over 10 km upstream from the sea.

seismogenic sources existing in and around the specific sea or ocean basin where the nuclear installation site is located.

5.57. If the specific studies and investigations performed and compiled in the geological, geophysical, seismological and tsunami databases demonstrate that there is no potential for the occurrence of tsunamis at the site, no further assessment of the tsunami hazard may be necessary. The potential of tsunami generation should be determined by taking into account scientifically sound extrapolations for any further assessments.

5.58. If, however, a potential for the occurrence of tsunamis at the site is suggested and demonstrated, as a second step, a site specific tsunami hazard evaluation should be performed that includes a detailed numerical simulations to derive the design basis tsunami.

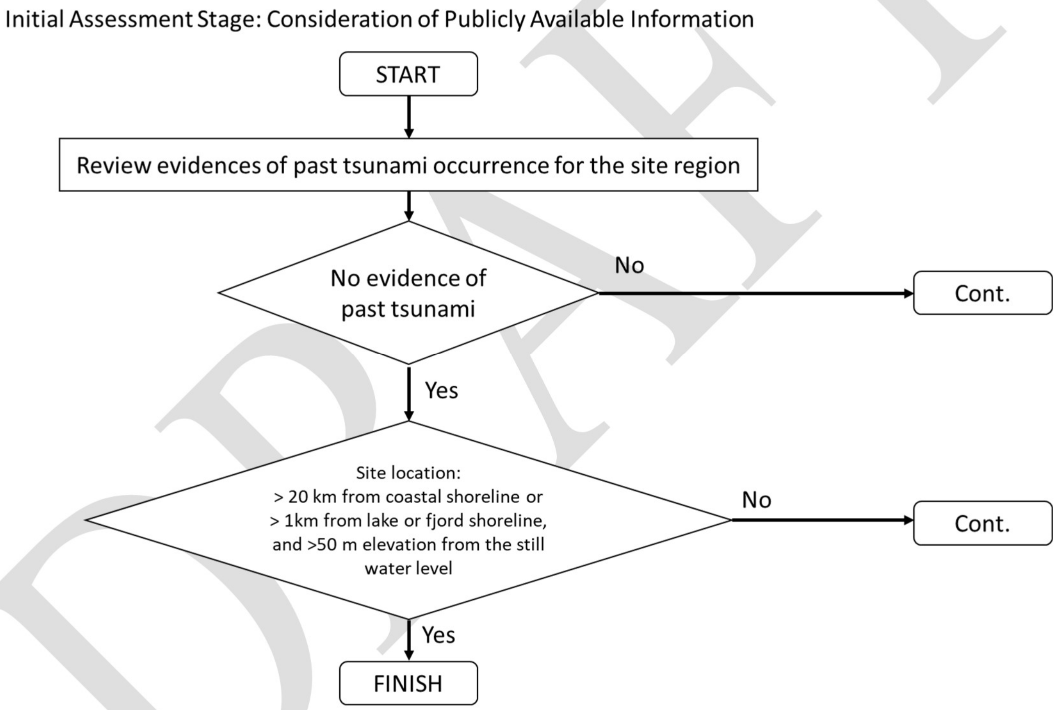

FIG. 1. Flowchart of initial assessment of tsunami flooding.

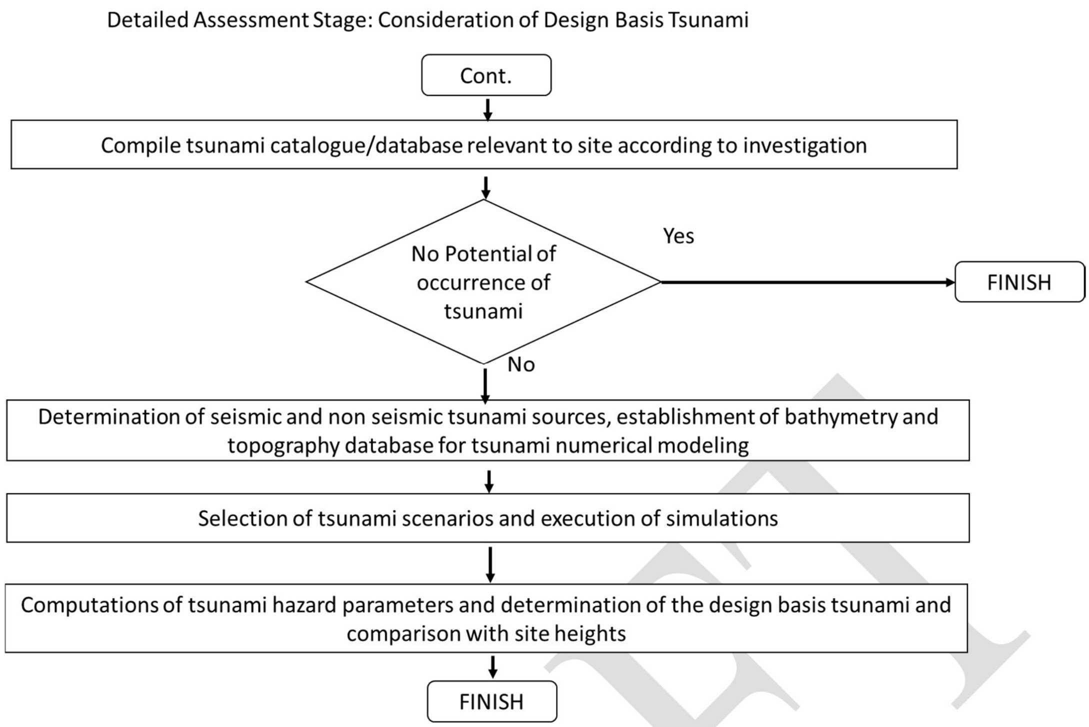

FIG. 2. Flowchart of detailed assessment of tsunami flooding.

5.59. For assessing the tsunami hazard for all types of tsunami source, the numerical simulations should cover the generation, propagation and coastal processes, with appropriate initial conditions and boundary conditions, and with high resolution bathymetry and topography data including buildings with corner coordinates and elevations, if possible. Tsunami sources are categorized seismic and non-seismic tsunamis. Depending on the relationship between the sources, the generation of tsunamis by a combination of them should be considered.

5.60. For an initial condition for earthquake induced tsunamis, the elastic model of the earthquake source should be used to provide the sea floor deformation due to the earthquake. This is then used as the initial water wave field. For landslide induced and volcanic phenomena induced tsunamis, the generation mechanisms are fundamentally different from that for seismic sources, with much longer duration. For this reason, the dynamics of interactions between sources and water waves should be considered.

5.61. The long wave or shallow water theory, integrated from the sea floor to the water surface, should be applied for solving propagation, coastal amplifications including runup/ drawdown and coastal inundation. The non-linear and bottom friction terms can be neglected for deep water (more than 100 m) but should be considered for shallow water area (less than 100 m). For such tsunami simulations, two-dimensional non-linear or linear shallow water equation models should generally be used. For small scale sources or long distance propagation over gentle gradient seabed, the dispersion effect with wave frequency may need to be considered. For these cases, either two-dimensional Boussinesq equation type models or three-dimensional computational fluid dynamics should be used.

5.62. The resolution and accuracy of the near-shore bathymetric and topographic data obtained as described in Section 3 (see paras. 3.37 and 3.38) have a substantial effect on the computed results. The spatial grid size should be small enough to represent properly the coastal and underwater morphology near the site. Spatial grid size, time steps and connecting borders between meshes of different size should be specified to provide stability to the numerical computation.

5.63. The high tide and low tide levels as well as long term sea level rise should be considered in the numerical simulation.

Hazard evaluation for earthquake induced tsunamis

5.64. For earthquake induced tsunamis, the hazard should be evaluated by using either a deterministic hazard analysis or a probabilistic hazard analysis, or preferably both methods. The choice of the approach will depend on a number of factors. Whichever method is used, a quantitative estimate of the uncertainties in the results of the hazard evaluation should be determined.

5.65. The overall uncertainty will involve both aleatory uncertainty as well as epistemic uncertainty that arises owing to differences in interpretation of tsunami sources and runup heights by informed experts. Such interpretations should be treated in the tsunami hazard analysis in a consistent manner, providing for a suitable representation of current thinking on tsunami sources, propagation modelling and coastal processes. Care should be taken to avoid bias in these interpretations. The project team for the evaluation of tsunami hazards should not promote any one expert hypothesis or model. It should evaluate all viable scientifically accepted hypotheses and models using the data compiled and then should develop an integrated evaluation that incorporates both knowledge and uncertainties.

5.66. Some of the data that are used indirectly in the evaluation of tsunami hazards might not be site specific; for example, the seismogenic data used to characterize the generation mechanism of distant sources. There may therefore be a part of the uncertainty that is irreducible with respect to site specific investigations.

Deterministic methods

5.67. A numerical simulation performed using a deterministic approach[45] should be based on the following steps:

(a) Build and validate the numerical simulation model on the basis of experimental or/and theoretical benchmark problems and records of observations of past tsunamis:

   (i) Evaluate the significant past tsunamis (i.e. in the instrumental or historical record or from paleo-information) in the near field and far field that have affected the site region;
   (ii) Identify and validate the corresponding runup and draw down heights (and inundation distance if known) in the coastal region near the site by considering the historical topography and bathymetry;
   (iii) Identify the corresponding seismogenic fault parameters or relevant non-seismic source parameters;

[45] The current practice in some States is included in Annex II.

(iv) Construct and execute the numerical model including generation, propagation and coastal processes for all selected historical and past tsunamis;

Compare the simulation results with the historical runup heights and runup from past tsunamis (if known);

(v) Adjust the model as necessary.

(b) Apply the numerical model to estimate seismogenic sources and the associated fault parameters (and non-seismic sources and parameters, if applicable) for the evaluation of tsunami hazards:

(i) Select seismic sources for both near field and far field tsunamis and identify the related fault parameters and their range of variation;
(ii) Determine applicable seismic tsunami scenarios in accordance with the seismogenic sources identified in (i);
(iii) Determine non-seismic tsunami sources and applicable scenarios;
(iv) Perform the numerical simulations for applicable tsunami scenarios and obtain the tsunami hazard parameters at the nuclear installation site;
(v) Check the high and low water levels at the site and at critical points (e.g. intake and discharge structures, flood protection structures, doorways or other openings) for each scenario. For the low water level, estimate the maximum duration for which the water intake function doesn't work. In addition to water levels, estimate other natural hazard parameters such as water velocities and hydrodynamic forces on key structures, sediment erosion and deposition, and waterborne debris.

5.68. The following uncertainties should be taken into account (both the aleatory and the epistemic part should be estimated when relevant):

(a) Uncertainties with regard to the tsunami source;
(b) Uncertainties in the numerical calculation;
(c) Uncertainties in the bathymetry and coastal topography.

It is difficult to estimate each of these uncertainties quantitatively. Furthermore, it is also difficult to select one tsunami source among all the potential tsunamis examined. A large number of numerical calculations under various conditions within a reasonable range of parameters (a parametric study) considering seismic and non-seismic tsunamigenic sources should therefore be performed to take uncertainties into consideration.

5.69. For seismic sources, a parametric study of the dominant factors of the fault model should be performed by considering the characteristics of earthquakes in each seismic zone. The factors for a parametric study should be selected appropriately from among the fault position, length, width, depth of upper edge, strike direction, dip angle, slip angle or combination of segments. The range of the parametric study should be set within reasonable limits. If statistically based fault model factors are available, the range of the parametric values should be adopted from the standard deviation. Note that for megathrust earthquakes of Mw 8-class or greater[46], the tsunami should be numerically simulated using a non-uniform slip model.

5.70. From the set of simulations performed, maximum runup and drawdown heights, flow velocities, inundation distances, drawdown durations, and inundation durations should be

[46] Such as those associated with the 2004 Indian Ocean tsunami and 2011 Tohoku earthquake and tsunami.

identified. As the last step, these hazard parameters should be compared to any available information from past tsunamis to verify that they are bounding and to identify the available margin.

Probabilistic methods

5.71. Probabilistic methods for the evaluation of earthquake-induced tsunami hazards have been applied by some States. The evaluation approaches are analogous to probabilistic seismic hazard evaluation. By adopting logic-tree approaches, both epistemic and aleatory uncertainties should be systematically incorporated into tsunami hazard evaluations.

5.72. The results of the probabilistic tsunami hazard evaluation should be the mean or median annual frequency of exceedance of runup and draw down elevations. Additionally, values that can indicate the width of the uncertainty of results should also be determined (e.g. both 5% and 95% fractiles). Mean or median annual exceedances and uncertainty bounds for other hazard parameters (e.g. duration, flow velocities) should also be determined.

5.73. The general approach to the probabilistic evaluation of tsunami hazards should be directed towards appropriate quantifications and modelling of the uncertainties at various stages of the evaluation process to obtain reliable results driven by data. Experience shows that the most effective way of achieving this is to collect a sufficient amount of reliable and relevant data supplemented with expert opinions. There is generally a trade-off between the time and effort necessary to compile a detailed, reliable and relevant database and the degree of uncertainty that the analyst should take into consideration at each step of the process.

Hazard evaluation for submarine landslide induced tsunamis

5.74. Landslide sources for submarine landslide induced tsunamis should be characterized using the maximum volume parameter, as determined from sea floor mappings or geological age dating of historical landslides. A slope stability analysis should be performed to assess the potential capacity for tsunami generation of the candidate landslides. Also, a method to identify the location prone to submarine landslide e.g. slope gradient map of bathymetric data, material characteristics and other available data should be included.

5.75. Owing to the insufficiency of data for probabilistic analysis in most regions, deterministic methods are usually used for hazard evaluation for landslide induced tsunamis[47]. The source parameters of the analysis are the dimensions and geometry of the landslide, and the speed and rheology of the falling material. The numerical model should couple the landslide with the resulting water motion.

5.76. Owing to the small size of a source in comparison with that for an earthquake induced tsunami, the impacts of a landslide induced tsunami are generally limited around the source but sometimes they are observed at more than several tens of kilometres from the source. The impact of a landslide tsunami around the source will depend mainly on the slope gradient map of the bathymetric data near the coast and bathymetric data up to e.g., the continental shelf is necessary to take into account the landslide sources. If the landslide source is near the coast, then the tsunami effect is more prominent; if the source is in the ocean and far from the coast

[47] In some States probabilistic methods are used for hazard evaluation for landslide induced tsunamis.

then its height at the coast may be negligible. Therefore, the landslide source size and location should be taken into account.

Hazard evaluation for subaerial landslide induced tsunamis

5.77. The evaluation method of subaerial landslide induced tsunamis is similar to that of submarine landslide induced tsunamis. However, landslide sources for subaerial landslide induced tsunamis should be characterized using the maximum volume parameter, as determined from topographic map or geological age dating of historical landslides. Candidate landslides should be located along the coast or shoreline of a water body adjacent to the site and have the potential to plunge into that water body if they collapse. A slope stability analysis should be performed to assess the potential capacity for tsunami generation of the candidate landslides.

Hazard evaluation for tsunamis induced by volcanic phenomena

5.78. Volcanic sources for tsunami should be characterized by estimating the volume of rock that might be mobilized and displace large volumes of water (from volcanic eruptions or unstable volcanic slopes), and the rate of mass flow. Underwater volcanic eruptions can also displace large volumes of water from the release of volcanic gases. Tsunami hazards should be evaluated using deterministic numerical models. SSG-21 [3] provides recommendations on the evaluation of volcanic hazards.

Values of parameters deriving from the hazard evaluation

5.79. The results of a tsunami hazard evaluation should include the maximum water level at the shoreline, runup height, inundation distance, maximum water level at the nuclear installation site and at critical locations (e.g. intake and discharge locations, stilling basin for intake, harbour and coastal protection structures), and minimum water level (drawdown level) at the nuclear installation site, and the duration of the drawdown at the intake location (with a corresponding annual frequency of exceedance for probabilistic evaluations). In addition, associated effects such as tsunami wave loads, water-borne debris impact, topography change (i.e. scouring or sedimentation), and suspended sediment effects on intakes should be considered.

SEICHE

5.80. When a site is located on the shore of an enclosed or semi-enclosed body of water, the potential for seiche (oscillation of the water surface) should be taken into consideration. In particular, the following should be considered:

(a) Free oscillations of the water surface in an enclosed or partially enclosed water body can be excited by a single impulse such as, a change in wind speed or direction, sharp change in the atmospheric pressure field, wave interactions, tsunamis, landslides into water, underwater volcanic eruptions and other disturbances (such as a local seismic displacement that could produce an extreme ‘sloshing’ of the entire basin).
(b) Forced oscillations of the water body may arise from a continuous application of an excitation to the water column at an entrance to an embayment or canal or from periodic winds at the water surface. A simple example is that of a train of long period waves arriving at a coastal embayment, inducing oscillations of similar period. If the frequency

of the incoming waves matches that of one of the local oscillation modes for the embayment, a resonant amplification of the water height along the shoreline may occur and this may also generate strong currents. Seiche motion in some water bodies can reach several metres or more.

5.81. The possibility for generation of seiches and associated site flooding, should be assessed coincidently with other flooding hazards. In particular, storm surge, large wind events and tsunamis should be examined for their potential to create seiches on water bodies near the site. The evaluation of the seiche hazard should therefore be conducted both separately and in conjunction with the other natural hazard evaluations for site flooding.

Hazard evaluation

5.82. For flooding by seiches, the hazard should be assessed by using either a deterministic hazard analysis or a statistical hazard analysis, or preferably both methods.

5.83. The oscillation modes will depend on the geometry and bathymetry of the water body, and the amplitudes of the oscillation will depend mainly on the magnitude and frequency of the exciting force and on friction. Provided that the forcing action, geometry, and bathymetry are properly specified, it should be possible to calculate the modes and amplitudes of the oscillation. However, except for very simple geometry and bathymetry, calculations should be performed using numerical modelling.

5.84. Numerical models should be used for simulating seiche oscillations and seiche induced flooding. These model results report the water surface elevation as a function of time at any point within a water body of arbitrary shape. They usually need as input: (a) a specification of the overall geometry (bathymetry and coastal topography) and of the antecedent wave environment; and (b) the time dependence of the excitation (tsunami wave, surge wave, wind wave, etc.) at the open boundary or source location. The amplitude time history of the seiches for the location of the installation site should then be calculated. Numerical models should be validated using observed data and/or benchmark problems.

5.85. If a time series of water level oscillation measurements around the basin and associated forcing actions are available, a statistical analysis should be performed for the evaluation of the seiche hazard.

Values of parameters deriving from the hazard evaluation

5.86. The maximum runup height along the site protections, the overtopping flow rate, and the associated duration should be evaluated. The maximum drawdown heights and the associated duration should be evaluated to support the assessment of low water levels.

FLOODS DUE TO EXTREME PRECIPITATION EVENTS

5.87. Paragraphs 5.88–5.121 provide recommendations on the evaluation of potential flooding hazards due to precipitation events at the nuclear installation site as well as in the watershed. Recommendations on the meteorological model that is used to develop the potential scenarios for the temporal and spatial distribution for precipitation falling on the site and watershed are provided in paras 4.41–4.63. In general, the portion of the watershed upstream of the nuclear installation site, and that downstream portion that may have backwater effects on the site, should be addressed. The evaluation should consider both the direct effects of local precipitation on the site and indirect effects from upstream watershed runoff, while taking into account the potential for concurrent events and cumulative effects (e.g., precipitation coinciding with saturated soil conditions, or with high river stages).

5.88. An extreme precipitation event is characterized by heavy rainfall, snowfall or other forms of precipitation within a specific period and geographical area. Precipitation events are generally characterized by the average depth of water (or water equivalent) falling on a given area during a given time period (e.g. mm/hr). It is important to note that the notion of what may constitute an extreme precipitation event is tied to the size of the catchment or watershed area in question. For example, a short but intense small scale event such as a thunderstorm could potentially represent an extreme precipitation event in a small watershed, resulting in significant flooding, while the same event occurring in a much larger watershed may have very little impact. Conversely, a large-scale or long duration low intensity event in a large watershed may result very little precipitation directly on the site but result in flooding on the river mainstem as rainfall runoff is routed through the watershed. Thus, the hazard evaluation should consider the potential for flooding at the nuclear installation site due to local intense precipitation at the site as well as the potential for riverine flooding at the site due to rainfall occurring in elsewhere in the watershed.

5.89. Flooding conditions at the site should generally be characterized using two successive steps. The first step is the simulation of the hydrologic processes such as precipitation, snowmelt, evaporation, and infiltration, to determine the runoff or river discharge resulting from the precipitation. The second step is the simulation of the hydraulic processes to determine the flooding conditions at the site (e.g. water elevation, water velocity) resulting from the runoff or river discharge. Where sufficiently long and reliable records of river discharge exist, hydrologic simulation may be replaced or supplemented by analysis of observed data.

Hazard evaluation of local intense precipitation and associated site drainage

5.90. Site specific local rates of intense precipitation, determined using methods discussed in paras 4.41–4.63, should be used to estimate the response of the site drainage system, water level elevations, ponded depths, water velocities, and duration of flooding. Different precipitation temporal distributions (such as front-loaded, middle-loaded, and back-loaded) should be considered. The rainfall estimate should be combined with estimates of snow or hail, if appropriate. Infiltration can reduce run-off, however the infiltration capacity depends on the degree of soil saturation. The values of the infiltration losses should consider antecedent soil moisture and the soil moisture state during extreme rainfall events.

5.91. Runoff models, such as the unit hydrograph[48] method or other runoff discharge methods, should be used to compute the flow and volume of site drainage, and to determine the necessary capacity of drains, channels and outlets (subsurface drains are usually designed to discharge rainfall at intensities considerably less than those of the design basis precipitation). A hydraulic model should be used to estimate water level (including potential ponding) and velocities. Additional factors that should be considered in the analysis include the possible blockage of some or all pipe drains and culverts. If active drainage systems are necessary to provide adequate flood protection, defence in depth should be ensured through the implementation of

[48] A unit hydrograph is the runoff hydrograph that would result from a unit of rainfall uniformly distributed over the basin in a unit of time.

appropriate preventive and mitigating measures to be incorporated into the design and operation of the drainage system. Since the locally intense rainfall event may coincide with flooding throughout the watershed, backwater effects on the site drainage outfalls should be taken into consideration.

5.92. The effect of the local precipitation on the roofs of buildings and structures important to safety should be studied. Roof drains are usually designed to discharge rainfall at intensities considerably less than those of the design basis precipitation. Since the roof drains could be obstructed by snow, ice, leaves or debris, buildings with parapets could pond water (or combined water, snow and ice) to such a depth that the design load for the roof would be exceeded. Several methods can be used to cope with this, among which are the omission of parapets on one or more sides of the building, limiting the height of the parapet so that excess water will overflow and heating the roof to prevent the build-up of excessive amounts of snow and ice.

Deterministic methods

5.93. The deterministic modelling approach for hazard evaluation for local intense precipitation applies the site-scale probable maximum precipitation rainfall (see paras 4.52–4.55) combined with conservative assumptions regarding infiltration and operability of subsurface and roof drains to derive a demonstrably conservative estimate for flooding and ponding on the nuclear installation site. Different temporal distributions for the probable maximum precipitation rainfall depth should normally be assessed to identify the distribution that maximizes flooding at key locations on the site (e.g. doorways, penetrations).

Probabilistic methods

5.94. Probabilistic modelling approaches for hazard evaluation for local intense precipitation apply a statistical or probabilistic model for the rainfall and treat key variables such as infiltration and operability of drainage systems as uncertain, representing them with probability distributions.

5.95. The most commonly used probabilistic modelling approach is a nested Monte Carlo simulation. The outer loop of the simulation samples the epistemic variables (e.g. hydrologic and hydraulic model structure, model parameter), while the aleatory variables (precipitation timing, amounts, temporal pattern) are sampled in the inner loop. Execution of the inner loop for a single realization produces a magnitude vs frequency curve for flood hazard parameters of interest (e.g. water level, water velocity, flood duration). This process should be repeated for a large number of realizations to produce a family of magnitude–frequency curves from which mean values and other percentiles of the hazard parameters should be derived.

Hazard evaluation of riverine flooding - computation of watershed discharge

5.96. Computation of peak river discharge near the site should be performed by simulating the hydrologic processes, such as precipitation, snowmelt, evaporation, infiltration, and run-off, in order to determine watershed discharge using either a deterministic analysis or a probabilistic analysis. The peak river discharge should also be estimated by a statistical analysis of observed river discharge.

Deterministic methods

5.97. Deterministic methods may be used to compute peak river discharges near the site. In this approach the flood hazard should be derived from the design basis precipitation estimated in accordance with paras 4.57–4.59. The conditions that generate runoff should be evaluated based on an analysis of the meteorological, hydrological and physiographic characteristics of the basin. The unit hydrograph method may be used to calculate the flood hazard from the design basis precipitation. The design basis precipitation and the conditions generating runoff should be estimated not on the basis of a single storm event but on a set of storm events, by utilizing storm transposition, maximization and estimation of coefficients in which the hydrologist and meteorologist together apply their judgement. The contributions of experienced experts should be considered in order to reduce the uncertainties to an acceptable level.

5.98. The positions of the storms over the basin should be selected in such a way that the maximum runoff (in terms of volume or peak water level, whichever is more limiting) would occur.

5.99. In basins where snow melt can contribute significantly to the flood hazard, special consideration should be given to the maximization of a combined rain and snow melt. To compute the maximized contribution of snowmelt to flooding, the seasonal accumulation of snow should be maximized, and a worst case melt sequence should be selected. A design basis precipitation event appropriate to the time of year should then be added to the maximized snow melt event, and the additional snow melt due to precipitation (if it is rain) should be included.

5.100. Losses of water (i.e. infiltration) should be estimated by comparing the incremental precipitation with the runoff from recorded storms. Usually, losses are expressed as an initial loss followed by a continuing constant loss over a period of time[49]. The variation of the level of underground water should be considered in estimating the basin water losses.

5.101. When two sequential storms are postulated, the water losses for the second storm should be assumed to be less because of increased soil saturation leading to decreased infiltration. In many cases, losses are ignored, which is the most conservative approach.

5.102. Typically, a unit hydrograph might represent the hydrograph resulting from an excess rainfall increment of 10 mm in one hour. The time increment should be decreased or increased, depending on the size of the drainage area. In practice, unit hydrographs should be developed for rainfall patterns that are not uniform. Where orographic factors produce fixed but non-uniform patterns, the unit hydrograph should be developed for the pattern typical for large storms in the basin. The unit hydrograph should be derived from recorded flood hydrographs and their associated rainfall.

5.103. Unit hydrographs derived from small floods might not represent the true flood characteristics of the basin when applied to large storms[50]. Non-linear effects generally increase

[49] For example, typical losses might be an initial loss of 10 mm, followed by a continuing loss of 2 mm per hour. It is often not worthwhile making detailed studies of losses as long as conservatively low estimates are selected. If, for example, the maximum hourly increment in the design basis precipitation is 150 mm, the effect of a loss of 2 mm per hour with such rainfall is insignificant compared with the errors inherent in the other parameters.

[50] The assumption of linearity for the unit hydrograph model is not always valid since the hydraulic efficiency of the drainage basin increases with increasing runoff up to a certain limit, and since changes may occur in channel flow from within bank to out of bank.

the peak river discharge and decrease the time to peak of the unit hydrograph. Estimating non-linear effects for large flood events by comparing the unit hydrographs derived from floods of various sizes should also be considered. If there are not sufficient field observed data from large flood events available, unit hydrograph adjustments on the order of 5% to 20% of the peak river discharge and/or reductions of the time to peak of 33% can be found in the technical literature.

Statistical methods

5.104. Statistical methods need long time series (typically, more than 50 years) of observed data from a gauge representative of the river discharge at the site. The representativeness of the gauge for the site should be justified. One approach that should be considered is to compare the size of the watersheds at the station and at the site; the gauge is representative if the difference is less than a few per cent. The data set should be augmented with historical flood data, such as high-water marks, that can be converted into an approximate peak river discharge. Geologic evidence should also be used to extend the data set as paleo-flooding information. When historic and paleo water levels are converted to river discharges, attention should be paid to changes in the morphology of the river plain. The dataset of river discharge data can also be augmented by translating observed data from upstream or downstream river discharge gauges along the same river. A homogeneous data set should be constructed: therefore, anthropogenic changes within the watershed (e.g. construction of dams, modifications to reservoir storage operational procedures for existing dams), during the data observation period should be properly taken into consideration. Forecasted changes, including the future construction of dams or planned changes to reservoir storage operational procedures, should also be factored into the hazard evaluation.

5.105. Once the data set has been developed, an annual frequency of exceedance for large floods (e.g. a frequency of 10^{-3} per year or less) should be computed through extrapolation by using a probabilistic model. To allow for uncertainties in sampling, the selected river discharge value is usually a confidence level upper limit, not the mean value, for the chosen recurrence interval. In more complex river systems with multiple tributaries or tidal downstream boundaries a multivariate statistical model can be ap-plied to take the correlations into account before sampling. A safety factor should be added to take into account uncertainties. This safety factor should be added to the river discharge rather than the still water elevation.

Probabilistic methods

5.106. The most commonly used probabilistic modelling approach for estimating watershed discharge is a nested Monte Carlo simulation. The outer loop of the simulation samples the epistemic variables (e.g. hydrologic model structure, model parameters), while the aleatory variables (precipitation timing, amounts, temporal pattern, spatial pattern) are sampled in the inner loop. Stochastic storm simulation and continuous simulation methods should be used to model the watershed discharge. Execution of the inner loop for a single realization produces a magnitude vs frequency curve for flood hazard parameters of interest (e.g. water level, water velocity, flood duration). This process should be repeated for a large number of realizations to produce a family of magnitude–frequency curves from which mean values and other percentiles of the hazard parameters should be derived.

Hazard evaluation of riverine flooding - site hydraulic parameters

5.107. To compute the water level, water velocity and other parameters during a flood near the nuclear installation site, a numerical model should be used. A time history of flooding plus an accurate inundation map should be generated. The extent of the numerical model should include a sufficient distance upstream and downstream of the nuclear installation site so that the boundary conditions specified do not affect results at the site. The model should cover an area that extends laterally to include the entire extreme floodplain.

5.108. The numerical model, which is usually either a one-dimensional or two-dimensional model, should accurately represent variations in topography and in the roughness of both the river and floodplain. The underlying model grid should be more refined near the nuclear installation site. The model should capture sudden discontinuities in the flood stage and in water discharge caused by dykes, spillways, bridges and other features near the site. Usually, the models can not represent the potential for debris buildup or ice jam at downstream bridges that can generate backwater effect to the site. A specific evaluation of the potential for river flow blockage should be performed on the basis of bridge geometry and if the blockage cannot be excluded, the bridge should be modelled as a weir.

5.109. Backwater effects that can also be induced by estuaries, confluences, hydraulic structures and other features should be taken into account in the downstream boundary condition. The analyst should verify that the downstream boundary condition does not affect the results at the nuclear installation site and that any uncertainties are taken into account by making conservative assumptions.

5.110. The numerical model should be calibrated and validated against data sets available for observed and recorded floods. These data sets should include the measured values of water discharge, water level and, if available, water velocities. A main parameter for calibration is the roughness in the floodplain. However, observed floods are usually not representative of the studied extreme floods, and roughness parameters in the floodplain should be estimated from land use information using a conservative approach.

5.111. For floods with a relatively small rate of change of stage, steady state routing may be appropriate (e.g. the routing of a flood through a large reservoir). However, unsteady flow routing should be applied when the time variation of the stage is significant or when a more accurate representation of the maximum flood stage is necessary (e.g. routing of a flood through a free-flowing river).

5.112. A unique stage discharge relationship can occur only when the river discharge is uniform over time. During a large flood event when the river discharge is varying rapidly, the timing of the peak river discharge will probably not coincide with the peak water level. This phenomenon should be considered in interpreting results from unsteady flow models.

5.113. Base water flow in a river should be representative of the season of the year and the period of time during which the reference flood may be expected. Since base water flow is generally a small percentage of the river discharge during flood events, an estimate of the base water flow is generally sufficient for most hazard evaluations.

5.114. A large flood event can generate breaches of levees along the river that modify the water levels both in the river and in the floodplain. The behaviour of the levees during the flood event should be evaluated considering possible failure mechanisms (e.g. piping, overflow and overtopping, shearing of the backside slope). The behaviour assumed for these structures (breach or resist) could also be justified based on its unfavourable nature for the site flooding conditions or can, in case of a probabilistic approach, be included in the sampling.

5.115. River channels may meander as a result of a flood event. The potential for meandering away from the nuclear installation site may cause a loss of cooling water. Likewise, a meandering towards the site may induce site flooding. The stability of the river channel near the site should be analysed in the hazard evaluation and appropriate design and operational measures for shore protection should be implemented if necessary.

5.116. In addition to inundation, floods could potentially affect the safety of the nuclear installation by undermining flood protection barriers, by causing direct hydrodynamic forces on any inundated buildings, by sedimentation and/or clogging of safety features on the site, or by eroding and destabilizing structures. Impact loads due to water-born debris should also be considered. The potential for this should be considered in the hazard evaluation.

5.117. Detailed three-dimensional numerical and/or physical models of the site should be considered as a means of estimating water velocities and hydrodynamic forces on inundated structures. If increased roughness coefficients have been considered for the conservative estimation of water stage, adjustment of these roughness coefficients to obtain conservative water velocity values should be considered.

5.118. A combination of numerical and physical models should be considered to study phenomena such as sedimentation, erosion and scouring.

5.119. The general approach described in paras 5.107–5.118 for assessing the site hydraulic parameters is common for deterministic methods and probabilistic methods. However, deterministic methods involve conservative hypothesis to cover some uncertainties, whereas probabilistic methods involve more detailed analyses of the uncertainties. In either case, future changes in climatic conditions — including potential increases in the frequency and intensity of extreme precipitation and flooding events — should be considered in the hazard evaluation, in line with current scientific understanding and available projections (see Section 9).

Values of parameters deriving from the hazard evaluation

5.120. The results of a hazard evaluation for site-scale flooding due to local intense precipitation that should be used as input for design and evaluation of flood protection include:

(a) Peak water level and time history of water surface elevation at key locations;
(b) Water velocities at key locations.

5.121. The results of a hazard evaluation for watershed-scale riverine flooding should include:

(a) Flow rate: the peak flow rate and the water discharge time history of the entire flood event (flood hydrograph) at the nuclear installation site.
(b) Water level: peak water level and time history of water surface elevation at the site.
(c) Water velocity: the mean water velocity near the site. In many cases estimates of velocities at specific parts of the cross-sections are necessary for the analysis of hydrodynamic effects on structures and the estimation of sedimentation and the potential for erosion near the site.

(d) Streambed and bank stability: the potential for meandering of rivers, channel diversions, and sedimentation and scouring of the streambed and banks, both during and after the flood event.

(e) Sediment transport: the suspended sediment and the bed load.

(f) Debris transport (e.g., size, mass, velocity)

FLOODS DUE TO THE SUDDEN RELEASE OF IMPOUNDED WATER

5.122. The sudden release of water impounded by water retaining structures or features located upstream of a nuclear installation site may induce flooding at the nuclear site (water might be impounded by human made structures, such as dams dykes and tanks, or by natural obstructions such as ice jams and debris dams). Water release can occur owing to hydrological, seismic, or geotechnical processes, human actions, or other causes.

5.123. Possible events and processes that might lead to sudden release of water and that should be considered in the hazard evaluation include:

(a) Flood induced overtopping and subsequent erosion and breaching of earthen dams;
(b) Seismically induced embankment failure of earthen dams;
(c) Seismically induced cracking and subsequent failure of concrete dams;
(d) Seepage and internal erosion (piping) of earthen dams;
(e) Geotechnical issues or defects in dam foundations or embankments leading to excessive or uneven settlement, cracking, or excessive pore pressures, or other structural failures;
(f) Deterioration of concrete structural members or embankment protection (e.g. corrosion, alkali–silica reaction) leading to structural failure;
(g) Defects due to the action of burrowing animals or the roots of vegetation;
(h) Failures of spillways, gates and other appurtenances;
(i) Operational issues leading to an accidental or intentional release of water;
(j) Landslide into the reservoir leading to overtopping;
(k) Failure or mis-operation of on-site water control structures (e.g. dykes, berms, tanks, cooling tower basins)
(l) Wave induced erosion and subsequent breaching.

5.124. The principal processes leading to sudden release of water from debris dams, and which should be considered in the hazard evaluation, are erosion and instability due to the static and dynamic forces exert by the impounded water accumulating upstream of the obstruction. For ice jams, air temperature is also a significant factor affecting breakup.

5.125. One important difference between a flood due to precipitation and a flood due to the failure of a water control structure is that the latter could generate a wave of great height moving downstream at high speed, which could arrive at the nuclear installation site with only a short warning time. A considerable dynamic effect could be exerted on the nuclear installation site and on the structures built on it.

5.126. Hydrological failure of water control structures (i.e. associated with precipitation in the watershed) could occur owing to insufficient outlet (e.g. spillway) capacity compared with inflow to the reservoir, either because of faulty operation or because the water inflow exceeds design values. This causes an increase in the water level and the dam could be overtopped. In the case of an earth fill or rock fill dam, overtopping may cause erosion of the embankment, leading to failure of the dam. For concrete dams, overtopping could lead to erosion near the foundation, undermining the dam and leading to failure. Hydrologic failure scenarios should be considered as potentially causing the most severe floods at the site as the failure will occur at the time of maximum reservoir storage (failures due to a seismic event or geotechnical issues such as piping typically are generally not assumed to occur coincident with maximum reservoir storage). Moreover, high flows will also likely be present in the river reaches downstream of the dam.

5.127. Faulty operation of dam facilities as well as intentional release of water (to save the dam or to do emergency repair work) can create significant floods. In this regard, an investigation should be made of upstream dams, particularly those dams with spillway gates controlling potentially large flows, to assess the magnitude of possible water releases and to investigate the potential operational issues (including maintenance issues with gates).

5.128. Flooding caused by ice jams contribute to winter and early spring floods in high latitude areas of the world. Streams and rivers at high latitudes (i.e. cold regions) tend to form ice cover when temperatures cool below freezing (freeze-up). As temperatures warm above freezing, the ice cover breaks apart (break-up). Ice jams may form during freeze-up and breakup, but breakup jamming should usually be considered to be the main concern as much higher flows typically prevail during break-up. Sudden release of water due to collapse of an upstream ice jam could cause flooding at the nuclear installation site. Recommendations on ice jam phenomena are provided in paras 6.20–6.28.

5.129. In regions where glaciers occur, glacial lake outburst flooding, when a water body water impounded by a glacial ice or glacial terminal moraine (or both) is suddenly released, should be considered. The water body may be a marginal lake (i.e. a lake impounded by the glacier front) or it may be a sub-glacial lake (i.e. a water body capped by the glacier). Collapse of the impoundment and release of the impounded water may be caused by number of phenomena (e.g. buildup of water pressure, melting, erosion, seismic activity, volcanic activity).

5.130. Sudden release of water due to collapse of an upstream debris dam could cause flooding at the nuclear site and, where applicable, this should be considered in the hazard evaluation. Debris flows and subsequent debris dams may arise due to several phenomena. In regions subject to landslides, slope failure near a stream or river could result in a debris dam that blocks the channel and creates an impoundment. Debris flows can also form during rainfall events on fire-affected landscapes. Debris dams could also form due to volcanic activity (e.g. lahars). In some cold regions, snow avalanche could lead to similar flooding phenomena.

5.131. Flooding at the nuclear site can also be caused by failure of (or operational issues with) on-site water control structures (e.g. tanks, impoundments, cooling tower basins, dykes/levees). Consideration should be given to the volume of water stored or impounded, the location of the structure relative to SSCs important to safety, and potential failure mechanisms. Failure mechanisms could be associated with external hazards (e.g. a tank or other impoundment might fail during a seismic event or high intensity winds). Failure could also be associated with structural defects or maintenance issues.

Hazard evaluation

5.132. The hazard evaluation should generally begin with a survey of all upstream water control structures that might potentially impact safety of the site. The information to be collected to make an initial evaluation includes:

(a) Name of structure;
(b) Type (e.g. earthen/rockfill dam, concrete dam, earthen dyke or levee, composite earthen–concrete dam);
(c) Height and elevation;
(d) Capacity (e.g. reservoir volume);
(e) Water release features (i.e. type, number, and capacity of spillways, outlet works, gates, valves);
(f) Operating rules (if available);
(g) Design inflow flood (if available).

5.133. All upstream dams and other water control structures within the watershed, existing or planned, should be considered initially at the source of a sudden release of impounded water due to potential failures, faulty operation or intentional releases. Some upstream structures may be eliminated from further consideration because of their small storage volume, distance from the site or low differential head, or because of a major intervening natural or artificial capacity for water retention.

5.134. The investigation of the watershed upstream of the site should consider reaches in which the formation of a natural blockage of the channel (e.g. from landslide) is possible, and the potential consequences of sudden release of water if the blockage collapses. The investigation should also consider how structures such as mine waste dumps (i.e. tailings dams), highway fills across valleys or low bridges might act as dams during floods. Even if some dykes and levees do not continuously impound water, these structures should be considered in the hazard evaluation since they could abruptly fail during a flood event.

5.135. The potential failure of two or more upstream water control structures being caused by the same event, such as a flood or an earthquake, should be investigated. For example, a dam that would otherwise be safe during a flooding could fail as a result of the failure of an upstream dam (i.e. cascading failure). Thus, the potential failure of all water control structures along the path to the site should be taken into consideration unless their survival can be established. In addition to cascading failures, coincident failure of structures on different tributaries upstream of the site should be considered. For example, dams located on separate upstream tributaries could fail due to an earthquake or flooding event. Depending upon size and location of these dams, the flood waves resulting from their failure could arrive more or less simultaneously at the site.

5.136. The simultaneous faulty operation or intentional release from two or more water control structures should be taken into consideration if there is a reasonable likelihood that the events may be connected.

5.137. All existing or planned water control structures on the site, such as tanks, impoundments, cooling tower basins, and dykes or levees, should be considered in the investigation[51]. Some structures may be excluded from further consideration due to insignificant water storage capacity or location and/or elevation relative to equipment

[51] In accordance with the practices of some Member States, failures of these structures are considered either as internal events or as external events.

important to safety (e.g. where the topography is such that failure would result in water flowing away from such equipment). The failure potential and consequences for other structures should be evaluated using engineering analysis. The potential for multiple failures (e.g. due to earthquake) should be considered.

5.138. Structures on tributaries joining the channel downstream of the nuclear site should be considered in the investigation if backwater effects during a sudden release could impact the flood hazard at the site.

5.139. A reduction of the flood level at the site due to sudden release from a downstream water control structure should not be credited unless it can be demonstrated for certain that the structure would fail.

Failure analysis for water control structures

5.140. Failure of upstream water control structures should be postulated unless their survival can be demonstrated with adequate confidence by means of engineering analysis. It is generally expensive and time consuming to demonstrate the safety and stability of many water control structures, for example conducting a dam safety analysis. Thus, it may be more efficient to make a simple conservative analysis by assuming the sudden and complete failure of the structure. If the results of this analysis show no significant flooding impacts at the nuclear installation site, further analyses are unnecessary. Otherwise, the water control structure should be evaluated for failures due to hydrologic and seismic hazards, geotechnical and mechanical defects, and for the potential for accidental releases. The effect of intentional releases should be evaluated in all cases.

5.141. Hydrologic processes (i.e. rainfall and subsequent flooding in watershed upstream of the water control structure) may lead to several modes of failure, all of which should be evaluated. For example:

(a) Floods larger than the capacity of spillways or other outlets may lead to overtopping and failure of earthen dam embankments.
(b) Excess pore pressures in embankments, foundations or abutments due to high reservoir water levels may induce failures in earthen dams.
(c) Excess pore pressures in foundations or abutments may induce failures of concrete dams.
(d) Flood-borne debris may clog spillways or other outlets, leading to overtopping and failure.

5.142. The potential for hydrologic failure of dykes and levees should be evaluated. Overtopping and failures related to excess pore pressure in embankments and foundations are the most common failure modes.

5.143. Seismic hazards that may directly impact and induce failure of water control structures include vibratory ground motion and fault displacement. Associated geological and geotechnical hazards often include soil liquefaction and differential settlement. In addition, seismically induced waves in the reservoir should be analysed with regard to possible overtopping and subsequent breaching. The failure of gates and other appurtenances due to seismic motion should also be investigated.

5.144. For each structure, a up to date seismic hazard analysis (see SSG-9 (Rev. 1) [2]) should be performed (or reviewed if available from another source). A detailed seismic stability analysis involves proper documentation of the condition of the structure. Analysis, inspection and maintenance reports produced by the structure’s owner/operator or appropriate regulatory or technical bodies should be used in the stability analysis. Additional data should include the results of strength tests of the structure’s foundation areas, as well as and field surveys and other inspections, together with pertinent data collected by instrumentation installed at the structure site.

5.145. Water moving slowly through an earthen dam embankment and/or percolating slowly through any dam’s foundation is known as seepage. This is typical and usually is not a problem if water movement through and under the dam is sufficiently controlled. However, excessive seepage that saturates the embankment or increases internal pressure (i.e. porewater pressure) within the embankment or foundation can make the embankment or foundation unstable and lead to failure. The potential for this should be considered in the hazard evaluation.

5.146. Uncontrolled seepage can also erode soil from the embankment or its foundation, resulting in failure. This is called "piping." Typically, piping begins at the downstream side of the dam and progressively develops in the upstream direction, eventually developing a flow path to the reservoir. Signs of piping include, in order of severity, increased seepage flow rate, discharge of muddy or discoloured water, sinkhole(s) on or near the embankment, and possibly a whirlpool at the reservoir water surface near the embankment. Fully developed piping is virtually impossible to control and will likely cause failure.

Stored water at the time of sudden release

5.147. The volume of water stored by the water control structure at the time of sudden release should generally be considered to be the maximum possible in most cases. However, lower water levels could be assumed with sufficient engineering justification. For example, a normal water level could be considered in the case of seismically induced failure, since earthquakes and extreme floods (that would fill the reservoir) are not strongly correlated events.

5.148. The breach hydrograph from a failed structure (i.e. water discharge from the breach as a function of time) depends on the degree and mode of failure, the resulting headwater and flow relationship, and the geometry and volume of the reservoir. The stage–capacity curve, which defines the relationship between the water surface elevation (stage) and the stored volume in the reservoir, should be used to estimate the available water volume at the time of failure. Unsteady flow methods should be used for downstream routing of failure flood waves, especially in the upper river reaches.

5.149. In a hydrological failure scenario the breach hydrograph should be developed by assuming the maximum water level in the reservoir combined with the design basis inflow flood to the reservoir at the start of breach.

Breach modelling of failed water control structures

5.150. If survival of the water control structure cannot be demonstrated, failure and breaching should be postulated. The breach size and time to development should be estimated in order to develop a breach hydrograph. Routing of the breach hydrograph to the site can be performed using flood routing approaches.

5.151. The breach size and time to development will depend on the loading due the hazard (e.g. seismic loading, hydrologic loading), construction material (e.g. concrete, earthen fill, rock fill), and type of structure (e.g. gravity dam, arch dam, buttress dam). The simplest approach to breach modelling is to assume that the structure fails completely and instantaneously. While this assumption is convenient when applying simplified analytical techniques for analysing the resulting flood wave and is somewhat appropriate for concrete arch dams, it is not considered realistic for either earthen or concrete gravity dams, which tend to fail partially, progressively, or both. Large earthen dams do not tend to fail completely, nor do they tend to fail instantaneously.

Breach modelling for concrete dams

5.152. Concrete gravity dams tend to have a partial breach as one or more sections formed during construction of the dam are forced apart, shifted, or overturned. The time for breach formation depends on the number of sections that fail but is typically of the order of minutes. The challenge of modelling breach of concrete dams is in predicting the number of sections that might be displaced. A dam breach flood prediction model should be used to run several cases in which the breach width parameter representing the combined lengths of assumed failed sections is varied; the resulting reservoir water surface elevation and the hydraulic loading on the dam can then be estimated. Because the loading diminishes as the breach width increases, a limiting safe loading condition, which would not cause further failure, should be estimated. The breach size and shape should then be determined by considering the size and shape of the failed section(s), and using weir formula or hydraulic simulation software to compute the outflow hydrograph and peak outflow.

5.153. Unlike concrete gravity dams, concrete arch dams tend to fail completely and it should be assumed that the breach forms in only a few minutes. Although the actual breach geometry for complete failure is the profile of the river valley, it is usually be approximated as a rectangle or a trapezoid. Buttress and multi-arch dams should be modelled in a similar fashion, where sections are assumed to fail completely.

Breach modelling for earthen embankments dams

5.154. For breach modelling of earthen embankment dams, the following should be assumed:

(a) The overtopping failure typically begins at a point on the top of the dam and expands in a generally trapezoidal shape.
(b) The water flow through the expanding breach behaves approximately as flow over a weir.
(c) In the case of internal erosional failure (i.e. piping), the breach opening initially forms at some point below the top of the dam. As erosion proceeds, piping flow through the embankment initially behaves as orifice flow. The piping enlarges until the top of the embankment collapses, or the breach becomes large enough that open channel flow occurs. Beyond this point, breach enlargement is similar to the overtopping case.
(d) The total time of failure can range from a few minutes to a few hours, depending on the height of the dam, the type of materials used in construction, and the magnitude and duration of the flow of escaping water.

5.155. Breach modelling of embankment dams should be based on regression analysis of historical data from observed dam failures, or mechanistic modelling using physically based breach models. Breach parameters developed using regression approaches should then be used in a hydraulic model that determines the breach outflow hydrograph through the parameterized opening using a weir or orifice flow equation. The same scenario applies to breach parameters developed using some physically based breach models, while other physically based models couple erosion and hydraulic processes to compute the breach outflow hydrograph directly.

5.156. It should be taken into account that modelling of the breach development process and prediction of the breach outflow hydrograph are major sources of uncertainty in dam failure analysis. Numerous regression equations have been developed for breach parameters, time for breach development, and peak water discharge; however, these have large uncertainties and are dependent on the analyst and the types of dam failure studied. It should also be taken into account that predictions developed using physically based breach models are also uncertain, due to the difficulty in calibration of sensitive model parameters (e.g. critical shear stress of embankment material).

5.157. A sensitivity analysis should be made to select final breach parameters from a wide range of results for breach width and breach formation time calculated from a wide range of available methods. This analysis should also consider the impact at the downstream locations. Based on the selected breach parameters, stage and outflow near the dam may vary greatly; however, this effect may be smaller at larger downstream distances due to routing effects.

Levee and dyke breach modelling

5.158. Failures of dykes or levees can either increase or decrease the flood hazard at the nuclear installation site (e.g. failure of a levee upstream might result in lower hazards at the site). Beneficial failure should not be assumed, but may be appropriate in certain cases, with sufficient engineering justification.

5.159. In general, earthen embankment levees providing flood protection to the nuclear site should be assumed to fail when overtopped. The case for nonfailure should be developed using detailed engineering analysis supported by site specific information, including material properties of the embankment and foundation soils, material properties of embankment protection (if any), and levee condition. Other forms of levees (e.g. pile walls, concrete flood walls) should be evaluated for potential failures applicable to the particular type of levee.

5.160. Levees are generally not designed to withstand high water levels for long periods. However, no generally accepted method currently exists for predicting how long a levee will continue to function under high loading conditions. Therefore, historical information is the best available basis for predicting levee performance. The historical information should be from levees that have design and construction characteristics similar to those of the levee being analysed.

5.161. Because there is no widely accepted method for modelling breach development in the case of levees, conservative assumptions regarding the extent of the breach and the failure time should be used.

5.162. In general, two-dimensional modelling should be used for inundation mapping of a nuclear installation site from an on-site or nearby levee.

Flood wave routing

5.163. Recommendations on routing of the flood to the site are provided in paras 5.96–5.121. The site survey conducted for a dam failure scenario to establish the roughness coefficient of the river, and the flood plains should be conducted to greater distances and heights than those used to assess riverine flooding. The evaluation of the flood hazard at the site should consider the contribution of peak water discharges during extreme floods from smaller rivers and tributaries joining the main river between a dam and the site.

Values of the hazard parameters

5.164. The hazard parameters for sudden release of impounded that should be calculated as part of the flood analysis include:

(a) The peak flow rate and the water discharge time history of the entire flood event (flood hydrograph) at the nuclear installation site;
(b) The peak water level and the time history of the water surface elevation at the site;
(c) The velocity of flood water;
(d) Time of arrival of flood wave and total duration of flood at the site;
(e) The dynamic and static forces resulting from the flood waters.

BACKWATER EFFECTS DUE TO IMPOUNDING

5.165. Nuclear installations located on rivers, estuaries, or lakes may potentially experience a rapid rise of water level at the site due to downstream blockages or impoundments. The blockage or impoundment may arise from a variety of phenomena such as landslides, ice jams, and build-up of water borne debris. For the purpose of this Guide, the term landslide is used to encompass several related phenomena (e.g. soil slope failure, rock or snow avalanche, debris flow or volcanic a landslide).

5.166. Almost every landslide has multiple causes. Slope movement occurs when forces acting downslope (mainly due to gravity) exceed the strength of the earth materials that compose the slope. Causes include factors that increase the effects of downslope forces and factors that contribute to low or reduced strength. Landslides can be initiated in slopes already on the verge of movement by rainfall, snowmelt, changes in water level, stream erosion, changes in ground water, earthquakes, volcanic activity, disturbance by human activities, or any combination of these factors. Earthquake shaking and other factors can also induce landslides underwater.

5.167. Sudden impoundment of water may be caused by an ice jam that forms downstream of the site. Recommendations on ice jam phenomena are provided in paras 6.20–6.28.

5.168. Sudden water impoundment can also occur when debris in a channel blocks the flow of water. Debris such as large woody debris (e.g. logjams, snags) can cause blockages to waterways, particularly near constrictions such as bridges. During large scale flooding events additional debris from the flood plain can also be entrained and enter the channel resulting in more severe blockages.

Hazard evaluation

5.169. The effects of obstruction of the river channel by floating material may be very difficult to predict. A survey of the meteorological, hydrological, and geological conditions in the site region should be performed to investigate the potential for downstream blockages or impoundments. Historical records or archives should be reviewed for occurrences of past events (e.g. types of event, location, severity).

Values of parameters deriving from the hazard evaluation

5.170. The water velocity, peak water level, the time to peak water level and duration of inundation are the important parameters that should be derived from the hazard evaluation of impoundment of water.

BORES AND MECHANICALLY INDUCED WAVES

5.171. A tidal bore is a hydraulic phenomenon in which the rising tide induces waves in a river. These waves are generated by the blockage of the river flow and move upstream, opposite to the normal direction of river flow. Mechanically induced hydraulic waves can form in a channel or a reservoir in the vicinity of a dam or a water discharge control structure. Waves are induced when a water discharge passing through the structure is suddenly stopped (e.g. due to a load rejection at a hydroelectric power plant). The waves likewise move upstream through the channel or reservoir and opposite to the normal direction of river flow. The wave height can be amplified by a reduction of the channel cross-section and by reflection from structures and shorelines.

5.172. The observed records of water surface elevation should be examined for evidence of either tidal bores or mechanically induced waves. In the case of mechanically induced waves, all dams and water discharge control structures in the vicinity of the site should be considered for their potential to generate waves that might affect the nuclear installation site.

Hazard evaluation

5.173. If there is a potential for bores or waves of significant height to occur near the nuclear installation site, or from the water control structures at the site along a reservoir or water intake or discharge channel, several deterministic scenarios should be considered in the evaluation of the flood hazard. The event that initiates the bore or the mechanically induced wave should be clearly identified in the evaluation. The analysis should also consider a range of water levels in the reservoir or canal and a range of water discharges to the river or canal.

5.174. For a channel with simple geometry, the height of the mechanically induced wave can be derived from the simple formulae:

$$h = Vc/g \tag{1}$$

$$c = \sqrt{gH} \tag{2}$$

where h is the height of the mechanically induced wave, V is the average speed of flow before flow cutoff, c is the wave propagation velocity, g is the gravity acceleration, and H is the water depth before flow cutoff with $H >> h$.

5.175. For locations with complex bathymetry, a numerical (one dimensional, two dimensional or three dimensional) or physical model should be used to propagate the wave from the water control structures to the nuclear installation site.

Values of parameters deriving from the hazard evaluation

5.176. If the site is susceptible to flooding from a tidal bore or a mechanically induced wave, the maximum runup height along the site protections, the overtopping flow rate, and the associated duration should be evaluated.

HIGH GROUNDWATER LEVELS

5.177. An increase in the groundwater level in the uppermost aquifer (i.e. water table) can be caused by several phenomenon. The following should be taken into account in the hazard evaluation:

(a) For a nuclear installation site near a river or in a coastal area, a rise in the groundwater level may be related to an increase in the water level in surface water bodies that are hydraulically connected to the aquifer. Additional phenomena, such as a large rainfall event or the failure of a water control structure, also could cause groundwater levels to increase.
(b) Variations in groundwater levels depend on the properties of soil and rocks, primarily the permeability and porosity of geological media. The range of yearly variations of groundwater levels may vary from centimetres to tens of metres owing, in particular, to the broad diversity of geological media. Fractured rocks can present high permeability (even associated low porosity). These conditions lead to a potential for large amplitude variations of the groundwater levels (e.g. groundwater level increase of more than 30 m in response to a precipitation event).
(c) Karst areas also should be considered; karst features can respond rapidly to rainfall events, resulting in rapid changes in groundwater levels in some cases.

Hazard evaluation

5.178. The frequency of significantly high groundwater levels should be determined on the basis of a hydrogeological study of the nuclear installation site to specify the regime and the extent of groundwater bodies. The hazard should be assessed by means of either a deterministic or a statistical hazard analysis. In using a statistical approach, special attention should be paid to the reliability and the sufficiency of the piezometric data. Where on-site measurements of groundwater level are limited in number or in the period they cover, consideration should be given to extending their record statistically by correlating observed groundwater levels with, for example, records of wells observed for longer periods and meteorological records.

5.179. The use of hydrogeological modelling should be considered. In certain cases, the hydrogeological conditions make it possible to determine in a simple and conservative way the physical limits of the groundwater level, without resorting to complex models. For example, the hydrogeological conditions of a site can justify considering the groundwater level equal to the ground level. Models are generally calibrated using observed water levels, which might not be representative of the levels reached during an extreme event. The conservatism of the assumptions of the model relating to the formations above the water table should therefore be justified.

5.180. All the possible causes of groundwater rise that are relevant for the site should be identified by considering precipitation and other relevant hydrological phenomena. The predominant causes should then be identified in the analysis and the extreme groundwater level should be derived from extreme conditions relating to these causes. In this process, conservative assumptions should be considered in the specification of the initial conditions (i.e. the initial water level).

Values of parameters deriving from the hazard evaluation

5.181. The extreme groundwater levels at the site and the associated pressures on structures should be characterized. If groundwater levels are expected to reach the ground surface or the levels of groundwater drains, the expected water discharge rate should be characterized, together with the ways in which the water would be discharged. The potential need for dewatering should be identified where appropriate.

LOW WATER LEVELS

5.182. Low water levels or low flow rates have the potential to affect the availability or sustainability of cooling water. Several different phenomena that might to lead to low heat sink water level or low flow should be considered, including:

(a) Damage to water control structures (e.g. Downstream hydroelectric plants or dams, downstream or upstream levees, water intakes or pipelines).
(b) Upstream blockage or diversion (e.g. Land slide, ice jam)
(c) Weather conditions (e.g. Drought);
(d) Low tide;
(e) Drawdown due to tsunami (including meteo-tsunami) or seiche;
(f) Set down due to winds blowing offshore;
(g) Water level depression due to high atmospheric pressure;
(h) Combinations of the above phenomena.

Hazard evaluation

5.183. The history of low water and low flow conditions at and in the vicinity of the site should be compiled. A thorough listing of types of phenomenon, locations and durations of these events, and descriptions of hydrometeorological characteristics accompanying these events should be included. These listings and descriptions should be sufficient to establish the history of droughts (see paras 6.8–6.10) or other low water or low flow events in the vicinity of the site.

5.184. If a low level of water could affect the availability or reliability of the ultimate heat sink, the consequences of low water level, are required to be evaluated (see Requirement 11 of SSR-1 [1]). Different scenarios should be considered, including, if relevant, those involving natural causes or damages to water control structures. Their plausible combinations should also be considered.

5.185. For river sites, the potential for morphological changes (e.g. changes in riverbed bathymetry, blockage due to bank collapse) that could affect water levels or flow rates should be assessed.

Values of parameters deriving from the hazard evaluation

5.186. The estimated minimum water level and estimated minimum flow rate are the main parameters that should be derived from the hazard analysis.

6. OTHER NATURAL HAZARDS RELATED TO METEOROLOGICAL, HYDROLOGICAL AND SPACE WEATHER PHENOMENA IN SITE EVALUATION FOR NUCLEAR INSTALLATIONS

6.1. This section provides recommendations on other natural phenomena that can occur and that are not already considered in other Safety Guides. All of the phenomena considered have the potential to affect the safety of nuclear installations by causing common cause failure for systems important to safety, such as electrical power supply systems, decay heat removal systems (e.g. ultimate heat sink) and other vital systems. Some of these phenomena are related to meteorological or hydrological hazards (e.g. wildfire, drought) and some are not (e.g. space weather hazards).

WILDFIRES

6.2. Wildfires (referred to as forest fires in SSG-35 [6]) are considered as fires occurring in forests, grasslands or wildland areas. As recommended in para. 4.3 of SSG-35 [6], the potential impact of forest fires should be considered during site selection for a nuclear installation. Considerations should include whether climate change or land use change may be expected to increase the range, frequency or intensity of wildfires.

6.3. In areas where there is a potential for wildfires, the potential hazard to structures that contain radioactive material or SSCs important to safety should be evaluated.

6.4. The likelihood of fire ignition and propagation to the site should be assessed. Factors such as weather conditions, forested areas close to the site (typically within 10–30 km), historical fire patterns and the most probable wind direction should be considered. If this likelihood is considered sufficiently high, for example based on historical fire frequency, fire danger indices, proximity of vegetation, and prevailing wind patterns, the hazard to the nuclear installation should be evaluated.

6.5. To characterize the potential for wildfire hazards at a nuclear installation site, consideration should be given to the amount of burnable mass (vegetation) in the immediate vicinity of the site, with additional consideration of the regional characteristics. Consideration should also be given to the range of conditions and the intensity of a wildfire in proximity to the installation (e.g. burn rates of a wildfire serve as input to how hot the fire is and the speed at which it travels).

6.6. The following should be taken into account in the hazard evaluation for wildfires:

(a) The direct effects of wildfires include heat flux, smoke, embers, and ash. Wildfires can also cause significant disturbances on the electrical grid, which can lead to loss of off-site power[52]. Wildfires might also restrict site access (e.g. and affect the ability to bring in additional resources).

(b) Wildfires have the potential to change the characteristics of the landscape around a nuclear installation site. For example, wildfires can increase flooding risks by destroying vegetation that absorbs water and stabilizes the soil, leading to more surface runoff during heavy rain events. Burned trees and loose soil contribute to debris flows, which can block streams and increase flood hazards. Additionally, the loss of forest cover alters water flow patterns, potentially causing rivers and streams to experience higher and faster flows, making affected areas more prone to flash floods and erosion. These secondary hydrological effects may be long-lasting and should be accounted for in multi-hazard scenarios affecting the site.

DROUGHT

6.7. Drought is closely related to several meteorological parameters such as precipitation, temperature, and humidity. The following should be taken into account in the hazard evaluation for drought:

(a) Drought conditions inside a selected area are driven by the amount of precipitation within an extended period, the run-off of water, and evaporation of water from the soil and vegetation from this area.

(b) Droughts are usually described and quantified by drought indices, which may be specific for certain regions like arid regions or are more generalized. Commonly used drought indicators are the Palmer drought severity index, the standardized precipitation index, and the standardized precipitation evaporation index.

(c) Droughts may, in the long run, impact the availability and temperature of cooling water from the adjacent water body or from groundwater tables through wells. Droughts are not a direct hazard at a site, but can lead to low water levels (see paras 5.182–5.186).

(d) Droughts may impact the nuclear installation site directly through changes in ground settling behaviour, most likely through additional not anticipated differential settlement, possibly impacting buried pipes, cable ducts, or other components.

(e) Droughts may enhance the likelihood or intensities of wildfires, sandstorms, and dust storms, and can result in changes to the landscape through deforestation, subsequent erosion, and changes in the water retention capacity thus impacting flooding hazards.

6.8. Climate change directly impacts at least two driving factors for drought (temperature and rainfall) although the regional impact may vary greatly and may also be impacted indirectly by changing wind, blocking weather patterns, changes in vegetation or other factors. The impact of climate change on the likelihood and severity of droughts should therefore carefully be assessed.

BIOLOGICAL PHENOMENA AND DEBRIS

6.9. Biological phenomena is a general term that covers a large variety of phenomena, including:

[52] In certain situations where there is high likelihood of wildfires (e.g. high intensity winds combined with high fuel loads and drought conditions), transmission lines may be shut down to avoid liability for wildfire, resulting in loss of an off-site power source even though a fire has not occurred.

(a) Massive arrival of debris[53]:
  (i) In the water (e.g. seaweed, aquatic plants, fishes, wood);
  (ii) In the air (e.g. leaves, pollen).
(b) Massive developments of biological organisms into specific systems of a nuclear installation:
  (i) In the water (e.g. as biofouling, development of mussels);
  (ii) In the air or on land (e.g. rodent invasion, insect infestation).

6.10. The arrival, or internal development, of biological organisms might affect: the availability and/or quality of cooling water; the availability and/or quality of air used by the ventilation system; and the thermal efficiency of heat exchangers due to fouling. For example, a total loss of cooling water can occur due to marine ingress, malfunction in ventilation systems might occur because of clogging by leaves in the inlet system, instrumentation and control cables can be affected by corrosion assisted by bacteria.

6.11. In the case of massive arrival of debris, the nature of debris involved in such events can be significantly different depending on the site location, the season, or from one year to another. These debris can be categorized as follow:

(a) Fauna: this kind of debris corresponds to fish, jellyfish, mussels, clams, shrimp, seal or other animal life present in the site region.
(b) Flora: this kind of debris corresponds to algae, aquatic plants, wood particles, trees, leaves, or other plant, bacterial, or fungal life possible at a site.
(c) Non-biological: this kind of debris includes all material of non-organic origin that may be moved in large quantities by meteorological or hydrological processes to impact a nuclear installation. This may include wind-driven snow, sand and dust, small stones, water-borne sediments, plastics and pumice.

In some events, debris can be composed of a mix of both biological and non-biological material.

6.12. In the case of development of biological organisms and/or proliferation of debris, the nature of these organisms or materials can be significantly different considering the site location, the seasonal or yearly fluctuations, or the SSCs of the nuclear installation. Historical records should be analysed to ensure that SSCs important to safety could not be adversely affected by the presence of biological organisms or debris to provide data for evaluating the hazard.

6.13. Accurate quantification of the intensity of biological phenomena is generally not possible. For some non-biological debris (e.g. wind-driven plastics), accurate quantification is also not-possible. Hazard evaluations for biological phenomena should generally be based on:

(a) Identification of the species existing in the vicinity of the nuclear installation site;
(b) Potential initiators that can bring the debris to the site (e.g. marine currents, high river flow, winds, biological thermotaxis);
(c) Expected potential impacts from these biological species on the nuclear installation;

[53] For the purposes of this Safety Guide, debris represents any material, organic or non-organic, that is advected through the air and/or water. This does not include human induced external hazards or events, recommendations for which are provided in SSG-79 [4].

(d) Monitoring of the biological species (growth rates, changes with time);
(e) Methods for prevention and mitigation of impacts on the nuclear installation.

Special consideration should be given to expected periods of increased biological phenomena that could impact the SSCs at a site.

6.14. Recommendations are provided in SSG-68 [10] on the design of protection measures against biological (both fauna and flora) and non-biological debris.

ICE (FRAZIL ICE AND ICE FLOES)

6.15. Ice formation in the body of water adjacent to the facility might have the potential to affect a nuclear installation site. Two forms of ice are of primary concern:

(a) Frazil ice, which may lead to clogging of cooling water systems.
(b) Floating ice floes or pack ice, which may lead to ice jams in the adjacent water body, or which may lead to damage to flood control structures (e.g. levees) or SSCs.

6.16. Frazil ice develops in turbulent, supercooled water environments such as river rapids and riffles. This supercooling typically happens during cold, clear nights when heat loss to the atmosphere is high. Frazil ice crystals manifest as small particles distributed throughout the water column. When frazil ice forms nearby, these crystals, together with the supercooled water, can be drawn into cooling water systems, potentially causing rapid clogging. The possible presence of frazil ice should be taken into account when designing cooling water intake systems.

6.17. An ice jam is any stationary accumulation of ice that restricts flow. Ice jams may be categorized as freeze-up jams made primarily of frazil ice, breakup jams made primarily of fragmented ice pieces, and jams that combine both. The following should be taken into account in the hazard evaluation:

(a) As the frazil particles are transported downstream, they join to form disk-shaped floes. These disks gradually rise to the surface where they stick together to form frazil pans that may in turn form into large ice floes. A jam forms when the floating frazil ice stops moving downstream and begins to accumulate.
(b) Break-up jams, which consist of fragmented ice, typically occur during thaw periods, often in late winter or early spring. These jams are formed when an ice cover breaks apart, resulting in broken ice pieces that move downstream until they encounter an intact downstream ice cover, another obstruction, a reduced water slope, or adverse hydraulic conditions. At these points, the fragmented ice pieces stop moving, accumulate, and form a jam. The size of the jam depends on the amount of ice coming from upstream and the size and strength of the ice pieces.
(c) The severity of flooding caused by these jams depends on the flow conditions. Breakup of the ice cover in late winter or early spring usually coincides with a rapid increase in runoff and river discharge, often due to significant rainfall or snowmelt. Due to the higher flows typically present during breakup periods, breakup jamming is usually the primary ice-related concern.
(d) Ice jams that affect the site can occur upstream or downstream the site. With an upstream ice dam formation two scenarios are possible. First, the flow rate at the site is drastically reduced until the ice dam is overtopped or broken, which may impact the cooling water

supply. Second, with the sudden breaking of an ice dam a flood wave is generated that may lead to rapid flooding of the site without warning time. With a downstream ice dam formation, the water level at the site may rise unexpectedly through backwater effects.

6.18. Considerations should be given to the potential for ice jams at or in the vicinity of a nuclear installation site. This should be based on the regional historical record, as well as a history of meteorological conditions that could lead to the formation of frazil ice. Potential locations for an ice jam include river bends, bridges, weirs, restricted flow paths and islands.

6.19. Drifting ice floes on a river may, especially if combined with increased flow rates, lead to damage to flood control structures such as levees. In addition, drifting ice floes in a flood situation with the water level reaching SSCs may lead to unanticipated mechanical impacts on SSCs. Potential damages to flood control structures or SSCs through drifting ice should be taken into account.

ICEBERGS

6.20. Icebergs are very large pieces of ice that have broken off from glaciers or shelf ice and are floating in open water. Smaller pieces of icebergs, known as ‘bergy bits’ are large chunks of ice floating in the sea, generally result from disintegrating icebergs. For the purposes of paras 6.21–6.24, the term ‘iceberg’ is inclusive of bergy bits.

6.21. In general, icebergs are not a hazard to nuclear installations. However, recent designs include reactors that are floating or are located at a fixed position off the coast (e.g. a platform). These may be present in areas where icebergs have historically been observed. For installations off a coast, or out at sea, icebergs may pose a risk of either damaging the reactor SSCs or transport vessels.

6.22. A description of the recorded history of icebergs in a site region should be provided if this is determined to be a credible hazard. Depending on the shape of the nearby coastline (if close enough to influence local currents) and the prevailing winds in the site region, the area under consideration could vary greatly from one site to another. Since icebergs are a transient hazard and move primarily based on water (or tidal) currents and secondarily based on wind patterns, if a nuclear installation is located off the coast and relies on sea transport (e.g. for supplies and personnel), the potential for icebergs along the transport routes should be considered.

6.23. Classification[54] of icebergs should include the historical range of visible ice, based on height and width for a site region. Typically, around 90% the total mass of an iceberg is underwater; therefore, an estimate of the dimensions of the iceberg below the water surface should also be provided.

6.24. In cases where a floating nuclear installation is moved from one location to another, consideration and precautions should be taken to document the location of existing icebergs that are near or along the path of transport.

[54] Different national and international organizations provide classification schemes for icebergs. These organization include the World Meteorological Organization, the United States National Oceanic and Atmospheric Administration and the International Ice Patrol.

SALT SPRAY

6.25. Salt sprays are emitted by breaking waves, both nearshore and offshore and by waves impacting on coastal structures, and are transferred inland by wind. The evaluation of the hazard due to salt spray should take into account the following:

(a) Sea salt may be deposited on the surfaces of equipment at nuclear installation sites located near coastal areas. The amount of accreted sea salt depends on wave height, wind speed, locations and types of coastal structure, distance from coastlines, and surrounding buildings.
(b) Rapid deposition of sea salt on insulators can cause insulation failures, and accumulation of sea salt due to long term deposition can cause corrosion of transmission towers, power lines and other equipment. Rapid accretion of wet and hard packed snow containing sea salt, can lead to salt deposition on insulators and can cause insulation failures, resulting in insulator flashover.
(c) Sea air contains a small amount of salt particles that can be carried inside the nuclear installation. This can lead to stress corrosion cracking of stainless steel components important to safety.

SPACE WEATHER

6.26. Space weather hazards refer to adverse and potentially disruptive conditions in the space environment, primarily influenced by solar activity and the solar wind. Solar activity can vary with time and generate massive coronal mass ejections or energetic particles. The evaluation of the hazard due to such phenomena should take into account the following:

(a) On Earth, the phenomena can induce geomagnetic disturbances and/or irradiation by high-energy particles (mainly neutrons) generated by energetic solar particles. These phenomena can, for example, damage satellites, the electricity network and electronic devices, and disrupt communication and navigation systems.
(b) A single solar event can give rise to multiple phenomena. For example, high energy particles arrive first (within minutes) while the magnetic disturbances arrive later (after about 18 hours or more).
(c) The electrical equipment of a nuclear installation that could be impacted by the geomagnetic currents can be all electrical equipment that are grounded, or that are included in an electrical loop allowing the flow of direct current.

6.27. The estimated exposure to space weather hazards should be evaluated in the site characterization process. Generally, polar regions are more prone to solar activity, however sites in the mid-latitudes may be affected on a less frequent basis. If needed, protective measures, such as specific electrical insulation or particular electrical configurations should be implemented.

METEOROIDS AND METEORITES

6.28. Meteoroids and meteorites[55] are a regular phenomenon. Meteoroids (i.e. travelling through space) range from sub millimetre size to kilometre size. Known impact velocities at the top of the atmosphere are up to 72 km/s. The probability of meteoroids impacting on the top of the atmosphere does not vary much with geographical location. The evaluation of the hazard due to meteoroids and meteorites should take into account the following:

(a) Small meteoroids usually disintegrate in the upper atmosphere and the fractured pieces vaporize due to the extensive heat generated through collisions with atmospheric particles and molecules. Bigger meteoroids become meteorites, which are portions of meteoroids that do survive the impact with the earth's atmosphere and impact the earth's surface.
(b) For meteorites impacting the earth's surface with free fall velocity (i.e. meteorites stopped by the atmosphere) damage to SSCs of a nuclear installation are feasible from direct hits. Additional damages may result from a pressure wave due to the air burst of the original meteoroid.

6.29. The hazard evaluation for meteoroids and meteorites should start with the incident rate at the top of the atmosphere, which is documented in scientific literature. For the hazard evaluation, a distinction should be made between meteoroids small enough to disintegrate in the earth's atmosphere and vaporizing before hitting the earth's surface, and meteorites i.e. that actually hit the surface. With regard to meteorites, a distinction should be made between meteorites that hit the earth's surface with free fall velocity (i.e. after losing their initial velocity through impact with the atmosphere) and meteorites big enough to retain most of their initial velocity at the top of the atmosphere.

6.30. If it is necessary to evaluate the hazard to a nuclear installation from a meteorite impact, a spectrum of meteoroids at the top of the atmosphere — ranging at least from several centimetres in diameter to several tens of metres —with a range of impact velocities and impact angles at the top of the atmosphere should be considered.

6.31. For meteorites hitting the earth's surface with most of their initial velocity, several other impacts on the nuclear installation site (i.e. in addition to a direct hit on SSCs) are possible and should be evaluated, if necessary. Meteorites with most of their initial velocity create craters with depths and diameters commensurate with the impact energy on the earth's surface. These impacts produce ejecta, pressure waves, heat blasts, vibratory ground motions and — if they impact on large water bodies — tsunami-like phenomena all of which may hit a nuclear installation even if the impact point is far away from the nuclear installation site. The potential impacts should be considered in the hazard evaluation.

7. DEVELOPMENT OF DESIGN BASIS AND BEYOND DESIGN BASIS PARAMETERS IN SITE EVALUATION FOR NUCLEAR INSTALLATIONS

[55] Usually, meteoroids and meteorite impacts are excluded from further considerations due to the overall low occurrence frequency of large meteorites with damage potential. In some member states, there are no regulatory requirements for hazard evaluation of these events. Additional considerations may be taken for meteorites impacting large enough water bodies and generating tsunami like waves.

7.1. SSG-68 [10] provides recommendations on the derivation of design basis events based on the hazard evaluations described in this Safety Guide. This includes recommendations on design against design basis events, deriving external event loading conditions, and what to consider for beyond design basis events.

7.2. Site specific hazard evaluation and engineering design should be integrated and iterative. Both activities involve a common understanding of the potential hazards, the controlling hazards that drive the design, the parameters needed for engineering design, as well as a clear understanding of the interfaces between the two activities.

7.3. The hazard evaluation should identify the hazards for which the nuclear installation is to be designed to withstand, and should provide hazard magnitudes and, where applicable, annual exceedance frequencies. The hazard evaluation should also document the assumptions made in the process, describe evaluation methods, including screening, and characterize and quantify uncertainties.

7.4. The hazard parameters derived in accordance with Sections 4–6 of this Safety Guide might not completely determine the design of SSCs important to safety for the nuclear installation. It is an engineering task to derive the actual loads on SSCs, whether it be thermal, mechanical or other loads. For example, the wind loading on a structure is a function of the geometry of the structure as well as the wind speed. Some thermal loads, such as ambient air temperature, are also used in combination with other factors for considerations on the ageing of components (e.g. electrical components and their insulation) or certain systems like the heating, ventilation and air-conditioning system. Recommendations on the derivation of external event loading conditions are provided in SSG-68 [10].

7.5. The derivation of design basis parameters may be influenced by other considerations, such as national regulations, preference for use of standard designs, constructability, and operational and maintenance considerations. However, these considerations, should not override safety considerations.

7.6. Although a given hazard might not impose a safety constraint on the design, designers may choose to include it for other reasons such as operational efficiency or maintenance. For example, high water temperatures in a lake or river that does not provide the ultimate heat sink, could still be important to the design because of ecological constraints on operations.

7.7. Often the available data for quantifying the hazard severity at low annual exceedance frequencies is sparse, leading to large uncertainty or wide confidence intervals. If additional data cannot be collected to reduce uncertainty, reasonably conservative values should be used. This might include, for example, using a higher quantile estimate (e.g. 85th percentile rather than the mean estimate), or simply adding additional margin.

DEVELOPMENT OF METEOROLOGICAL DESIGN BASIS PARAMETERS

7.8. In general, each meteorological hazard should be determined individually. However, credible combinations that might compound or increase the hazard effect should be considered[56]. For example, freezing precipitation and winds can be an important combination

[56] For the purpose of obtaining information on the temporal distributions of different input variables, the characterization of all input parameters as random processes, with given autocorrelation and cross-correlation functions, would be desirable. However, simplified approaches may assist in establishing adequate load combination criteria.

when determining loads on some structures. In addition, conditions representing maximum evaporation and drift loss, as well as high water temperature, should be considered for designing certain types of ultimate heat sink. Meteorological events that drive hydrological events, such as precipitation, should be addressed in conjunction with hydrological hazards. Annex I contains example sets of meteorological design basis parameters used for nuclear installations.

7.9. The values of the design basis parameters may be derived by statistical or probabilistic approaches, associating magnitudes to annual exceedance frequencies (or average return periods), or else derived by deterministic approaches (e.g. historically observed worst case meteorological conditions with added margin). Consideration should be given to the potential for variability of hazard parameters over long time periods, including changes induced by climate change (e.g. increased air temperature, altered wind and precipitation patterns, increased frequency of extreme events), based on the expected lifetime of the nuclear installation. This consideration should be informed by the recommendations provided in Section 9.

DEVELOPMENT OF HYDROLOGICAL DESIGN BASIS PARAMETERS.

7.10. The estimation of the design basis external flood for a nuclear installation should include consideration of individual extreme events, as well as combinations of events. Combined events should be considered because the controlling flood may arise due to simultaneous or sequential events, each of which is in itself less severe than the resultant combined extreme event. The interdependence of the potential flood causing phenomena should be examined in relation to the specific characteristics of the site. In addition, sensitivity analyses should be conducted to ensure that the design basis flood takes into account relevant and significant uncertainties involved in characterizing and quantifying natural events.

7.11. Flooding mechanism combinations can be coincident (i.e. concurrent, but independent hazards), concurrent correlated (i.e. two or more mechanisms happening at the same time, but are associated with the same flood causing phenomena) or correlated induced (i.e. one flooding mechanism induces one or more other flooding mechanisms). An example of coincident combination is riverine flooding due to a seismically induced dam failure that occurs concurrently with rainfall-induced flooding in the watershed or locally at the site. An example of a concurrent correlated combination is when both storm surge flooding and rainfall runoff flooding at an estuary or tidal river site are caused by the same storm event. An example of a correlated induced combination is when flooding at a riverine site is due to rainfall runoff flooding that induces a hydrologic dam failure. However, for some flood causing event combinations the distinction between dependent events and independent events is not always clear. For example, sequential precipitation events may be weakly correlated and hard to distinguish from fully independent events.

7.12. The annual frequency of exceedance for each combination should be estimated, if possible. The probability of combined events should be based on the development of models of the phenomena of interest as random processes. If the processes are judged to be independent, then their joint occurrence should be represented by the product of their individual probability functions. When processes are dependant, a joint probability distribution should be developed (e.g. by direct estimation or by copula approaches). All credible combinations of events should be carefully analysed taking into account the stochastic and non-linear nature of the phenomena involved as well as any regulatory requirements or guidance applicable for such cases. Furthermore, the antecedent conditions relevant to the flood causing events or event combinations should also be taken into account.

7.13. The likelihood of certain combinations may be related to the duration of one or more events in the combination. For example, a riverine flooding event on a large river could last for weeks to months, which impacts the probability of other compounding flood events occurring during this period (e.g. dam failure). Extended periods of wet weather may increase the likelihood for landslide-induced flooding events.

7.14. A target annual frequency of exceedance for screening event combinations should be established in accordance with regulatory requirements and the relevant reference water levels. Certain combinations of events can be excluded from consideration provided that:

(a) The postulated combination does not produce an effect at the site (i.e. negligible consequence);
(b) The annual frequency of exceedance for the combined event is less than the established screening target; or
(c) The combination is considered not physically plausible.

7.15. For certain combinations, quantitative probability estimates are difficult to determine and simplified qualitative or deterministic methods should be applied to take uncertainties into account. Engineering judgement should be used in selecting the appropriate combinations and simplifications (i.e. to ensure conservatism). For example, coastal marine conditions and river conditions as well as local precipitation could influence selection of combined events for estuary sites.

7.16. Wind wave activity should be considered in association with many flooding events, taking into account the following:

(a) Floods generated by meteorological events are often associated with high intensity winds.
(b) In a storm surge or a seiche, wind waves are a dependent event and the waves generated by the storm producing the surge should be considered.
(c) For tsunamis and riverine flooding, the coincidental occurrence of extreme wind waves is considered unlikely and only wind waves with a shorter recurrence interval should be considered in the combination. For example, some States analyse riverine flooding at recurrence intervals of 10,000 years or more but combined with waves associated with 10–100 year winds.

7.17. A seiche may be initiated by several means (e.g. fluctuations in barometric pressure, storm surges, variations in wind speed, tsunami, and incident wave trains). Thus, the occurrence of seiches may depend on other flood causing events described in this Safety Guide. This should be considered in selecting the appropriate event combinations for a site where seiches can be important.

7.18. Where applicable, the impact of associated effects on design basis flood parameters should be considered. For example, the predominate flood causing process could be modified by associated effects such as, debris dams, ice effects and erosion.

7.19. The design basis low surface water level or low flow parameters may be influenced by several processes (e.g. drawdown due to tsunami or seiche, failure of a downstream water control structure, prolonged drought). The processes, or combination of processes, applicable to the site should be evaluated to determine the design basis low water level or low flow parameters.

7.20. Depending on the site and the design of the nuclear installation, both low groundwater level and high groundwater level may constitute the design basis groundwater parameters.

DEVELOPMENT OF DESIGN BASIS PARAMETERS FOR OTHER NATURAL HAZARDS

7.21. The other natural hazards considered in Section 6 should also be considered in the development of design basis parameters. In general, each of these hazards should be determined individually. However, credible combinations (including combinations with meteorological and hydrological hazards) that may compound or increase the hazard effect should be considered. For example, clogging due to sediments and water-borne debris may occur at the same time, and be driven by the same hydrological processes. Wildfires are more likely during prolonged drought conditions. Wildfire impacts on land cover and soil conditions may modify the frequency and intensity of flooding events. These hazards should be considered in site evaluation and in considering site protection measures (see Section 8).

DEVELOPMENT OF BEYOND DESIGN BASIS PARAMETERS

7.22. As stated in footnote 3 of SSG-68 [10]:

> "The term 'beyond design basis external event' is used to indicate a level of external hazard exceeding those hazard levels considered for design, derived from the hazard evaluation for the site. The purpose of identifying beyond design basis external events is to ensure that the design incorporates features to enhance the capability of the installation to withstand such events. In addition, the identification of such events is used in evaluating the margins that exist in the design and in identifying potential cliff edge effects."

7.23. Beyond design basis external events and associated beyond design basis hazard parameters should be based on the site characterization and evaluation. As with selection of design basis hazard parameters, hazard evaluation and the engineering design should be integrated and iterative with respect to the selection of beyond design basis hazard parameters.

7.24. The hydrological, meteorological and other natural hazards considered in this Safety Guide have the potential to affect the site region, and external resources for the site: consequently, such regional impacts should be also considered in the beyond design basis hazard evaluation, particularly in relation to the duration of hazard effects. Such impacts include loss of off-site power, and challenges in relation to access to the site and the availability of off-site resources used in the emergency preparedness and response.

7.25. One approach to deriving beyond design basis hazard parameters is to apply an additive margin or multiplicative factor to selected design basis hazard parameters (or to selected inputs or intermediate parameters in the hazard evaluation process). The choice of the parameters and the magnitude of the additive or multiplicative factor should be based on their impact on the hazard levels (e.g. peak flood discharge drives water levels for riverine flooding). Another approach is to postulate an event or a combination of events that were excluded from the definition of design basis hazard parameters (e.g. failure of water retaining structures that were considered as safe for the design basis flooding hazard). These two approaches can be used regardless of whether the hazard evaluation uses deterministic, statistical or probabilistic methods. For statistical or probabilistic methods, to ensure that the frequency or probability of the beyond design basis hazard parameter is assessed correctly, the likelihood of the additive margin, multiplicative factor, or additional postulated event should also be estimated.

7.26. Another approach, which can be applied to statistical or probabilistic hazard evaluations is to adopt a lower annual exceedance frequency than that specified for the design basis external event. Generally, this approach should include additional data and/or additional model runs to ensure statistical stability in the computed hazard level quantile and confidence limits at the lower frequency.

7.27. The available margin and identification of potential cliff edge effects should be assessed by reevaluating relevant loading cases using the beyond design basis external hazard parameters. While available margin quantification is usually straightforward, identification of potential cliff edge effects may be significantly more complex. Multiple trials, adjusting different factors by different amounts, should be considered to ensure that particular cliff edge effects are revealed.[57] For any identified potential cliff edge effects, the following should be determined for use in engineering design:

(a) The external event (or combination of events) for which a cliff edge effect could occur;
(b) The change in severity (or duration) of the event at which the cliff edge effect could occur;
(c) The hazard parameter or loading condition corresponding to triggering the cliff edge effect;
(d) The exceedance frequency of the triggering hazard level (if practicable).

8. SITE PROTECTION MEASURES IN SITE EVALUATION FOR NUCLEAR INSTALLATIONS

8.1. This section provides recommendations on measures for protecting a nuclear installation site from the effects of the meteorological, hydrological and other natural hazards addressed in Sections 4–6. Selection of site protection measures should be based on a thorough understanding of the meteorological, hydrological and related features of the site and its surroundings. Protecting the site or mitigating the impacts on the site is, in general, feasible for hazards such as wildfires and flooding from nearby water bodies. In general, permanent passive protection features should be preferred over temporary or active protection measures.

8.2. This section focuses on protection of the site, whereas SSG-68 [10] provides specific recommendations on the design of the nuclear installation (i.e. specifically the SSCs of the installation) to cope with the effect of external events, excluding earthquakes. Thus,

[57] For example, in the case of an earthen berm designed to provide flood protection at a coastal site, a cliff edge effect such as overtopping of the berm and subsequent flooding could be identified by postulating progressively higher flood water levels. Another cliff edge effect such as erosional failure of the berm due to wave action would be revealed by increasing the duration of the flooding event.

recommendations on flood barriers directly connected with the nuclear installation structures (e.g. retaining walls, penetration closures/seals) are provided in SSG-68 [10]; recommendations on geotechnical aspects of these structures are provided in NS-G-3.6 [5].

8.3. Recommendations on procedures for site protection and event response are provided in IAEA Safety Standards Series No. SSG-77, Protection Against Internal and External Hazards in the Operation of Nuclear Power Plants [12]. The safety of personnel should be considered during an event (e.g. when high intensity winds, heavy precipitation, or flood waters are impacting the site). Consideration should also be given to limitations and uncertainties in event forecasts or warnings and the evolving nature of the event. Periodic safety reviews, as required in SSR-1 [1], should be used to reassess site protection measures in light of evolving hazard information, new scientific knowledge (e.g. climate change projections), and operational experience.

FLOOD PROTECTION

8.4. A nuclear installation site should be protected against external flooding from nearby water bodies such as rivers, lakes or the sea using one of the following approaches[58]:

(a) The 'dry site' concept: certain items important to safety are constructed above the assessed flood level from nearby water bodies, with account taken of wind wave effects and effects of the potential accumulation of ice and debris (some items such as cooling water pumps relied on for the ultimate heat sink could still be exposed to flooding from nearby water bodies and should have additional protection). This should be accomplished by locating the nuclear installation at a sufficiently high elevation or by means of construction arrangements that raise the ground level at the site. If any engineered fill is necessary to raise the ground level, this should be considered as an item important to safety and should therefore be adequately designed and maintained (e.g. engineered fill may need to take into account seismic design requirements).

(b) Permanent external barriers such as levees, sea walls and bulkheads: these should be considered as items important to safety. Care should be taken that appropriate design bases (e.g. for seismic qualification where relevant) are selected for the design of the barriers. Levees, sea walls and bulkheads should be designed to ensure that these external barriers do not act as a dam preventing drainage of water from the site (in some cases additional measures such as pumps may be necessary). Periodic inspections, monitoring and maintenance of external barriers should be conducted. In some cases, this may involve agreements and/or coordination with organizations external to the nuclear installation.

8.5. In some cases, protection can be achieved by a combination of the two approaches outlined in para. 8.4. For both approaches, a defence in depth strategy should be adopted. In addition to site protection provided by site elevation or permanent barriers, protection of the nuclear installation should be augmented by waterproofing and by the appropriate design of all SSCs necessary to ensure that the fundamental safety functions are fulfilled. Careful assessment should be applied in both approaches with respect to local intense precipitation, which may lead to unexpected water levels and flow velocities on the site.

[58] In most States method (a) is preferred to method (b) which includes the construction of permanent external barriers.

8.6. Considerations for protecting a nuclear installation site from the impact of flooding hazards should also include the following aspects:

(a) The effectiveness of pre-existing flood protection features (e.g. dykes, levees, dams for flood protection of the surrounding area).
(b) Possible interactions between the site protection structures and the nuclear installation structures or operations (e.g. flood barriers might hinder site access).
(c) The impact of constructed structures, including flood controls structures, may change the flooding behaviour at the site relative to pre-construction conditions (e.g. water level may change). Construction of flood control structures, including on-site flood protection, may involve changes to the flood model developed before modifications to the site area (e.g. changes to stage-discharge relationships, infiltration rate and impervious areas, roughness coefficient). A conservative approach should be taken to estimating changes to water level due to the construction of on-site flood barriers; consequently, the site area should be assumed to be impenetrable to water in the flood modelling.
(d) The feasibility and effectiveness of temporary flood protection measures, such as:
    (i) Temporary levees, berms and closures;
    (ii) Portable pumps.
(e) The reliability of flood protection structures should be analysed in a manner similar to that for the other structural items important to safety. For example, flood events themselves will present challenges to the structure (e.g. hydrostatic and hydrodynamic forces, flood-borne debris and ice, erosion).

SITE DRAINAGE

8.7. The site should be properly graded to drain local intense precipitation away from SSCs important to safety. Recommendations on design considerations such as site drainage systems, protection of doorways and other openings are provided in SSG-68 [10].

8.8. On-site water control structures (e.g. ponds, tanks, cooling tower basins) should be located and designed such that uncontrolled releases drain away from SSCs important to safety.

SITE PROTECTION FROM WILDFIRE

8.9. Nuclear installation sites should implement various practical safety measures to protect from wildfire. Common precautions include:

(a) Vegetation should be managed and cleared for an appropriate distance surrounding the installation to reduce the potential impact of wildfires spreading to the facility. This can be achieved through vegetation management practices.
(b) Firebreaks (physical barriers that are designed to prevent the spread of fires) should be constructed, where deemed appropriate. These can be roads, cleared areas, or other obstacles that hinder the progress of wildfires.
(c) Systems for wildfire detection and warning, where available (e.g. from national meteorological services), should be used to provide early warning.

8.10. Recommendations on the design of the nuclear installation to prevent smoke and heat from fires of external origin from impairing the fulfilment of safety functions and the stability of structures important to safety are provided in SSG-68 [10].

DISRUPTION OF OFF-SITE POWER, TRANSPORT ROUTES AND MEANS OF COMMUNICATION

8.11. Operating experience highlights the potential disruption of the electrical grid (leading to a loss of off-site power), transport routes, and means of communication at and around nuclear installation sites as a result of many of the external hazards described in this Safety Guide. Conditions at and around the site might lead to additional challenges, which include contacting outside emergency personnel, the turnover of operator shifts, and the dissemination of information to the public.

8.12. When possible, the operating organization in coordination with local authorities, should make adequate provisions to ensure the availability of means of transportation to and from the site. Consideration should be taken to ensure the transportation of personnel to and from the site, supplies such as fuel, and any other items to maintain the installation in a safe state. Such functions should be guaranteed for the duration of the response to external events.

8.13. The availability of means of communication during and after the external event might not be under the direct control of the operating organization. Since the availability of such means of communication is a key part of external event response and emergency planning, a dedicated analysis of the external event scenario should be performed together with the relevant authorities.

9. EVALUATING CHANGES OF HAZARDS OVER TIME IN SITE EVALUATION FOR NUCLEAR INSTALLATIONS

9.1. During initial site evaluation, potential changes in hazards with time should be considered and estimated, where feasible. To take into account changes in hazards with time additional safety margin(s) should be considered in the design of nuclear installations (see Section 7).

9.2. Hazard re-evaluation should be performed periodically during the operation of the nuclear installation, as well as following a hydrological, meteorological or other extreme event, to ensure that sufficient safety margins are maintained[59]. Regardless of national requirements for periodic review, the nuclear installation operating organization should maintain awareness of potential changes in hazards. For example, climatological, meteorological, hydrological, and geological monitoring data can be reviewed periodically to identify trends or changes that indicate the need to re-evaluate hazards or protection strategies. Changes in hazards parameters can be detected by making periodic surveys of conditions in the region. These surveys of conditions should be performed at specified intervals or after a ‘significant’ event (e.g. extensive forest fires, construction of dams, levees, bridges). Physical conditions can be surveyed mainly by means of aerial surveys, and remote imaging and sensing (e.g. satellite imaging), supplemented, as necessary, with ground surveys.

[59] Some States require periodic hazard re-evaluation at fixed intervals (e.g. 5 years, 10 years) while others perform continuous monitoring and reassess hazards after ‘significant’ events.

9.3. Various causes of change to meteorological hazards over time should be considered, including:

(a) Regional climate change associated with global warming;
(b) Changes in global climate patterns (i.e. teleconnections);
(c) Land cover or land use change in the area around the site that could affect wind patterns and temperature observations.

9.4. Various causes of change to hydrological hazards over time should be considered, including:

(a) Changes in climatological and meteorological drivers (e.g. sea level, precipitation, temperature, winds) due to climate change or natural changes in global climate patterns;
(b) Physical geography or geomorphology changes in the site region due to geologic processes (e.g. changes in drainage basins, estuaries, coastal profiles, or offshore bathymetry);
(c) Land cover or land use changes in the area around the site (e.g. urbanization driven changes in impervious surface area, land cover changes impacting rainfall runoff in river basins or local flooding behaviour);
(d) Changes in river regulation (e.g. construction, modification, or removal of water control structures).

9.5. Changes in the other natural hazards described in Section 6 should also be considered.

CHANGES DUE TO CLIMATE CHANGE

9.6. Due attention should be paid to the implications of climate variability and change, and in particular, to the possible consequences in relation to meteorological, hydrological and other natural hazards that should be considered for the planned operating lifetime of the nuclear installation[60]. Over such a period, it is expected that the global climate is likely to undergo changes, with regional variability. Consequently, the variability of and changes in regional climate should be considered, with account taken of uncertainties in the climate projections (see Annex IV). Uncertainty in climate projections are typically addressed by using multiple models (i.e. model ensembles) and regional downscaling.

9.7. Climate change projection models are increasingly considered as part of the hazard evaluation. Historical data might not fully represent the future climate and extreme event conditions due to climate change. Therefore, observational records should be supplemented or extended using climate model outputs. Practical approaches should be considered as a means of enhancing the prediction capabilities of extrapolation methods beyond historical patterns, such as:

(a) Enhancing hazard calculations by integrating regional or local climate change trends into historical data[61] (see Table IV- 2 in Annex IV).
(b) Developing a composite synthesis dataset that integrates climate projection data with historical data.

[60] In some Member States the expected lifetime for nuclear power plants is 80- to 100-years.
[61] For example, for temperature assessments, a range of 1.5–4.4 degrees Celsius could be applied, varying by time horizon and climate scenario.

(c) Updating climate projections as new information becomes available (e.g. during periodic safety reviews).

9.8. Annex IV gives information on the contents of the Intergovernmental Panel on Climate Change Sixth Assessment Report, World Meteorological Organization relevant reports, and on the likelihood of future global trends on the basis of projections for the twenty-first century made by using greenhouse gas emission scenarios and different climate models. Regional trends could be different from the global projections. Regional models should therefore be used, if available[62]. Results for the distant future are still affected by large uncertainties resulting from both greenhouse gas emission scenarios and climate models. Local observations should be used for statistical analysis to take account of observed trends and could be used for extrapolation to evaluate extreme parameters in the short term (i.e. a few decades).

9.9. The major effects that should be considered with regard to hazards to nuclear installation sites are related to the following causes:

(a) Changes in air and water temperatures;
(b) Changes in sea level;
(c) Changes in the frequency of occurrence and in the intensity of some meteorological and hydrological phenomena considered in this Safety Guide (e.g. tropical cyclones, storm surge, precipitation, heat and cold waves, and drought).

The extent to which these changes varies across regions and subregions should be taken into account.

9.10. Climate models show that both air and water temperatures will continue to rise over the next decades, with varying degrees of acceleration depending on the region and local climatic factors. It is likely that sea level will rise, although not uniformly across regions, in more than about 95% of the ocean area by the end of the century. In general, the intensity, frequency and duration of meteorological and hydrological extreme phenomena, such as intense tropical cyclones, storm surges, heavy precipitation, drought and hot extremes will continue to increase and those of cold extremes will continue to decrease, at global and continental scales. The projected increase in the intensity of heavy precipitation translates to an increase in the frequency and magnitude of pluvial floods, surface water and flash floods. Therefore, these expected changes should be considered in the hazard evaluation. Reference to the international practice, such as IPCC AR6 [13] and WMO guidelines [14], should be made in hazard evaluation, as important potential support to decision-making. These include:

(a) Downscaled climate prediction and projections regional data from global-scale models, including extremes;
(b) Implementation of a global archive giving access to individual and ensemble results of climate simulations; assessment of extremes from time series presenting a trend;
(c) Use of internationally recognized climate indices.

[62] WMO Regional Climate Centres (RCCs) are designed to assist WMO Members in a given region to deliver better climate services and products including regional long-range forecasts, and to strengthen their capacity to meet national climate information needs.

CHANGES DUE TO NATURAL CLIMATE PATTERNS

9.11. Due consideration should be given to the naturally occurring oscillations that may impact the local and regional weather patterns at a given site. For datasets with shorter timescales — of the order of a few years to a decade — consideration should be given to the phase of the oscillations and the possible effects on hazard evaluation. For the most accurate information at national or local level, the operating organization should consult with national meteorological and hydrological services.

9.12. Considerations on oceanic and atmospheric oscillations that are known to influence hazards described in Sections 4–6 on a larger scale should include:

(a) The El Niño/Southern Oscillation, which is a naturally occurring phenomenon involving fluctuating ocean temperatures in the central and eastern equatorial Pacific, coupled with changes in the atmosphere (e.g. changing tropical cyclone activities and rainfall patterns worldwide);
(b) The Pacific Decadal Oscillation, which covers vast areas of the Pacific Ocean over periods of 20 to 30 years. The associated change in location of the cool and warm water masses alters the path of the jet stream, changing (e.g. storm paths and intensities in the northern hemisphere);
(c) North Atlantic Oscillation which is an oscillation on the surface sea-level pressure difference between the Subtropical high and the Subpolar low. North Atlantic Oscillation phases may be a contributing factor (e.g. to the landfall probability for north Atlantic hurricanes and other phenomena, such as rainfall patterns and storm tracks).

CHANGES DUE TO GEOLOGIC PROCESSES

9.13. Consideration should be given to geological-driven changes resulting in changes to hydrological hazards at the nuclear installation site, for example:

(a) Uplift or subsidence due to tectonic processes can cause changes in erosion and sedimentation rates in river basins and changes in relative sea level in coastal or estuary sites, with subsequent changes in hydrological hazards (e.g. riverine flooding, tidal flooding, storm surge, tsunami).
(b) A sudden permanent uplift of the earth's surface due to an earthquake could result in a permanent low water scenario in areas close to large earthquake rupture zones. Similarly, a permanent subsidence of the earth's surface due to an earthquake could result in a permanent inundation in areas close to large earthquake rupture zones.
(c) Coastal sediment transport processes and shoreline erosion can result in changes to near-shore bathymetry and topography.

9.14. The stability of the shoreline near the site should be investigated together with the effects of the nuclear installation on the stability of the shoreline (e.g. blocking of littoral drift and subsequent updrift sediment accretion and downdrift erosion). The investigations should include the collection and analysis of all available historical data on the stability of the local shoreline. For sandy or silty beaches, the stability of the shoreline should be evaluated assuming onshore–offshore movement and the littoral transport of beach materials. When the coast is formed by cliffs, changes may occur in the coastline over a long period, and it may be possible to deduce this from historical maps.

9.15. To investigate the shoreline stability, it is usually not sufficient to consider only storms that cause severe storm surge because this might not produce the conditions critical to erosion. Seasonal occurrence of repetitive storm patterns and storms of rather longer duration or wind fields with directions such that they cause higher waves for longer duration at the site should be considered in the analysis of the effects of shoreline erosion.

9.16. An analysis of shoreline stability should include:

(a) An investigation to establish the configuration of the shoreline, including its profile (e.g. berms, dunes, human made structures, immediate bathymetry);
(b) An investigation to determine the typical distributions of the grain size or composition of the beach materials in the horizontal and vertical directions;
(c) A study of tidal movements (vertical and horizontal, including sea level changes), wave exposure and climatology;
(d) An assessment of the conditions for longshore transport at the site and at the facing seabed;
(e) An evaluation of the extent of movement of sand;
(f) Establishment of the trends in shoreline migration over the short term and the long term and of the protection offered by vegetation;
(g) Determination of the direction and the rate of onshore–offshore motion of sediment, of the expected shapes of the beach profiles and of the expected changes in their shapes;
(h) Evaluation of the impacts of the nuclear installation, including the cooling water structures, on the shape of the shoreline.

9.17. The following should be considered in studying the wave conditions (i.e. the heights of waves, their periods and the directions of their propagation) near the coast:

(a) Observations of the waves in the ocean area adjoining the coast;
(b) Local wind data from the region;
(c) Data of greater detail and reliability obtained by recording the wave conditions with wave gauges for at least one year;
(d) Wave patterns extrapolated from a similar location nearby if local data are not available.

9.18. The computation of the longshore transport for determining the long term stability of the shoreline and its stability under severe flood conditions needs data on the heights, periods and directions of breaking waves, which should be evaluated by means of wave refraction diagrams, and data on the characteristics of beach sediments.

9.19. Theoretical predictions are of unknown accuracy and might not be applicable to all coastlines. In addition, the data used to formulate the prediction usually show large experimental scatter. Consequently, theoretical calculations should be supplemented by observations and historical information on actual movements of coastlines.

CHANGES IN LAND USE AND LAND COVER

9.20. Potential land use and land cover changes associated with human activities that can result in changes to hydrologic hazards should be considered in the hazard evaluation. Examples include:

(a) Human-caused land subsidence (e.g. due to groundwater pumping, oil and gas extraction);
(b) Changes in impervious surface areas and changes in surface roughness due to development, which can cause changes in rainfall runoff rates and subsequent flooding behaviour of river systems;
(c) Human-caused deforestation or reforestation, which can cause changes in rainfall runoff rates and subsequent flooding behaviour of river systems;
(d) Human-caused wildfires or controlled burns, which can cause changes in rainfall runoff rates and subsequent flooding behaviour of river systems as well as potential changes in erosion and subsequent debris flows.

9.21. Potential land cover changes due to natural processes that can impact hydrological hazards should be considered in the hazard evaluation. Examples include:

(a) Land cover changes due to natural succession of vegetation or other processes such as disease or past infestations, which can cause changes in rainfall runoff rates and subsequent flooding behaviour of river systems;
(b) Lightning-induced wildfires, which can cause changes in rainfall runoff rates and subsequent flooding behaviour of river systems as well as potential changes in erosion and subsequent debris flows.

9.22. Land cover changes (both due to human activities or to natural processes) as well as land use changes might also influence other natural hazards described Sections 4 and 6 in some ways and should be considered in the hazard evaluation. Examples include:

(a) Land use changes and landcover changes can cause changes in wildfire probabilities and intensities;
(b) Land use changes such as extended pavements or constructions might change local temperature regimes;
(c) Land cover changes due to droughts or human activities may change rainfall patterns and intensities.

CHANGES IN RIVER REGULATION AND COASTAL STRUCTURES

9.23. Changes in river regulation can have significant impacts on flooding hazards, and this should be considered in the hazard evaluation. Examples include:

(a) Construction, removal, or modification of water control structures (e.g. dams, levees, weirs);
(b) Changes in operation of water control structures;
(c) Construction or removal of bridges or other structures, which can impact routing of flood flows;
(d) Changes to improve/maintain navigation (e.g. dredging, locks).

9.24. Changes in coastal infrastructure can have significant impacts on hydrological hazards such as storm surge, seiche, and tsunami, and this should be considered in the hazard evaluation. Examples include:

(a) Construction, removal, or modification of sea walls, breakwaters, jetties for erosion protection;

(b) Construction, removal, or modification of harbours, docks, or moorings;
(c) Changes to improve/maintain navigation (e.g. dredging).

10. MONITORING AND WARNING SYSTEMS FOR THE PROTECTION OF NUCLEAR INSTALLATIONS

10.1. Requirement 28 of SSR-1 [1] states:

> "All natural and human induced external hazards and site conditions that are relevant to the licensing and safe operation of the nuclear installation shall be monitored over the lifetime of the nuclear installation."

10.2. Paragraph 7.1 of SSR-1 [1] states:

> "The monitoring of external hazards and site conditions shall be commenced no later than the start of construction and shall be continued until decommissioning. The monitoring plan shall be developed as part of the objectives and scope of the site evaluation."

10.3. The purposes of monitoring of external hazards and site conditions are:

(a) Long term monitoring to support the initial hazard evaluations and to validate the design basis parameters;
(b) Long term monitoring to support the periodic re-evaluation of the site hazards (e.g. as part of the periodic safety review) (see paras 5.73–5.83 of SSG-25 [9]).
(c) An event warning system to give a timely warning — for operating organizations and off-site emergency response organizations — of an extreme event that might affect safe operation of the nuclear installation (further recommendations on warning systems for external hazards are provided in SSG-77 [12]).

10.4. The purposes of long term monitoring and event warning are different: therefore, the data and the systems used should be chosen based on their respective criteria. Steps should be taken to ensure the ability of the warning system to detect any extreme events in sufficient time to implement measures to maintain the nuclear installation in a safe state.

10.5. Management system processes (see Section 12) should be established to ensure the appropriate competences and responsibilities for installing the monitoring and warning systems, their operation, associated data processing and the timely prompting of operator actions. Standard operating procedures for responding to warnings should be established for each hazard relevant to the site. Warning systems should have regular testing and validation to ensure optimal performance.

10.6. The operating organization should establish a collaboration framework with the national meteorological and hydrological services, or other relevant entities, as authoritative sources of hazard information and associated services[63]. Under such collaboration, tailored products and services could be provided to address the specific needs of the operating organization.

10.7. Warning systems should be based on observations, forecasts, or a combination of observed and forecasted conditions. If the operating organization relies on forecasts or other warning measures provided by external organizations, reliable communication channels with those organizations should be available prior to and during the event.

10.8. Forecasts and warnings should be obtained from a trusted source (e.g. national meteorological and hydrological services), and responsible personnel should be trained in their proper use (i.e. to understand the purposes, limitations and uncertainties of the warnings and forecasts). Initial forecasts or warnings may have large uncertainties (and hazard conditions evolve in time even if forecasts are accurate), so response actions should be revised, as necessary, as subsequent forecasts or warnings are received.

10.9. In general, the following monitoring networks and warning networks should be considered:

(a) All sites should consider meteorological monitoring systems for basic atmospheric variables (e.g. temperature, wind speed and direction, humidity, precipitation, atmospheric stability);
(b) All sites should consider warning systems for identified meteorological phenomena (e.g. tropical cyclones, tornadoes, heavy precipitation, high intensity winds, high temperature);
(c) Coastal sites should consider tide gauge/water level monitoring systems and tsunami warning systems;
(d) Sites close to rivers should consider stream gauge monitoring systems and/or flood forecast systems[64];
(e) All sites should consider other warning or monitoring systems (e.g. for wildfires), where needed and feasible.

METEOROLOGICAL EVENT MONITORING AND WARNING SYSTEMS

10.10. If the region in which the nuclear installation site is located is covered by a warning system by an external organization (e.g. national meteorological or hydrological services) for meteorological events that could impact the site, arrangements should be made to receive the warnings reliably and on time. Otherwise, implementation of a dedicated monitoring system and warning system should be considered. The extent of the monitoring system and the frequency of observations should be consistent with local meteorological conditions.

10.11. Arrangements with national meteorological and hydrological services should be established, as most of these services also issue outlooks, watches and warnings[65] on the possible occurrence of severe weather, such as tropical cyclones, heavy rain with risk of flooding, severe thunderstorms with risk of tornadoes or hail, gale force winds, heat waves and cold spells, snow, ice, severe coastal tides, storm surges, landslides, avalanches, forest fires,

[63] Guidelines on Multi-hazard Impact-based Forecast and Warning Services, WMO-No. 1150 Parts I and II [15], can be taken as a general reference for developing such services.

[64] For some installations at coastal sites also a monitoring system for sea salt accretion is advisable, to identify possible problems early on and enact suitable countermeasures.

[65] The technical distinction among outlooks, watches and warnings may vary among issuing organizations.

fog, and sandstorms. Additional information and advice is generally given on the severity and intensity of the hazard, the expected time period for the given event to occur, and the possible impact(s). Such information and advice are generally made available by different means of communication and the methods of information dissemination will vary depending on the source. For example, specific messages may be sent to registered professional users, with periodic updates and using different information systems and media.

10.12. The use of weather radar and satellite imagery to provide information on the location and movement of hazardous atmospheric disturbances should be considered. Such information can provide an early warning of the approach of potential hazards.

TSUNAMI EVENT MONITORING AND WARNING SYSTEMS

10.13. When tsunami is a significant hazard at a nuclear installation site, the operating organization should establish reliable communication arrangements with tsunami monitoring and warning centres if such centres exist in the State or region (see Annex III). Each State should evaluate the level of alert for its coasts, on the basis of the tsunami database and the results of numerical simulations. The operating organization should establish standard operating procedures for receiving messages from the warning centre as disseminated (and updated) and the actions to be taken based on received information such as estimated tsunami arrival time and height.

10.14. In regions where there is no tsunami warning system, the operating organization should establish reliable communication arrangements with the national, regional or global seismic monitoring centre to be informed of occurrences of major earthquakes. The operating organization should establish standard operating procedures to be implemented upon receipt of major earthquake warnings. The operating organization should consider the feasibility of estimating the tsunami arrival time and height from the warning information received (e.g. by performing tsunami simulations using a database of pre-computed seismic scenarios developed by the seismic monitoring centre), and determine the immediate actions to be taken on the basis of the estimated tsunami hazard.

10.15. Where sea level monitoring stations are already established along coasts or offshore, the operating organization of the nuclear installation should make arrangements with the monitoring organization to receive data in real time from stations in the region. The national meteorological and hydrological services should be contacted, as they either maintain a network of such stations, have access to their data if operated by other national entities, or are aware of other stations run by public entities.

10.16. In coastal regions without sea level monitoring stations, the operating organization of the nuclear installation should coordinate with the national meteorological and hydrological services to set up a real time, sea level monitoring network for the collection and transmission of data to the nuclear installation if the region of the installation site is potentially affected by tsunamis. A sea level station should be established as near as possible to the nuclear installation site. Where the nuclear installation site is located on a river, another monitoring station should be established in the estuary.

10.17. Where tsunamis are potentially a significant hazard to a nuclear installation, the operating organization should install a water level monitoring system near the intake structures and receive data in real time.

10.18. If volcanic activity or landslides (submarine or subaerial) are a significant source for tsunamis that might impact the site, the tsunami monitoring and warning system should include these sources, in collaboration with any national and international institutions responsible for their observation and monitoring. In the absence of such institutions, the operating organization of the nuclear installation may need to establish such an observatory.

STORM SURGE AND SEICHE EVENT MONITORING AND WARNING SYSTEMS

10.19. Storm surges due to tropical or extratropical weather systems are typically large scale events for which it is not typically feasible for the operating organization of the nuclear installation to develop a forecasting system. Instead, the operating organization should make administrative arrangements to reliably receive timely warnings from a forecasting, or monitoring and warning system operated by an external organization (e.g. national meteorological or hydrological services, commercial providers). In some cases, forecasting and warnings may also be available for large scale seiche events driven by such weather systems. For sites subject to tsunami-driven seiche events, the tsunami warning system should also cover seiche hazards.

10.20. For sites subject to smaller scale seiche events (i.e. in a small lake, small, enclosed water body or semi-enclosed bay) the operating organization should consider installing its own monitoring and warning system (e.g. water level sensors, wave buoys), if an externally operated system does not exist.

FLOODING EVENT MONITORING AND WARNING SYSTEMS FOR DAMS, LEVEES AND RESERVOIRS

10.21. The operating organization of the nuclear installation should implement and maintain monitoring and warning systems for on-site and off-site water control structures under its control that could cause a flooding hazard. In addition to water level sensing systems, systems for monitoring the structural integrity of the feature should be provided.

10.22. The operating organization of the nuclear installation should make arrangements with external organizations to obtain warnings regarding impending or actual sudden unplanned releases of impounded water from off-site water control structures that are not under the control of the operating organization. Preferably, warning systems should be set up between the operators of the structure and the operating organization of the nuclear installation. If this is not practicable, warnings may need to be obtained via third parties (e.g. the national meteorological and hydrological service, emergency management officials, national or local dam safety officials).

FLOODING EVENT MONITORING AND WARNING SYSTEMS FOR RIVERS

10.23. If the watershed in which the installation is located is covered by a flood forecasting or hydrological monitoring and warning system operated by an external organization (e.g. national meteorological or hydrological services) for events that might generate external flooding hazards that could impact the site, the operating organization should make administrative arrangements to reliably receive timely warnings. Otherwise, the operating organization should consider implementation of a dedicated forecasting or monitoring system and warning system (preferably in cooperation with third parties such as the national meteorological or hydrological services or commercial providers of such services).

10.24. The design of the forecast, monitoring and warning system should be consistent with local hydrometeorological conditions (e.g. a small watershed subject to flash flooding vs a large watershed subject to spring snowmelt flooding). Hydrological monitoring and warning systems typically comprise stream gauges connected via telemetry to a monitoring and warning centre. A flood forecasting system should also include a hydrologic or hydraulic model driven by precipitation observations (e.g. meteorological stations, satellite, weather radar) or forecasts. Watersheds with significant water control structures (e.g. dams, reservoirs, levees) should be included in the warning system (see paras 10.20 and 10.21).

11. APPLYING A GRADED APPROACH TO METEOROLOGICAL AND HYDROLOGICAL HAZARD EVALUATION FOR NUCLEAR INSTALLATIONS

11.1. Paragraph 4.1 of SSR-1 [1] states that "In determining the scope of the site evaluation, a graded approach shall be applied commensurate with the radiation risk posed to people and the environment."

11.2. Paragraph 4.2 of SSR-1 [1] states that "The application of the safety requirements for site evaluation for nuclear installations shall be commensurate with the potential hazards associated with the nuclear installation."

11.3. Paragraph 4.3 of SSR-1 [1] states that "The level of detail in the evaluation of a site for a nuclear installation shall be commensurate with the risk associated with the nuclear installation and the site and will differ depending on the type of nuclear installation."

11.4. Paragraph 4.4 of SSR-1 [1] states that "The scope and level of detail of the site evaluation process necessary to support the safety demonstration for the nuclear installation shall be determined in accordance with a graded approach."

11.5. A graded approach may be applied using a radiological hazard categorization approach or a risk-informed approach. The goal of both approaches is to ensure that the application of safety requirements for site investigations and hazard evaluation is commensurate with the consequences of potential radioactive releases (i.e. as an indicator of the radiological hazard associated with the nuclear installation)[66]. The radiological hazard categorization approach is based upon the consequences of an uncontrolled (unmitigated or mitigated) radioactive release, while the risk-informed, approach is less prescriptive, seeking to employ more risk insights into the process. Regardless of the approach followed, the following factors should be considered:

(a) The stage in the lifetime of the nuclear installation (e.g. siting vs operation). For example, in applying a graded approach to hazard evaluations at existing nuclear installation sites additional factors should be considered, such as the time remaining until the installation is expected to be shut down.
(b) The complexity of the site and vulnerability to different hazards.

[66] This addresses only risks due to radiological hazards. Other hazards (e.g. chemical hazards) posed by the installation should be considered, in accordance with national regulations on such hazards.

RADIOLOGICAL HAZARD CATEGORIZATION APPROACH

11.6. In the radiological hazard categorization approach a graded approach is typically applied on the basis of the consequences of an uncontrolled, unmitigated radioactive release from the nuclear installation (some applications of the approach may consider mitigation; see para 11.11). Four radiological hazard categories, based on the consequences of unmitigated releases, are defined in Table 1. Categories range, from 'high', which corresponds to large nuclear power plants, to 'conventional', which corresponds to industrial facilities that have no or negligible radiological consequences.

11.7. The radiological consequences of potential failures depend on the nature of the nuclear installation and the characteristics of the site. Paragraph 4.5 of SSR-1 [1] states:

> "For site evaluation for nuclear installations other than nuclear power plants, the following shall be taken into consideration in the application of a graded approach:
>
> (d) The amount, type and status of the radioactive inventory at the site (e.g. whether the radioactive material on the site is in solid, liquid and/or gaseous form, and whether the radioactive material is being processed in the nuclear installation or is being stored on the site);
> (a) The intrinsic hazards associated with the physical and chemical processes that take place at the nuclear installation;
> (b) For research reactors, the thermal power;
> (c) The distribution and location of radioactive sources in the nuclear installation;
> (d) The configuration and layout of installations designed for experiments, and how these might change in future;
> (e) The need for active systems and/or operator actions for the prevention of accidents and for the mitigation of the consequences of accidents;
> (f) The potential for on-site and off-site consequences in the event of an accident."

TABLE 1. RADIOLOGICAL HAZARD CATEGORIES BASED ON THE CONSEQUENCES OF FAILURES IN A NUCLEAR INSTALLATION

Hazard category	On-site consequences	Off-site consequences	Levels of detail and complexity of hazard evaluation
High	Radiation exposures that could cause loss of life.	Potential for significant off-site radiological consequences.	Same as for large NPPs with conventional safety features (e.g. Gen-III or older reactors).
Medium	Potential for significant on-site consequences. Unmitigated radiological release necessitates site evacuation.	Small potential for off-site radiological consequences.	Potential for reduced level of detail for database collection and reduced level of complexity in methods used – commensurate with the reduced risk.

Low	Potential for only localized on-site radiological consequences. Unmitigated radiological release does not necessitate site evacuation.	No or negligible radiological consequences.	Potential for further reductions in levels of detail and complexity – commensurate with the low risk. Potential to use codes and standards applicable to conventional (i.e. non-nuclear) industrial facilities, but with increased safety factors.
Conventional	No or negligible radiological consequences.	No or negligible radiological consequences.	Use codes and standards applicable to conventional industrial facilities

Note: Quantitative definition of 'significant' or 'small' consequences depends on the regulatory framework of each Member State.

11.8. In applying the hazard categorization approach, the following factors should also be considered:

(a) The thermal power of the reactor;
(b) The characteristics of the structures of the nuclear installations, and the means of confinement of radioactive material, with due consideration for potential cliff edge effects in the event of an accident;
(c) The characteristics of the site and surrounding region that are relevant to the consequences of the dispersion of radioactive material to the atmosphere and the hydrosphere (e.g. topography, variability/distribution of wind speeds and directions, atmospheric stability, groundwater, surface water bodies, demography).

11.9. The simplest consequence analysis that should be performed for radiologic hazard categorization corresponds to an uncontrolled, unmitigated release of the full radioactive inventory present in the nuclear installation. This is a conservative bounding analysis, which provides a first approximation of the hazard category of the nuclear installation. If the result of this analysis is that such a radioactive release has no or negligible radiological consequences (i.e. for workers, the public and the environment), then the radiological hazard category of the installation can be classified as 'conventional' (see Table 1) and the meteorological and hydrological design basis can be established in the same way as for a conventional (i.e. non-nuclear) industrial facility.

11.10. When the uncontrolled, unmitigated release of the full radioactive inventory present in the nuclear installation would have no or negligible off-site consequences and only localized on-site consequences (i.e. 'low' hazard category in Table 1), the graded approach implies the use of a reduced level of detail for database collection and reduced level of complexity in methods used, commensurate with the low risk. In this case, the graded approach could also comprise application of conventional, non-nuclear safety standards but with additional safety factors or margins. The level of detail and complexity of the hazard analysis should be sufficient to confirm that these added safety factors or margins can be met. In either case, application of the graded approach should involve significant engineering judgement as well as guidance from the regulatory body.

11.11. When the uncontrolled, unmitigated release of the full radioactive inventory present in the nuclear installation would have a small potential for off-site radiological consequences, but have the potential for significant on-site consequences (i.e. ‘intermediate’ hazard category in Table 1), the graded approach would be similar to that used for the ‘low’ hazard category, except that the application of conventional, non-nuclear safety standards with additional safety factors or margins would not be appropriate. The level of detail in data collection and complexity of methods used should be greater than those used for the ‘low’ hazard category, commensurate with the increased risk. As with the ‘low’ hazard category, application of the graded approach to the ‘intermediate’ hazard category will involve significant engineering judgement as well as guidance from the regulatory body.

11.12. The graded approach can also be applied to scenarios in which engineered mitigation features are credited in the consequence analysis for radiological hazard categorization of the nuclear installation. If credit is taken for some engineered mitigating features, the source terms used should reasonably envelop all potential accident scenarios, and the robustness of the mitigating features should be clearly demonstrated. Application of credit for engineered mitigation features would allow the nuclear installation to use a lower hazard category in Table 1. For example, an installation categorized as ‘high’ hazard based on an unmitigated release might be categorized as ‘intermediate’ hazard when mitigation is considered.

RISK INFORMED APPROACH

11.13. Risk informed based principles may be used as an alternative or as a complement to a prescriptive radiological hazard categorization approach for the implementation of a graded approach. These principles aim to incorporate a design specific probabilistic safety assessment or similar analysis in order to guide decisions regarding the level of detail and level of complexity needed in the external event hazard evaluations.

APPLICATION OF A GRADED APPROACH TO HAZARD EVALUATION

11.14. The details of applying a graded approach to the evaluation of meteorological, hydrological and other natural hazards depends on design specific safety features, the site specific characteristics of hazards and the availability of data. Professional or expert judgment by qualified meteorologists, hydrologists, or other subject matter experts, should be used. Key decisions include the level of effort devoted to data collection and the complexity of analytical methods used. The hazard level finally adopted for designing the installation should be commensurate with the reduced database and the simplification of the methods, taking into consideration that both factors tend to increase uncertainties. In some cases, the burden imposed on designers by the increased uncertainty may be larger than the burden imposed on hazard analysts by performing a full hazard analysis. For example, a water level estimate with an uncertainty of 2 meters will be a greater design challenge than a water level estimate with an uncertainty of 0.5 meters.

11.15. Data collection efforts may be guided by regulatory requirements or performance based goals. For example, a regulatory body may require lower or higher annual exceedance frequency estimates for certain hazards based on radiological hazard category and/or design specific safety features. If available, results from probabilistic safety assessments or other engineering analyses may provide a basis for use of higher annual exceedance frequencies. Estimation of higher annual exceedance frequencies will generally need less data, so the hazard analysis may be completed with readily available data. Otherwise, some increased level of site specific data collection effort may be needed, commensurate with the risk.

11.16. The graded approach to hazard evaluation will often use simplified methods (e.g. less complex models) to reduce the level of effort. For example, using a one-dimensional hydraulic model for flooding hazard evaluation instead of a two-dimensional model may provide sufficient accuracy, commensurate with risk, in some cases. In some cases, conservative assumptions or estimates may provide sufficient bounding estimates for the hazard (e.g. for hazards that pose an overall low risk). Results from probabilistic safety assessments or other engineering analyses should be used to provide a basis for choosing simplified models or conservative estimates.

11.17. The extent to which a graded approach can be applied to hazard evaluation will depend on the nature of the specific event under consideration. Some hazards, due to the nature of the phenomena, may not be easily evaluated using a graded approach (e.g. lightning). Other natural hazards are more region dependent (e.g. tropical cyclones, extreme snow events) and it is likely that they can be considered in a less intensive manner, depending on the site. The degree of application of a graded approach for each hazard will depend significantly on the location of the proposed facility, and the hazard category (see Table 1) or the risk associated with the installation. Rare or extreme events, such as tornadoes and tropical cyclones, and associated effects, can represent serious hazard sources and should be thoroughly investigated in the region of the site, in accordance with the recommendations provided in Sections 4–6.

11.18. When applying the graded approach, information on potential hazards for a given site location should be collected to determine whether a given hazard could affect the SSCs important to safety. If no impact is found, then the methods and analysis should be described but additional analysis is not necessary. If the analysis determines that there would be an effect on one or more SSCs important to safety, then additional analysis should be performed, commensurate with risk.

11.19. In most cases, in order to determine if the hazard under consideration will have an impact or is likely to be a credible threat to SSCs important to safety, consultation with structural and/or mechanical engineering subject matter experts will be necessary. This should be an iterative process to determine thresholds (e.g. wind speed, snow load, temperature and humidity, water level) for each SSC important to safety.

11.20. Evaluation of hydrological hazards may allow for several approaches to applying a graded approach. Where appropriate, statistical analyses the use of systematic observations and historical records should be considered; these involve less effort than development and calibration of mechanistic models. Lower fidelity mechanistic models (e.g. lower resolution, lower dimension, fewer processes) should be considered instead of higher fidelity models. However, sites with large and complex sources of hydrological hazards (e.g. different types of tsunami source for coastal sites, large upstream dam(s) at close distance on a river site) affecting a site might not be amenable to the application of a graded approach.

CONSIDERATIONS FOR DESIGN BASIS DERIVED FROM A GRADED APPROACH HAZARD EVALUATION

11.21. The application of a graded approach to site characterization might result in an increased level of uncertainty in the meteorological, hydrological, or other parameters used as input for the design basis for the nuclear installation. This larger uncertainty should be taken into account when defining the design basis.

11.22. The design bases, the as-built configuration, and the conservatism of the nuclear installation's operating approach (i.e. safety procedures) should provide margins with regard to the chosen safety objectives. An analysis of historical events in the region as well as operating experience of similar designs, where available, should be used in justifying these margins.

11.23. Design specific probabilistic safety assessments or similar engineering analyses may provide additional confidence that a graded approach meets safety performance objectives.

12. MANAGEMENT SYSTEM FOR METEOROLOGICAL, HYDROLOGICAL, AND OTHER NATURAL HAZARD EVALUATIONS

12.1. A management system for the evaluation of meteorological, hydrological, and other natural hazards is required to be established to comply with Requirement 2 of SSR-1 [1], which states that "**Site evaluation shall be conducted in a comprehensive, systematic, planned and documented manner in accordance with a management system**."

12.2. IAEA Safety Standards Series No. GSR Part 2, Leadership and Management for Safety [16] establishes requirements for the management system; associated recommendations are provided in IAEA Safety Standards Series No. GS-G-3.5, Management System for Nuclear Installations [17]. The management system for hazard evaluations should be integrated with and fulfil requirements of the overall safety management system for the nuclear installation project. The management system should include provisions for timely and adaptive response to evolving conditions that may impact safety (e.g. potential changes in hazards with time).

SPECIFIC ASPECTS OF PROJECT MANAGEMENT FOR THE EVALUATION OF METEOROLOGICAL, HYDROLOGICAL, AND OTHER NATURAL HAZARDS

12.3. A project work plan for the hazard evaluations should be established that, at a minimum, covers the following topics:

(a) Objectives and scope of the hazard evaluations;
(b) Applicable regulations and standards;
(c) Roles and responsibilities for management of the project;
(d) Work breakdown, processes and tasks, schedule and milestones;
(e) Interfaces among the different tasks (e.g. data collection, analysis) and disciplines involved, especially the various specialists needed for the different aspects of hazard evaluation, with all necessary inputs and outputs;
(f) Project deliverables and documentation procedures.

12.4. To ensure the quality of the project, the management system for hazard evaluation should, at a minimum, include following generic processes:

(a) Document control.
(b) Control of work products.

(c) Project quality management programme:
   (i) Control of measurement and testing equipment;
   (ii) Control of records;
   (iii) Control of analyses;
   (iv) Validation and verification of software;
   (v) Control of non-conformances;
   (vi) Corrective actions.

(d) Purchasing (procurement).

(e) Audits (self-assessment, independent assessments, and review).

12.5. Processes covering all activities for data collection and data processing, field and laboratory investigations, analyses and evaluations should be applied. Locations of field samples should be referenced to a standardized coordinate system.

12.6. The project scope should identify all aspects of the hazards that might affect the safety of the nuclear installation site and that will be investigated within the framework of the project (see also Requirement 3 of SSR-1 on the scope of the site evaluation for nuclear installations). If any external event hazards associated with the meteorological, hydrological or other natural phenomena addressed in this Safety Guide are excluded from the scope, a justification should be provided.

12.7. The project work plan should include a description of all relevant project requirements, including applicable standards and regulatory requirements, in relation to all the hazards considered to be within the project scope. Before the operating organization conducts the hazard evaluation, the regulatory body should review the work plan to ensure that all applicable regulatory requirements have been included.

12.8. In developing the project work plan, it should be ensured that adequate resources, time and other provisions are available for collecting all the data that are necessary for the hazard evaluation and for responding to requests by experts.

12.9. The approaches and methods to be used should be clearly stated in the project work plan. Other documents (e.g. regulatory guidance documents, industry codes and standards) referenced in these approaches and methods should be clearly identified.

12.10. The project work plan should identify the intended objectives and uses of study results. It should incorporate an output specification that describes the specific study results necessary to fulfil the intended engineering uses and objectives (e.g. development of the design basis parameters: see Section 7). The output specification should be as comprehensive as possible, and should be updated, as necessary.

12.11. To make the hazard evaluation traceable and reproduceable, the documentation of the hazard evaluation should provide the following:

(f) A description of all elements of the evaluation process (e.g. data collection, data analysis, modelling);

(g) A description of the entities, participants and their roles (e.g. data collectors, analysts, authors, peer reviewers);

(h) Background material that informs the analysis, including raw and processed data;

(i) A description of the computer software used, including a description of the input and output files;

(j) An archival repository of key evaluation elements (e.g. raw and processed datasets, equipment calibration records, sensitivity studies, intermediate calculations, model input and output files, draft and final reports, peer review reports);

(k) Reference documents used in or produced during the evaluation, including documents supporting the treatment of uncertainties, professional judgement and related issues.

These should be maintained in an accessible, usable and auditable form. Documentation or references that are readily available elsewhere can be cited where appropriate.

12.12. The documentation should identify all sources of information used in the hazard evaluation, including information on where to find important citations that are difficult to obtain. Unpublished data that are used in the analysis should be included in the documentation in an appropriate, accessible and usable form. Where data that are restricted for security or proprietary commercial reasons have been used, it may be necessary to prepare redacted versions of documents. However, where redacted documents are used or passed to others (e.g. peer reviewers or nuclear installation designers) as part of the evaluation, the project organization should be responsible for ensuring that sufficient information is provided to enable tasks to be performed effectively and in the best interests of nuclear safety.

12.13. If earlier hazard evaluation studies for the same area are available, comparisons should be made to demonstrate how the use of different approaches or different data affect the conclusions. The comparisons should be documented in a way that allows their review.

12.14. Owing to the variety of investigations (e.g. field investigations, laboratory tests, calculations) and the need for expert judgement in the decision making process, technical procedures specific to the project should be developed to guide and facilitate the execution and verification of these processes, where appropriate. A peer review of such specific procedures should be conducted.

12.15. As part of the installation's overall management system, a project quality management programme should be established and implemented to cover all of the activities for data collection and data processing, field and laboratory investigations, and analyses and evaluations.

12.16. Requirement 7 of GSR Part 2 [16], states that "**The management system shall be developed and applied using a graded approach.**" Paragraph 4.15 of GSR Part 2 [16] states:

> "The criteria used to grade the development and application of the management system shall be documented in the management system. The following shall be taken into account:
>
> (a) The safety significance and complexity of the organization, operation of the facility or conduct of the activity;
>
> (b) The hazards and the magnitude of the potential impacts (risks) associated with the safety, health, environmental, security, quality and economic elements of each facility or activity;

(c) The possible consequences for safety if a failure or an unanticipated event occurs or if an activity is inadequately planned or improperly carried out."

12.17. A graded approach to the management system for the evaluation of meteorological, hydrological and other natural hazards for nuclear installation sites should be applied to areas such as processes and activities of the hazard evaluation, development of technical procedures for specific tasks, and peer review of the hazard evaluation. In general, the application of the management system should be most stringent for nuclear installations categorized as 'high' hazard, and least stringent for installations categorized as 'low' or 'conventional' hazard (see Table 1).

INDEPENDENT PEER REVIEW

12.18. Paragraph 3.4 of SSR-1 [1] states that "The results of studies and investigations conducted as part of the site evaluation shall be documented in sufficient detail to permit an independent review."

12.19. Paragraph 3.5 of SSR-1 [1] states:

> "An independent review shall be made of the evaluation of the natural and human induced external hazards and the site specific design parameters, and of the evaluation of the potential radiological impact of the nuclear installation on people and the environment."

12.20. The purpose of an independent review is to provide assurance that: (a) the documentation is complete; (b) a proper process has been used to conduct the hazard evaluation; (c) appropriate data and analysis methods have been used; (d) the analysis has addressed and evaluated uncertainties; and (e) the evaluation is traceable and reproduceable.

12.21. One of two independent review methods should be used: (a) participatory; or (b) late stage and follow-up. A participatory review is performed during the course of the study, allowing the reviewer(s) to resolve comments as the hazard evaluation proceeds and technical issues arise. A late stage and follow-up review is performed at the end or towards the end of the evaluation study. Conducting a participatory review will reduce the likelihood of rejection or major revisions of the study at a late stage.

12.22. Owing to the complexity of studies for the evaluation of meteorological, hydrological and other natural hazards, several independent review(s) of various studies are likely to be needed. The level and type of review can vary depending on the type and complexity of the study. Some studies may be multidisciplinary, requiring a review team to cover all relevant technical aspects. The reviewer(s) of a study should not have been involved in directing or conducting the study and they should not have a vested interest in the outcome. Those who are requested to perform a technical review should be able to demonstrate their qualifications and competence in the area of work being assessed. The management system should provide criteria for demonstrating qualifications needed by subject matter experts.

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ANNEX I EXAMPLES OF CRITERIA FOR CHARACTERIZING METEOROLOGICAL AND HYDROLOGICAL VARIABLES

FRANCE

I–1. Tables I–1 to I–5 provide examples of criteria for defining the design basis parameters for a given meteorological or hydrological variable as taken from the practice in France for new nuclear power plants. These meteorological design basis parameters correspond to single load cases that are associated in design codes with different load combinations and different load factors for designing structures, systems and components. For some hazards, design extension parameters also exist but are not reproduced here.

TABLE I–1. EXAMPLES OF FRENCH CRITERIA FOR CHARACTERIZING METEOROLOGICAL AND HYDROLOGICAL VARIABLES FOR NEW NUCLEAR REACTORS (EXCEPT FLOODING HAZARDS)

Site parameter	Criterion	Definition
	Air temperature	
Maximum high dry bulb temperature	7 d maximum dry bulb temperature with a 10 000 year return period and including the effects of climate change	This temperature is the upper bound of 70% confidence interval of the 7 d maximum average temperatures with a return period of 10 000 years, including the effects of climate change on the whole lifetime of the expected nuclear installation.
	Instantaneous maximum air temperature with a 10 000 year return period, including the effects of climate change	This temperature is the upper bound of the 70% confidence in maximum instantaneous temperatures with a return period of 10 000 years, including the effects of climate change on the whole lifetime of the expected nuclear installation.
Minimum Low dry bulb temperature	7 d minimum dry bulb temperature with a 10 000 year return period	This temperature is the lower limit of 70% confidence interval of the 7d minimum average temperatures with a return period of 10 000 years. As climate change is considered to increase the minimum average temperatures, its effects are not considered for this evaluation (i.e. conservative approach).
	Minimum daily dry air temperature with a 10 000 year return period	This temperature is the upper confidence level (70%) of the 12 h minimum average with a return period of 10 000 years. As climate change is considered to increase the minimum average temperatures, its effects are not considered for this evaluation (i.e. conservative approach).
	Instantaneous minimum air temperature with a 10 000 year return period	This temperature is the lower limit of the 70% confidence in minimum instantaneous temperatures with a return period of 10 000 years. As climate change is considered to reduce the probability of cold waves, its effects are not considered for this evaluation (i.e. conservative approach).

Site parameter	Criterion	Definition
		Humidity
Maximum high absolute humidity	Maximum absolute humidity	This value is the maximum value of the absolute air humidity (kg water per kg air).
Mean high absolute humidity	Mean high absolute humidity	This value is the mean value of the absolute air humidity (kg water per kg air).
		Water temperature
Maximum High Water Temperature	Maximum temperature daily water with a 10 000 year return period	This water temperature is the upper bound of the 70% confidence interval of temperatures daily maximums with a 10 000 year return period and taking into account the effects of climate change.
		Wind speed
Maximum high intensity wind speed	Maximum average value with a 10 000 year return period	This wind speed value is the average wind value with a return period of 10 000 years. For French sites, this value is calculated by multiplying the 50 year mean wind reference value (given by technical norms) by a coefficient defined on the basis of the estimated peak wind speed (gust and measured at 10 m above the ground) with a 10 000 year return period.
		Tornado
Maximum tornado wind speed	10 000 year return period	Maximum wind speed resulting from passage of a tornado having a 0.01% annual frequency of exceedance (10 000 year mean recurrence interval).
Pressure drop	10 000 year return period	Decrease in ambient pressure from normal atmospheric pressure resulting from passage of the maximum wind speed tornado.
Rate of pressure drop	10 000 year return period	Rate of pressure drop resulting from the passage of the maximum wind speed tornado.
		Wind generated missile
Automobile	> 10 000 year return period	The mass and velocity of a massive high kinetic energy missile that deforms on impact (e.g. an automobile) resulting from the passage of the maximum wind speed associated with high intensity winds or tornadoes.
Wooden plank	> 10 000 year return period	The mass and velocity of a missile resulting from the passage of the maximum wind speed associated with high intensity winds.

Site parameter	Criterion	Definition
Sheet metal siding	> 10 000 year return period	The mass and velocity of a heavy and medium-size rigid missile resulting from the passage of the maximum wind speed associated with high intensity winds.
Steel pipe	> 10 000 year return period	The mass and velocity of a rigid missile (e.g. 15 cm diameter steel pipe) resulting from the passage of the maximum wind speed associated with a tornado.
Steel sphere	> 10 000 year return period	The mass and velocity of a small rigid missile (e.g. 2.5 cm solid steel sphere) resulting from the passage of the maximum wind speed associated with a tornado.
	Snow	
Maximum snow load	Maximum snow load with a 10 000 year return period	The snow load corresponds to an exceptional snow load on the ground level equivalent to a 10 000 year return level. For French sites, this value is calculated by multiplying the 50 year return period maximum snow load by a coefficient defined on the basis of the observed maximum load, with a 10 000 year return period.
	Lightning	
First positive impulse	Peak current, impulse charge, specific energy and time parameters	The first positive impulse is characterised by: peak current, impulse charge, specific energy and time parameters.
First negative impulse	Peak current, average steepness and time parameters	The first negative impulse is characterised by: peak current, average steepness and time parameters.
Subsequent impulse	Peak current, average steepness and time parameters	The subsequent impulse is characterised by: peak current, average steepness and time parameters.
Long Stroke	Load and time parameters	The long stroke is characterised by: load and time parameters.
Flash	Load	The flash is characterised by its load.

I–2. Reference [I–1] defines eleven scenarios (‘reference flooding situations’) to consider when assessing the flood hazard for the site. These scenarios have been defined on the basis of engineering judgment and using a probabilistic target (annual exceedance probability of 10^{-4}, in order of magnitude, and covering associated uncertainties). For a specific site, the identified reference flooding situations have to at least encompass all the situations corresponding to the experience feedback that is relevant for the site.

TABLE I-2. SUMAMRY OF THE REFERENCE FLOODING SITUATIONS DEFINED IN REF. [1]

Site parameter	Criterion	Definition
		Flooding hazards for all types of site
Local intense precipitation	10 000 year return period	A rainfall event is characterized by the total precipitation over a given duration. The reference rainfall events are defined by the upper bound of the 95% confidence interval for the 100 year return period rainfall events calculated from the data of a weather station that is representative of the conditions of the site. Two scenarios are considered: The first scenario considers various durations of rainfall events to check the stormwater drainage system design The second scenario aims 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 has to be able to cope with a surface water runoff scenario when its local stormwater drainage system is completely blocked when a 1 h reference rainfall occurs.
Small watershed flooding	10 000 year return period	The considered flooding is due to precipitation on a watershed with surface area between 10 and 5,000 km². It is characterized by an instantaneous peak flow rate, for a 10 000 year return period. For watersheds with a surface area of between 10 and 100 km², the flow rate can be calculated from the 100-year return period rainfall events (upper bound of the 95% confidence interval) by multiplying the resulting flow rate by a factor of 2.
Flooding due to deterioration or malfunctioning of structures, circuits or equipment	10 000 year return period	The considered structures, circuits or equipment are those, close to or on the site but outside buildings housing important protection elements associated with nuclear safety, whose possible malfunctioning or deterioration could lead to the discharging of a significant quantity of water on the site. A conventional break failure is postulated for each structure, circuit and item equipment, unless a break can be excluded. In the case where breaking is excluded, the possibilities of deterioration or malfunction are nevertheless studied. It has to be verified that the hazards taken into consideration in the safety demonstration would not lead to a flood caused by multiple breaks in structures, circuits or equipment situated on or near the site.
Mechanically induced wave	10 000 year return period	The reference mechanically induced wave is a wave resulting from a rapid change in flow rate in a channel, situated on the site or upstream or downstream of it. It is characterized 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). 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.
High groundwater level	10 000 year return period	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. • The combination of an ‘initial level’ and the rise effect caused by an ‘initiating event’. The initiating event is the one event among those examined in order to characterise the reference flooding situations that causes the greatest rise in the groundwater level. 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. • A statistical analysis of the groundwater levels. The reference level can be defined as the level associated with a 100 year return period, taking the upper bound of the 95% confidence interval. The reference level is calculated using particularly unfavourable hydrogeological hypotheses.
Flooding hazards for coastal sites (French Atlantic coast)		
Hight sea water level (tide plus storm surge)	10 000 year return period	The reference high sea water level is the sum of: • The maximum height of the theoretical tide; • The thousand-year storm surge (upper limit of the 70% confidence interval), increased to take account of uncertainties associated to the evaluation of rare storm surges and resulting from outliers; • The change in mean sea water level extrapolated until the next periodic safety review.
Wind waves (combined with hight sea water level)	100 year return period (waves)	The reference wind waves on sea are characterized by the significant height and the associated period in accordance with the following steps: • Definition of extreme offshore waves on the basis of measurement of waves (or reconstitution from wind data), with a return period of 100 years (upper bound of 70% confidence interval), • Determination of the characteristics of these waves propagated to the near-shore area of the plant site over the reference high sea level.
Seiche (combined with hight sea water level)	1 year return period (seiche)	The potential for seiche has to be evaluated in coastal infrastructures such as port dock, water intake or discharge channels. The seiche hazard is analysed on the basis of available experience feedback. If a seiche hazard is identified, 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.
Flooding hazards for river sites		
Large watershed flooding	10 000 year return period	A large watershed generally covers an area larger than 5,000 km^2. A large watershed flooding is characterized 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 has to be considered. The proximity of the studied site to a confluence of watercourses may necessitate that the flood analysis takes this confluence into account.
Failure of a water-retaining structure		The analysis of the failure scenarios concerns water-retaining structures that lie across watercourses. 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. It is assumed that the reservoir is filled to the maximum level and that the failure leads to complete emptying of the reservoir. The reference level associated with the failure of this structure is the maximum level on the site resulting from propagation of the flood wave. For the entire path of the flood wave, the water-retaining structures crossed by the wave are assumed to fail when the peak of the wave hits the structure, unless it can be demonstrated that they resist. 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 has to be considered.
Local wind waves	10 000 year return period	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.

GERMANY

I–3. The table I-3 provides examples for design basis parameters in accordance with German regulatory requirements [I–2] and [I-3] respectively.

TABLE I-3. EXAMPLES OF CRITERIA FOR CHARACTERIZING METEOROLOGICAL AND HYDROLOGICAL VARIABLES AS TAKEN FROM THE PRACTICE IN GERMANY

Event	Criterion/parameter	Definition/value
	Flooding	
Storm surge (coastal site)	0.01% annual exceedance frequency	Maximum water level resulting from a 10 000 year storm surge. Influential factors may occur simultaneously, and potential effects have to be considered in combination. Influential factors: tide, potential overflow and collapse of dykes, wave run-up, sea level rise, swelling, duration and sequence of the storm surge event.
Riverine flooding (in principle also applicable for lakes)	0.01% annual frequency of exceedance	Maximum water level resulting from a 10 000 year river runoff. Influential factors may occur simultaneously, and potential effects have to be considered in combination. Influential factors: precipitation, snow and glacier melt, backwater effects, ice jams, potential overflow and collapse of levees, water retaining structures, wind driven surge and wave run-up (only for lakes), duration and sequence of the riverine flooding.
Estuary sites	0.01% annual exceedance frequency	Maximum water level resulting from either storm surge or riverine flooding. Influential factors: as above.
	Lightning	
Positive initial lightning strike	Crest value of current	200 kA 300 kA for robustness considerations[67]
	Average current gradient	20 kA/µs
	Front time	10 µs
	Time of half-value	350 µs
	Impulse charge	100 C
	Specific energy	10 MJ/Ω

[67] The 'robustness considerations' are applied to avoid cliff edge effects

Negative initial lightning strike	Crest value of current	100 kA 150 kA for robustness considerations
	Average current gradient	100 kA/µs
	Front time	1 µs
	Time of half-value	200 µs
Negative subsequent lightning strike	Crest value of current	50 kA
	Average current gradient	200 kA/µs 300 kA/µs for robustness considerations
	Front time	0.25 µs
	Time of half-value	100 µs
Height of Structure >= 60 m	Charge of the long-time current	400 C
	Duration of the long-time current	0.5 s
Height of structure <60m	Charge of the long-time current	200 C
	Duration of the long-time current	0.5 C

I–4. Additional considerations for meteorological and hydrological hazards are derived from the Western European Nuclear Regulators Association Reference Levels [I–4], which require an annual exceedance frequency of 0.01% or less for every hazard as a basis for the design basis hazard. The Reference Levels also require that the design basis events are compared to relevant historical data to verify that historical extreme events are enveloped by the design basis with a sufficient margin.

JAPAN

I–5. Table I–4 provides examples of the design basis parameters for a given meteorological variable for existing nuclear power plants in Japan. These meteorological design basis parameters correspond to single load cases that are associated in design codes with different load combinations and different load factors for designing SSCs. Reference [I–5] defines criteria for Tornadoes design basis parameters.

TABLE I-4. EXAMPLES OF DESIGN BASIS PARAMETERS FOR CHARACTERIZING METEOROLOGICAL AND HYDROLOGICAL VARIABLES AS TAKEN FROM PRACTICE IN JAPAN

Site parameter	Criterion/ parameter	Definition/value
		Wind (typhoon)
Maximum wind speed	Historic worst case	The 3 s gust wind speed at 10 m above the ground that is the historically observed maximum wind speed. This parameter is used to evaluate the structures.
High intensity wind speed	Fixed value	The 10 min gust wind speed at 10 m above the ground that is required by building regulations. This parameter is used to specify wind loads.

Air temperature		
Maximum dry bulb temperature	Historic worst case	The historically observed maximum dry bulb temperature at the observation station closest to the site. This parameter is used to evaluate the capacity of cooling towers, evaporative coolers and fresh air ventilation systems.
Minimum dry bulb temperature	Historic worst case	The historically observed minimum dry bulb temperature at the observation station closest to the site. This parameter is used for designing the heating equipment.
Precipitation		
Local intense precipitation	Historic worst case	The historically observed local intense precipitation at the observation station closest to the site. This parameter is used for water drainage systems and flooding evaluations.
Snowpack		
Ground snowpack hight	Historic worst case	The historically observed ground snowpack hight at the observation station closest to the site. This parameter is used for determining the design snow loads for roofs and for determining the hight of opening for fresh air ventilation systems.
Lightning		
lightning strike	Fixed value	Crest value of lightning current: 150 kA for robustness considerations. This parameter is used in the design of lightning protection systems.
Tornadoes		
Maximum tornado wind speed	1 million year return period	Maximum wind speed resulting from passage of a tornado that has a 1 million year mean recurrence interval. This parameter is used to specify wind loads due to the passage of a tornado.
Pressure drop	1 million year return period	Decrease in ambient pressure from normal atmospheric pressure resulting from passage of the maximum wind speed tornado. This parameter is used to evaluate the capacity of airtight structures to withstand a drop in atmospheric pressure due to the passage of a tornado.
Massive missile	1 million year return period	The mass and velocity of a massive high kinetic energy missile that deforms on impact (e.g. an automobile) resulting from the passage of the maximum wind speed associated with a tornado. This parameter tests the resistance of barriers to gross failure.
Rigid missile	1 million year return period	The mass and velocity of a rigid missile (e.g. 4.2 x 0.3 x 0.2 m square steel pipe) resulting from the passage of the maximum wind speed associated with a tornado. This parameter tests the resistance of barriers to missile penetration.
Small rigid	1 million year return period	The mass and velocity of a small rigid missile (e.g. 4 cm gravel) resulting from the passage of the maximum wind speed associated with a tornado. This parameter tests the configuration of openings in barriers.

UNITED STATES OF AMERICA

I–6. Table I–5 provides examples of criteria used in the United States of America for defining the design basis parameters for a given meteorological variable Reference [I–6] . These meteorological design basis parameters correspond to single load cases that are associated in design codes with different load combinations and different load factors for designing SSCs.

TABLE I–5. EXAMPLES OF USA CRITERIA FOR CHARACTERIZING METEOROLOGICAL AND HYDROLOGICAL VARIABLES

Site parameter	Criterion	Definition
	Air temperature	
Maximum dry bulb temperature and coincident wet bulb temperature	1% (2%) annual frequency of exceedance[68]	The dry bulb temperature that will be exceeded for 1% (2%) of the time annually and the mean coincident wet bulb temperature.[69] These parameters are used for cooling applications such as air conditioning.
	100 year return period	The maximum dry bulb temperature that has a 1% annual frequency of exceedance (100 year mean recurrence interval) and the projected coincident wet bulb temperature. These parameters may be needed for the operational design of equipment to ensure continuous operation and serviceability.
Maximum non-coincident wet bulb temperature	1% (2%) annual frequency of exceedance	The wet bulb temperature that will be exceeded for 1% (2%) of the time annually. This parameter is useful for cooling towers, evaporative coolers and fresh air ventilation systems.
	100 year return period	The maximum wet bulb temperature that has a 1% annual frequency of exceedance (100 year mean recurrence interval). This parameter is useful for cooling towers, evaporative coolers and fresh air ventilation systems.
Minimum dry bulb temperature	98% (99%) annual frequency of exceedance	The dry bulb temperature that will be exceeded for 98% (99%) of the time annually. This parameter is used in the sizing of heating equipment.
	100 year return period	The minimum dry bulb temperature that has a 1% annual frequency of exceedance (100 year mean recurrence interval). This parameter may be needed for the operational design of equipment to ensure continuous operation and serviceability.

[68] The annual frequency of exceedance levels for the air temperature are typically specified in technical specifications provided by the reactor vendors.

[69] Estimates of the duration for which the air temperature remains above or below given values (i.e. the persistence) may also be necessary for purposes of plant design.

Site parameter	Criterion	Definition
Ultimate heat sink[70]		
Meteorological conditions resulting in the minimum water cooling during any 1 day (5 days)	Historic worst case	The historically observed worst 1 day (5 day) daily average of wet bulb temperatures and coincident dry bulb temperatures. These parameters are used to ensure that design basis temperatures of equipment important to safety are not exceeded.
Meteorological conditions resulting in the maximum evaporation and drift loss during any consecutive 30 days	Historic worst case	The historically observed worst 30-day daily average of wet bulb temperatures and coincident dry bulb temperatures. These parameters are used to ensure that a 30 day cooling supply is available.
Wind speed[71]		
3 second gust wind speed	100 year return period	The 3 second gust wind speed at 10 m above the ground that has a 1% annual frequency of exceedance (100 year mean recurrence interval). This parameter is used to specify wind loads.
Precipitation (liquid equivalent)		
Local intense precipitation	Probable maximum precipitation	The probable maximum precipitation depth of rainfall for a specified duration and surface area. This parameter is used for water drainage systems and flooding evaluations.
	100 year return period	The depth of rainfall for a specified duration and surface area that has a 1% annual frequency of exceedance (100 year mean recurrence interval). This parameter is used for water drainage systems and flooding evaluations.
Snowpack		
Ground snowpack weight	100 year return period	The weight of the 100 year return period snowpack at ground level. This parameter is used for determining the design snow loads for roofs.[72]
Freezing precipitation (ice storms)		
Ice thickness and concurrent wind speed	100 year return period	The 100 year return period ice thickness due to freezing rain with concurrent 3 s gust wind speed. These parameters are used in the design of ice sensitive structures such as lattice structures, guyed towers, overhead lines, etc.
Lightning		
Lightning strike frequency	Lightning strikes per year	The number of lightning bolts that are projected to strike the planned installation annually. This parameter is used in the design of lightning protection systems.

[70] The site parameters listed here for the ultimate heat sink are applicable to a wet cooling tower. A different combination of controlling parameters may be appropriate to other types of ultimate heat sink such as cooling lakes and spray ponds.

[71] For those sites that are susceptible to the occurrence of hurricanes, these phenomena should be taken into account in the site parameters.

[72] The ground level snowpack weight should be converted to a roof load using appropriate exposure factors and thermal factors to determine the resulting applicable design roof load.

Site parameter	Criterion	Definition
Tornadoes and hurricanes[73]		
Maximum tornado wind speed	10 million year return period	Maximum wind speed resulting from passage of a tornado having a 0.01% annual frequency of exceedance (10 000 year mean recurrence interval). This parameter is used to specify wind loads due to the passage of a tornado.
Pressure drop	10 million year return period	Decrease in ambient pressure from normal atmospheric pressure resulting from passage of the maximum wind speed tornado. This parameter is used to evaluate the capacity of airtight structures to withstand a drop in atmospheric pressure due to the passage of a tornado.
Rate of pressure drop	10 million year return period	Rate of pressure drop resulting from the passage of the maximum wind speed tornado. This parameter is used to evaluate the capacity of ventilated structures to withstand a drop in atmospheric pressure due to the passage of a tornado.
Massive missile	10 million year return period	The mass and velocity of a massive high kinetic energy missile that deforms on impact (e.g. an automobile) resulting from the passage of the maximum wind speed associated with a tornado. This parameter tests the resistance of barriers to gross failure.
Rigid missile	10 million year return period	The mass and velocity of a rigid missile (e.g. 15 cm diameter steel pipe) resulting from the passage of the maximum wind speed associated with a tornado. This parameter tests the resistance of barriers to missile penetration.
Small rigid missile	10 million year return period	The mass and velocity of a small rigid missile (e.g. 2.5 cm solid steel sphere) resulting from the passage of the maximum wind speed associated with a tornado. This parameter tests the configuration of openings in barriers.
Hurricanes		
Maximum hurricane wind speed	10 million year return period	Maximum wind speed resulting from passage of a hurricane having a 0.01% annual frequency of exceedance (10 000 year mean recurrence interval). This parameter is used to specify wind loads due to the passage of a hurricane.
Massive missile	10 million year return period	The mass and velocity of a massive high kinetic energy missile that deforms on impact (e.g. an automobile) resulting from the passage of the maximum wind speed associated with a tornado or hurricane. This parameter tests the resistance of barriers to gross failure.
Rigid missile	10 million year return period	The mass and velocity of a rigid missile (e.g. 15 cm diameter steel pipe) resulting from the passage of the maximum wind speed associated with a tornado or hurricane. This parameter tests the resistance of barriers to missile penetration.

[73] The higher of the tornado or hurricane wind speed is to be used for the design basis.

Site parameter	Criterion	Definition
Small rigid missile	10 million year return period	The mass and velocity of a small rigid missile (e.g. 2.5 cm solid steel sphere) resulting from the passage of the maximum wind speed associated with a tornado or hurricane. This parameter tests the configuration of openings in barriers.
	Flooding hazards	
Site parameter	Criterion	Definition
Flood level	0.3 m below site grade	The applicant should provide sufficient information to permit an independent hydrologic engineering review of all hydrologically related site characteristics, performance requirements, and bases for operation of SSCs important to safety, considering the following phenomena or conditions: • Probable maximum precipitation, on the site and on the contributing drainage area • Runoff floods for streams, reservoirs, adjacent drainage areas, and site drainage, and flood waves • resulting from dam failures induced by runoff floods • Surges, seiches, and wave action • Tsunami • Non-runoff-induced flood waves attributable to dam failures or landslides, and floods attributable to failure of on-site or near-site water control structures • Blockage of cooling water sources by natural events • Ice jam flooding • Combinations of flood types • Low water and/or drought effects (including setdown resulting from surges, seiches, frazil and anchor ice, or tsunami) on safety-related cooling water supplies and their dependability • Channel diversions of safety-related cooling water sources • Capacity requirements for safety-related cooling water sources

I–7. In Table I-5, the return period for the maximum wind speed for tornadoes and hurricanes correspond to the methods used in the United States of America. For applications in other States this criterion would need to be carefully reviewed against corresponding and specific regulatory requirements, specific safety goals and for balance with other definitions of external hazards.

I–8. Design basis hurricane wind speeds are expected to correspond to the same exceedance frequency of 10^{-7} per year as that used historically for design basis tornados. Tornado wind loads include loads caused by the tornado wind pressure, tornado atmospheric pressure change effect, and tornado-generated missile impact. Hurricane wind loads include loads due the hurricane wind pressure and hurricane-generated missiles.

I–9. The tornado and hurricane missile parameters presented in Table I-5 are similar to those used historically for only tornado analyses. However, the assumed hurricane wind field differs from the assumed tornado wind field in that the hurricane wind field does not change spatially during the missile's flight time but does vary with height above ground. Because the size of the hurricane zone with the highest winds is large relative to the size of the missile trajectory, the hurricane missile is subjected to the highest windspeeds throughout its trajectory. In contrast, the tornado wind field is smaller, so the tornado missile is subject to the strongest winds only at the beginning of its flight. This results in the same missile having a higher maximum velocity in a hurricane wind field than in a tornado wind field with the same maximum (3 s gust) windspeed. Due to these differences, for nuclear power plant sites where the design basis hurricane wind speed exceeds the design basis tornado wind speeds, analyses need to be performed to ensure that structures are designed to take into account the extra kinetic energy associated with hurricane-induced missiles.

REFERENCES TO ANNEX I

[I–1] AUTORITE DE SURETE NUCLEAIRE, Protection of Basic Nuclear Installations Against External Flooding, Guide of ASN, GEIDE N°13, ASN, Montrouge (2013).

[I–2] Kerntechnischer Ausschuss: Schutz von Kernkraftwerken gegen Hochwasser, KTA 2207, November 2022 (also available in English)

[I–3] Kerntechnischer Ausschuss: Auslegung von Kernkraftwerken gegen Blitzeinwirkung, KTA 2206, November 2022 (also available in English)

[I–4] Western Europe Nuclear Regulators Association, RHWG:WENRA Safety Reference Levels for Existing Reactors 2020, February 2021.

[I–5] NUCLEAR REGULATION AUTHORITY JAPAN, Tornado Impact Assessment Guide for Nuclear Power Pants, NRA JAPAN, September 2019) (in Japanese)

[I–6] Standard Review Plan for the Review of Safety Analysis Report for Nuclear Power Plants: LWR Edition – Site Characteristics and Site Parameters (NUREG-0800, Chapter 2). Section 2.3.1, "Regional Climatology," March 2007.

ANNEX II EVALUATION OF TSUNAMI HAZARDS: CURRENT PRACTICE IN SOME STATES

JAPAN

II–1. Paragraphs II–2 to II–28 present the current practice on tsunami hazard evaluation, which was updated based on the lessons learned from the accident at the Fukushima Daiichi nuclear power plant (the 2011 NPP accident).

II–2. The Japan Nuclear Regulation Authority developed and enforced new regulations and guidelines in 2013. Regulations and guidelines, including the earthquake and tsunami standards, have been strengthened, and a back-fitting system has been introduced for existing nuclear power plants. In addition, even if an accident or natural disaster that exceeds assumptions occurs, measures are necessary to prevent core damage. The regulations and guidelines are summarized in Ref. [II–1].

II–3. Japanese academic technical report on designing and operating nuclear installations to resist the impact of tsunamis was updated in order to incorporate lessons learned from the 2011 NPP accident. The Japan Society of Civil Engineers collected the latest knowledge on earthquakes and tsunamis and upgraded the technical report [II–2] in 2016. A notable feature of Ref. [II–2] is the newly proposed methodology for probabilistic tsunami hazard analysis for earthquake-induced tsunamis. This methodology is based on a logic-tree approach, where epistemic and aleatory uncertainties are systematically taken into account in the analysis. In addition, a deterministic hazard analysis methodology for tsunamis generated by landslides as well as earthquakes is addressed. Furthermore, methods and technologies for evaluation of tsunami loads are included; prediction models and numerical simulation technologies for hydrostatic load, buoyancy, hydrodynamic load, debris impact loads on sea walls, breakwaters, buildings, and tanks, and suspended sediment depositions.

II–4. The Atomic Energy Society of Japan published a standard on tsunami assessment method for nuclear power plants in 2012, which was updated in 2016 (Ref. [II–3]). The methodologies for such assessments, fragility analysis, and accident sequence analysis against tsunamis are described. The standard also addresses a method for determining probabilistically defined tsunami scenarios, which can be used for evaluations of tsunami impact for the design basis tsunami and beyond design basis tsunami.

Method for the determination of design basis tsunami by deterministic tsunami hazard evaluation for nuclear power plants in Japan

Overall policy

II–5. The design basis tsunami needs to be determined based on the latest scientific and technical knowledge and be appropriate from a seismological, geological, and geophysical viewpoint. In addition to tsunamis caused by earthquakes, submarine and subaerial landslides, volcano activities, and those combinations need to be evaluated. For determinations of design basis tsunami, tsunami numerical simulations need to be performed by considering uncertainties on the tsunami hazard evaluation.

Tsunami source for the design basis tsunami

II–6. Based on the seismological, geological, and geophysical background and field survey data for past tsunamis (paleo and historical tsunamis), the following events and their combinations need to be considered as tsunami sources:

(a) Inter-plate earthquakes;
(b) Intra-plate earthquakes in oceanic (subducting) plate;
(c) Offshore active crustal earthquakes;
(d) Submarine and subaerial landslides;
(e) Volcanic phenomena (e.g. eruptions, mountain collapses, caldera collapse)

II–7. For past tsunamis caused by inter- and intra- plate earthquakes, the tsunami source model is obtained by inversion analysis, and slip inhomogeneity is considered if necessary.

II–8. The uncertainties associated with tsunami sources need to be sufficiently considered in the hazard evaluation within a reasonable range.

Process flow for tsunami assessment

II–9. The first part of the process is 'Verification of fault model(s) and a numerical calculation system on the basis of historical tsunami(s)', and the second part is 'Determination of the design basis tsunamis', as shown in Fig. II–1.

Historical tsunami study

II–10. The first step is to conduct literature surveys for dominant historical tsunamis affecting the target site, and then the validity of recorded tsunami heights needs to be examined. On the basis of the results, fault models for numerical simulations for historical tsunamis can be set up. After setting up fault models for historical tsunamis, numerical simulations are performed. The reliability of the numerical simulation system is then examined. If the result satisfies the conditions, the second part can be commenced. If the result does not satisfy the conditions, fault models or numerical conditions are modified for improvement of the representation, and numerical simulations performed again.

Selection of tsunami sources and the standard source model

II–11. The first step in the second part of the process is to select the potential zones in which earthquake, submarine and subaerial landslides, and volcanic phenomena induced tsunamis can occur. Generally, the effects of near field tsunamis are greater than those of far field tsunamis. The latter cannot be neglected, however, because the effects depend on geographical conditions and directional relations to the tsunami source. In Japan, major source areas are at tectonic plate boundaries and active faults around the Japanese archipelago for near field tsunamis, and off the west coast of South America for far field tsunamis.

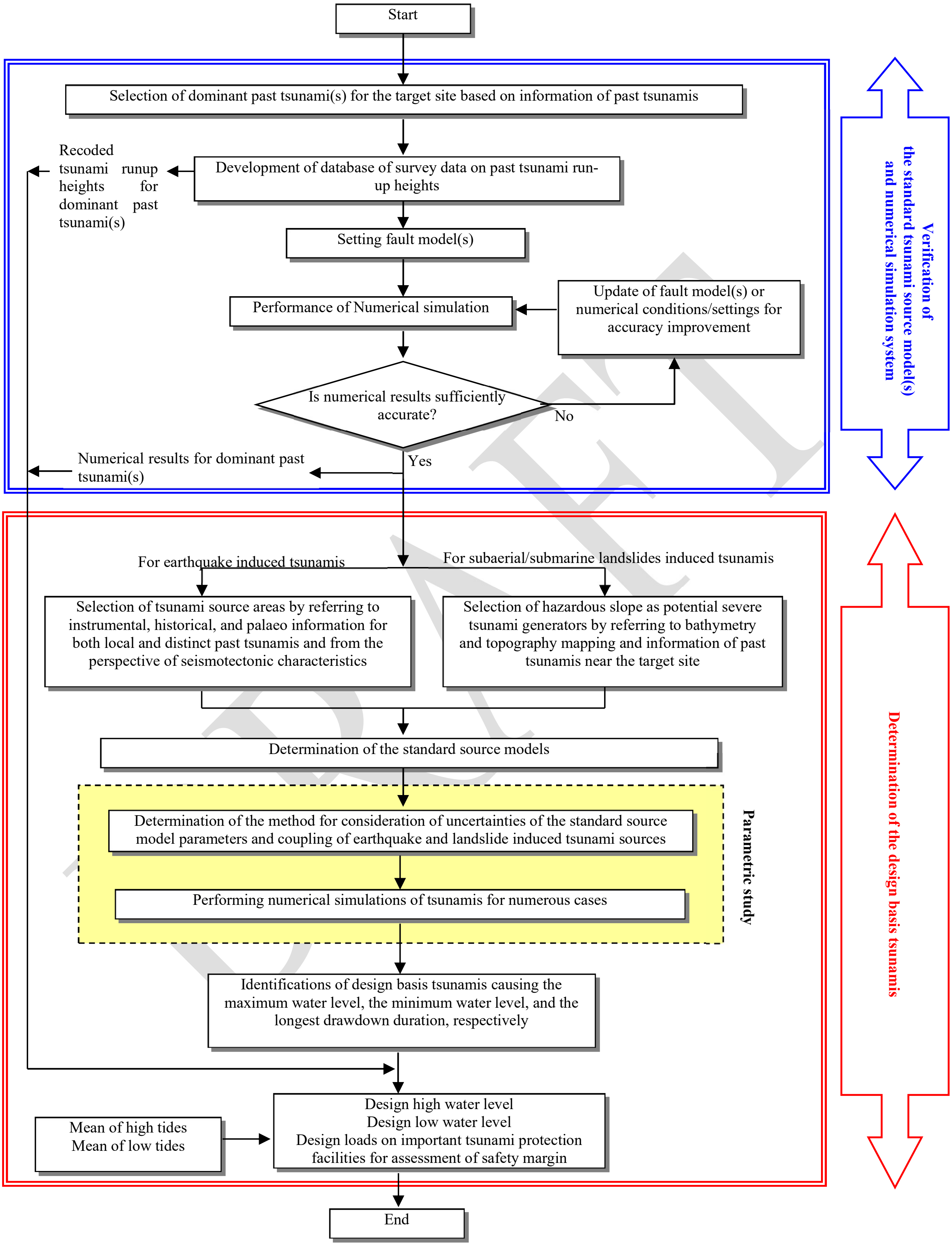

FIG. II–1. Flowchart for the assessment process for the design basis tsunami

II–12. The standard source models both for scenario earthquakes and landslides have then to be determined. These standard source models will provide the basis for parametric tsunami evaluation for sites (see Fig. II–2) and they have to be determined appropriately in consideration of the characteristics of each sea area. Therefore, parameters of the standard fault model needs to be carefully determined to reproduce historical tsunami runup heights.

Scenario earthquakes

II–13. In setting up models for scenario earthquakes, the standard fault model is set up to reproduce recorded historical tsunami heights in each region. In this process, the occurrence mechanism of historical earthquakes and/or tsunamis and seismotectonics such as the shape of the plate boundary surface, the relative motion of plates and the distribution of active faults are considered.

Parametric study

II–14. A concept for a parametric study of a tsunami source is shown in Fig. II–2. The upper part of the figure shows fault models for scenario earthquakes. Each rectangle in a dashed line represents a fault model. Not only the location, strike and size shown in the figure, but also the uncertainties in the static and dynamic parameters of the fault model (e.g. dip and rake angles, slip amount, rise time of the slip) can be considered. In the lower part of Fig II–2, each curved line represents a scenario tsunami, which is calculated on the basis of each fault model.

Selection of the design basis tsunami

II–15. The highest and/or lowest scenario tsunami is selected as the design basis tsunami. For the purpose of use for design, the design basis tsunami has to be the highest among all historical and possible tsunamis at the site in order to ensure the safety of nuclear power plants sited on the coast (Fig. II–2). It has to be noted that sometimes the tsunami sources that give rise to the maximum water levels and those that fall to the minimum water levels are different.

Verification

II–16. For verification of the design basis tsunami, the two conditions of para. II–22 need to be confirmed. The concept of verification is shown in the lower part of Fig. II–2.

Combination with other water level changes

II–17. After confirming the verification of the design basis tsunami, other water level changes such as tides need to be considered as appropriate. In the event that numerical calculation is performed on the basis of the mean tide, the mean of high and/or low tides has to be combined with the tsunami high and/or low water level respectively.

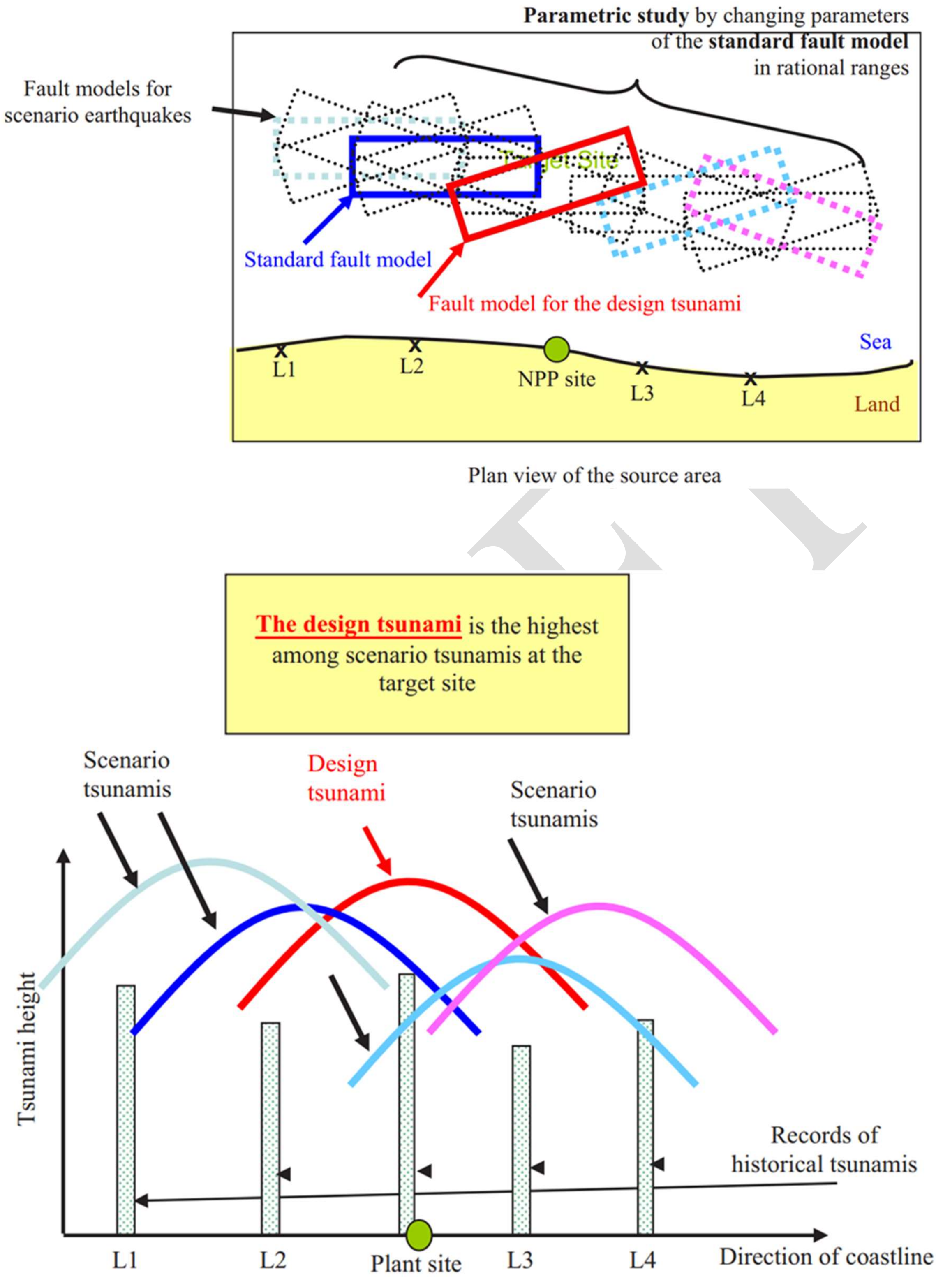

FIG. II–2. Concept of setting up of source fault and parametric study.

Evaluation of other tsunami associated phenomena

II–18. When the predominant period of the tsunami and the natural period of free oscillation for the harbour and/or the intake passage are equal, the water rise and fall may be amplified. The effect of resonance in the numerical simulation needs to be investigated.

II–19. Other associated phenomena such as the movement of sand sediment, inundation from an adjacent river and ground uplift and/or subsidence due to the movement of a fault have be evaluated on the basis of specific site conditions.

Consideration of uncertainties

II–20. There are uncertainties and errors, such as uncertainties of the tsunami source model, errors in the numerical calculation and errors in the data on submarine topography and coastal landform, included in the tsunami evaluation process. These uncertainties and errors have to be taken into account so that the water level of the design basis tsunami is not underestimated.

II–21. It is difficult to estimate each parameter quantitatively. Consequently, in the method of assessment of tsunamis of the Japan Society of Civil Engineers, the following procedure is adopted:

(a) Scenario earthquakes with various conditions within a reasonable range are set on the basis of a standard fault model;
(b) A large number of numerical calculations are performed in consideration of the uncertainties of the tsunami source parameters for scenario earthquakes;
(c) For the design, the tsunami that causes the maximum water rise and the maximum water fall at the target site is selected from among the scenario tsunamis.

II–22. The design basis tsunami height, evaluated by means of a parametric study, has to sufficiently exceed all the historical tsunami heights. To confirm its adequacy, it is necessary to ensure that the following two conditions are satisfied:

(a) At the target site, the height of the design basis tsunami has to exceed all the tsunami heights of analyses for the representation of historical tsunamis.
(b) In the vicinity of the target site, the envelope of the scenario tsunami heights has to exceed all the recorded historical tsunami.

Method for the probabilistic hazard evaluation for earthquake induced tsunamis

II–23. Methods for the evaluation of earthquake-induced tsunami hazards using probabilistic approaches have been applied to Japan’s nuclear power sites. The approaches are analogous to probabilistic seismic hazard evaluation. By adopting logic-tree approaches, both epistemic and aleatory uncertainties can be systematically incorporated into tsunami hazard evaluation. Results of the probabilistic hazard evaluation are typically displayed as the mean, median, and 5% and 95% fractile values of annual frequency of exceedance of runup and drawdown elevations.

II–24. The methodology flowchart is shown in Fig. II–3. As well as the deterministic tsunami hazard evaluation, the most important tasks are the thorough collection of data and information on past tsunamis and the analyses on potential of occurrence of severe tsunami events by considering seismological, geological, and geophysical background. For these analyses, it is important to gather opinions of experts on these themes and to model epistemic uncertainties on predictions of future severe tsunami events by following expert opinions.

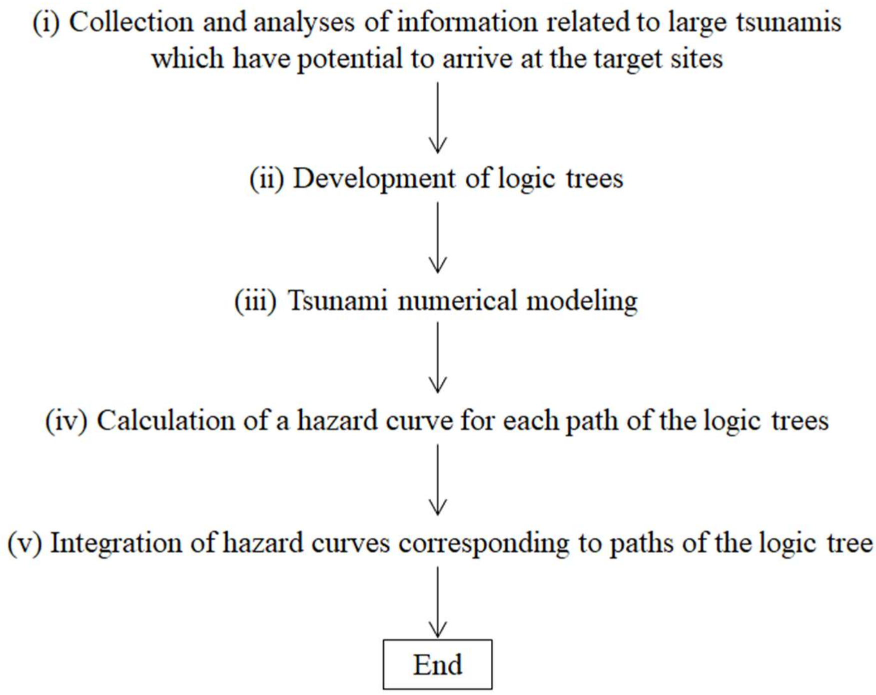

FIG. II–3. The methodology flowchart of the probabilistic hazard evaluation in Japan.

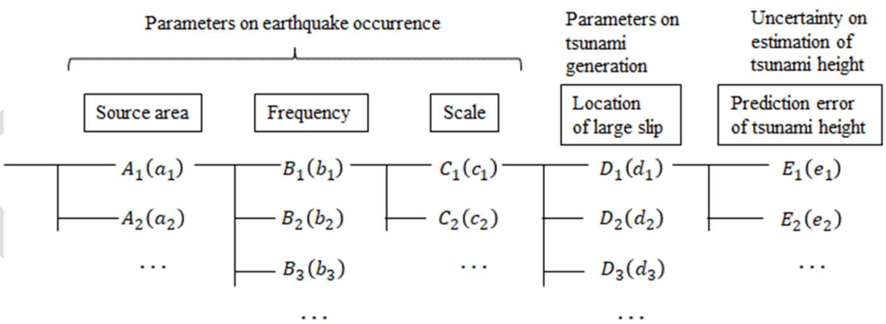

FIG. II–4. A schematic diagram of a logic tree.

II–25. Next, logic trees for each sea areas are developed. A schematic diagram of a logic tree is shown in Fig. II–4. A branch of the logic tree is set for each parameter whose decision is considered to be epistemic uncertainty, related to the earthquake occurrence, tsunami generation, and estimation of tsunami height. At each branch, there are path for various settings of the centre, body, and range of uncertainties for each parameter. Variation of the parameters corresponding to the settings of the selected path are considered as aleatory uncertainty. Furthermore, uncertainty on the numerically estimated tsunami height is considered by modelling the occurrence probability of the ratio of the measured or surveyed tsunami height to the predicted tsunami height as the lognormal distribution.

II–26. By considering both epistemic and aleatory uncertainties following the logic trees, a large number of tsunami scenarios are developed. For each tsunami scenario, a tsunami simulation is performed. In the probabilistic hazard evaluation of each nuclear power site in Japan, tsunami simulations for thousands to tens of thousands of cases have been performed. In the simulations, tsunami heights at the site and at the intake location can be computed (Fig. II–3 (iii)). The former tsunami heights are used for the evaluation of the maximum tsunami height, and the latter ones are used for the evaluation of minimum tsunami height (drawdown level).

II–27. Next, a hazard curve for each path of the logic trees is calculated i.e. the hazard curve in accordance with a specific scenario (Fig. II–3 (iv)). The schematic diagram for this calculation is shown in Fig. II–5. In the calculation for each path, random variabilities, or aleatory uncertainties, of parameters related to earthquake occurrence, tsunami generation, and uncertainty of estimated tsunami height, are considered. In order to incorporate the parameter variabilities into hazard curve calculation, parameters are discretized, and each bin value (a_1, a_2, …, a_7 in Fig. II–5 (a)) has a probability (P_1, P_2, … P_7 in Fig. II–5 (a)). For each parameter value combination, tsunami height is estimated by a numerical tsunami simulation (H_1, H_2, …, H_7 in Fig. II-5 (b)). Each estimated tsunami height is used as the median value of a lognormal distribution, which is a probability density function representing the uncertainty of the estimated tsunami height (the b lines in Fig. II–5 (c)). By the summation of the values that the lognormal distribution is multiplied by the probability of the bin value of the parameter, a probability density function of tsunami height for each path is calculated (the black line in Fig. II–5 (c)). By considering occurrence frequency of earthquake to the probability density function, annual frequency of exceedance of tsunami height is calculated for each path, and the width of the distribution expresses the aleatory uncertainty (Fig. II–5 (d)).

II–28. Finally, a set of hazard curves for each sea area is calculated (Fig. II–3 (v)) by the integration of the hazard curves corresponding to paths of the logic tree. The image of this operation is shown in Fig. II–6. By sorting the hazard curves considering a weight of each path, the mean, 5%, 50% (median), and 95% fractile curve can be obtained. The width among fractile hazard curves expresses the epistemic uncertainty.

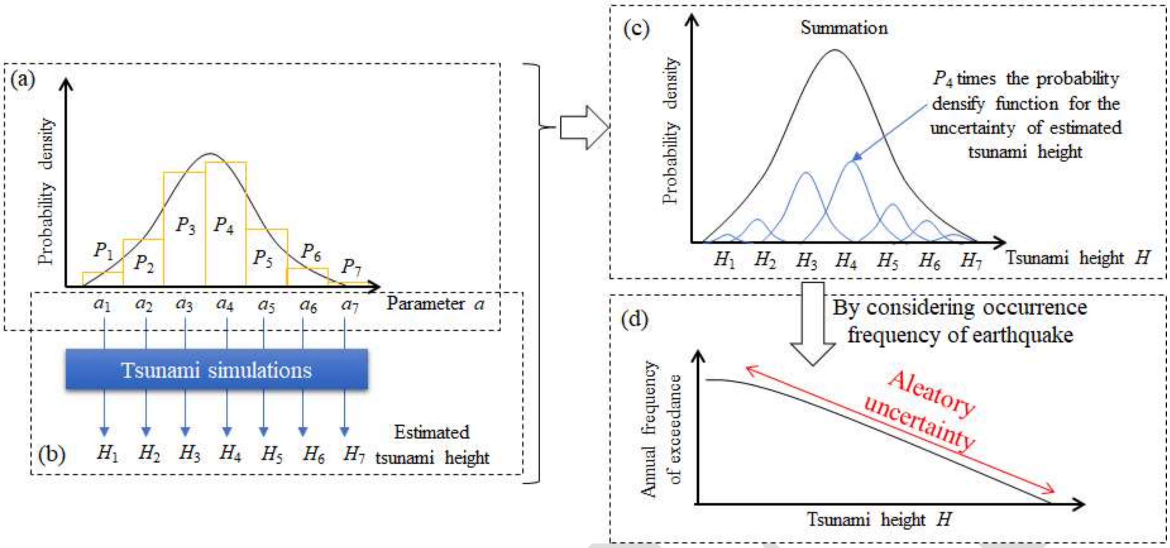

FIG. II–5. The schematic diagram for the calculation of a hazard curve for each path of the logic trees.

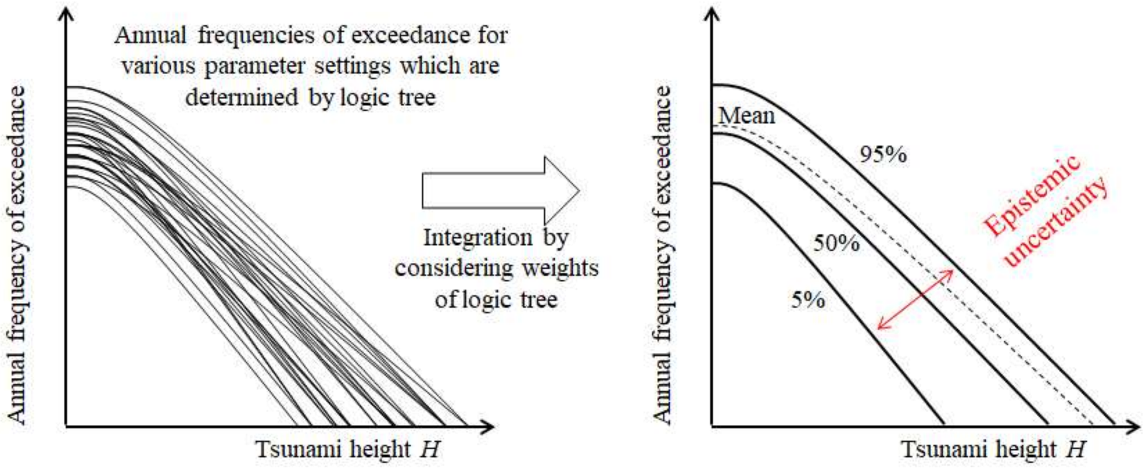

FIG. II–6. A image of the integration of the hazard curves corresponding to paths of the logic tree and the development of a set of hazard curves for each sea areas.

UNITED STATES OF AMERICA

II–29. The United States Nuclear Regulatory Commission considers and assesses tsunami related and tsunami like phenomena under its tsunami hazard and risk assessment protocols. To perform a tsunami hazard and risk assessment, the Nuclear Regulatory Commission uses a hierarchical framework and a variety of technical approaches as appropriate for each of the various source types. Currently, the guidance on tsunamis includes a deterministic approach based on an assessment of the probable maximum tsunami. Paragraphs II–30 to II–48 describe the approach currently used by staff in the review of licence applications.

II–30. The Nuclear Regulatory Commission is moving towards risk informed approaches and guidance. Probabilistic approaches can be proposed as a basis for review by the licensee. Most recent practice in the USA uses probabilistic approaches to determine tsunami hazards on the Pacific coast. Currently a lack of information on the rate of activity of tsunamigenic sources that might affect the Atlantic and Gulf of Mexico coasts of the USA limits the practical use of probabilistic methods.

Regulations and regulatory guidance

II–31. Nuclear Regulatory Commission regulations relating to the assessment of tsunami hazards, as provided in the Code of Federal Regulations (CFR), include the following:

- 10 CFR Part 100 [II–4], as it relates to identifying and evaluating hydrological features of the site. The requirements to consider physical site characteristics in site evaluations are specified in 10 CFR 100.20 (c) for new applications. 10 CFR 100.23(d) sets criteria to determine the siting factors for plant design basis with respect to seismic induced floods and water waves at the site.
- 10 CFR Part 50, Appendix A, General Design Criterion (GDC) 2 [II–5], for construction permit and operating licence applications, as it relates to consideration of the most severe of the natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin to allow for the limited accuracy and limited quantity of the historical data and the limited period of time in which they have been accumulated.
- 10 CFR 52.17 (a) (1) (vi), for early site permit applications, and 10 CFR 52.79 [II–6] for combined operating licence applications, as they relate to identifying the characteristics of hydrological sites. This includes appropriate consideration of the most severe of the natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin to allow for the limited accuracy and limited quantity of the historical data and the limited period of time in which they have been accumulated.

II–32. Regulatory Guide 1.59 [II–7] briefly discussed tsunamis as a source of flooding. This regulatory guide is currently being updated. The update of this guide will include tsunami induced flooding.

II–33. Section 2.4.6 of the Nuclear Regulatory Commission Standard Review Plan NUREG 0800 [II–8], describes review procedures and acceptance criteria for tsunami hazards currently used by staff.

II–34. The US National Oceanic and Atmospheric Administration is responsible for developing standards of accuracy for tsunami simulation models for the US federal government and for conducting research to support the National Tsunami Hazard Mitigation

Program. In 2007, The Administration provided the Nuclear Regulatory Commission with a report on tsunami hazard evaluation in the USA Ref. [II–9] that, together with NUREG/CR-6966 [II–10], forms the basis for the current approach to the review.

II–35. From 2006 to 2016, the Nuclear Regulatory Commission conducted a long term tsunami research programme. This programme, which included cooperative work with the National Oceanic and Atmospheric Administration and the United States Geological Survey, was designed both to support activities associated with the licensing of new nuclear power plants in the USA and to support the development of regulatory guidance.

Application of the hierarchical approach

II–36. A hierarchical approach to the evaluation of hazards that is acceptable to the Nuclear Regulatory Commission is described in NUREG/CR-6966. As noted in this document, a hierarchical approach to hazard evaluation consists of a series of stepwise, progressively more refined analyses that are used to evaluate the hazard resulting from a specific phenomenon. In the case of the evaluation of tsunami hazards, this approach is defined by three steps that answer the following questions:

(a) Is the site region subject to tsunamis?
(b) Could the plant site be affected by tsunamis?
(c) What is the risk to the safety of the plant caused by tsunamis?

II–37. The first step, which is essentially a regional screening test, is performed to determine whether or not a site can be excluded on the basis of its proximity to a water body capable of producing a tsunami or tsunami-like effect. If the region in which a site is located is not subject to tsunamis, no further analysis for tsunami hazards is necessary. This finding needs to be supported by evidence specific to the region. If such a finding cannot be conclusively shown, the second step is necessary.

II–38. The second step can be regarded as a site screening test. This step determines whether plant systems important to safety are exposed to hazards arising from tsunamis. The methods used to perform site specific hazard evaluations, including the calculation of site specific runup elevations, are described in para II–40. It may be possible to determine that, even though the general region of the site is subject to tsunami hazards, all plant systems important to safety are located at an elevation above the calculated maximum wave runup.

II–39. The third step is an assessment of the risk that there might be to a nuclear installation if the elevation of the SSCs important to safety cannot be conclusively shown to exceed the calculated tsunami runup. This step involves the most refined and complex analysis.

Areas of review by Nuclear Regulatory Commission staff

II–40. Nuclear Regulatory Commission staff review the technical areas summarized in the following. These review areas are described in more detail in the current version of Ref. [II–8], which is available for download at the Commission’s website.

Historical tsunami data. The staff review historical tsunami data, including palaeological tsunami data. Historical data may help in establishing the frequency of occurrence and other useful indicators such as the maximum observed runup height. The National Oceanic and

Atmospheric Administration National Geophysical Data Center collects and archives information on the sources and effects of tsunamis to support the modelling of tsunamis and tsunami related engineering for the US government, and it is used as a key source of data. International sources of information that are relevant to plants exposed to transoceanic tsunamis need also to be investigated.

(d) *Probable maximum tsunami*. Currently, staff review applications for adequacy on the basis of deterministic assessment of a probable maximum tsunami, as noted in Ref. [II–7]. The staff review the probable maximum tsunami with respect to the identification of the source mechanisms, the characteristics of these source mechanisms and the simulation of the wave propagating towards the proposed plant site. A discussion of tsunamigenic sources is provided in paras II–41 to II–43.

(e) *Tsunami propagation models*. The staff review the computational models used in the hazard analysis. Elements of tsunami modelling are discussed in more detail in paras II–44 to II–48.

(f) *Wave runup, inundation and drawdown*. The staff review the runup caused by the probable maximum tsunami. An appropriate initial water surface elevation for the body of water under consideration, before the arrival of the tsunami waves, is assumed. For example, to estimate the highest tsunami wave runup at a coastal site, the 90th percentile of high tides is used as the initial water surface elevation near the site. To estimate the lowest drawdown caused by receding tsunami waves, the 10th percentile of the low tides is used. Any inundation indicated by the assessment needs to be considered in the design basis for flooding of the plant and may necessitate flooding protection for some SSCs important to safety. Staff also review the drawdown caused by tsunami waves and how it might affect intakes important to safety, if they are used in the plant design and are exposed to the effects of the tsunami. The staff also review the duration of the drawdown to estimate the time period during which an intake might be affected. The suggested criteria of Regulatory Guide 1.27, Ref. [II–11] apply when the water supply comprises part of the ultimate heat sink. It has to be demonstrated that the extent and the duration of the inundation and the drawdown caused by the tsunami waves are adequately established for the purposes of the plant design basis.

(g) *Hydrostatic and hydrodynamic forces*. The staff review the hydrostatic and the hydrodynamic forces on SSCs important to safety caused by the tsunami waves. Because the tsunami occurs as a train of waves, several incoming and receding wave cycles need to be considered. Local geometry and bathymetry can significantly affect the height, velocity and momentum flux near the locations of SSCs important to safety. The suggested criteria of Ref. [II–11] apply when the water supply comprises part of any water cooled ultimate heat sink. It has to be demonstrated that potential hydrostatic and hydrodynamic forces caused by tsunami waves are adequately established for the purposes of the plant design basis.

(h) *Debris and water borne projectiles*. The staff review the likelihood of debris and water borne projectiles being carried along with the tsunami currents and their ability to cause damage to SSCs important to safety. The suggested criteria in Ref. [II–11] apply when the water supply comprises part of the ultimate heat sink. It needs to be demonstrated that any possibility of damage being caused to SSCs important to safety by debris and water borne projectiles is adequately established for the purposes of the plant design basis.

(i) *Effects of sediment erosion and deposition*. The staff review the deposition of sediment during the tsunami, as well as the erosion caused by the high velocity of flood waters or wave action during the tsunami and its effects on the foundations of SSCs important to safety, to ensure that these are adequately established for the purposes of the plant design basis. The suggested criteria in Ref. [II–11] apply when the water supply comprises part of the ultimate heat sink.

(j) *Consideration of other site related evaluation criteria*. Ref. [II–4] describes site related proximity, seismic and non-seismic evaluation criteria for power plant applications. Subpart A to Ref. [II–4] addresses the requirements for applications before 10 January 1997, and Subpart B is for applications on or after 10 January 1997. The staff's review will include evaluation of pertinent information to determine whether these criteria are appropriately used in the postulation of worst-case tsunami scenarios.

Characterization of tsunamigenic sources

II–41. Tsunami hazards along the coastlines of the USA arise from two predominant source categories: landslides and seismic sources. Sources in these categories exist in both the near field and the far field. A regional assessment of tsunamigenic sources needs to be performed to determine all the sources that may generate the probable maximum tsunami at the proposed plant site. The source mechanisms considered in the assessment include earthquakes, submarine and subaerial landslides, and volcanoes. The characteristic of the sources that are used for the specification of the probable maximum tsunami need to be conservative.

II–42. The landslide sources are characterized using the maximum volume parameter determined from seafloor mappings or geological age dating of historical landslides. A slope stability analysis is then performed to assess the efficiency for the potential generation of tsunamis of the candidate landslides. The tsunamigenic source types caused by volcanic activity considered in the assessment of the probable maximum tsunami include pyroclastic flows, collapse of submarine caldera, explosions, and debris avalanches or flank failures.

II–43. To support licensing activities in relation to new reactors, the Nuclear Regulatory Commission has implemented a long term tsunami research programme. As part of this programme, the US Geological Survey provided a report summarizing the tsunamigenic source mechanisms in the Atlantic Ocean and the Gulf of Mexico [II–12]. The information detailed in this report is used by Commission staff as a starting point for tsunami assessment for proposed sites located near these water bodies.

Modelling methods for tsunamis

II–44. The National Oceanic and Atmospheric Administration has produced reports on tsunami hazard evaluation and tsunami modelling best practices [II–13 and II–14], which form the basis for Nuclear Regulatory Commission reviews of tsunami modelling submittals. As part of the licensing process, the staff review the computational models used in the tsunami hazard analyses. Tsunami propagation models need to be consistent with those used by the National Oceanic and Atmospheric Administration, published in peer reviewed literature, and verified by means of extensive testing.

II–45. The staff review the propagation of the probable maximum tsunami waves from the source towards the proposed site. If appropriate, the shallow wave approximation is used to simulate propagation of the probable maximum tsunami waves in deep waters. The simulation of the propagation of tsunami waves in shallow waters, where the shallow wave approximation is not valid, is performed using methods that capture the non-linear wave dynamics.

II–46. The staff review the model parameters and input data used to simulate the propagation of the probable maximum tsunami waves towards the site. The model parameters need to be described, and conservative values chosen. All other data used for model input need to be described and their respective sources noted. Usually, data from bathymetry and topography that are archived and maintained by the National Oceanic and Atmospheric Administration National Geophysical Data Center [II–15], the United States Geological Survey and the US Army Corps of Engineers are sufficient for sites in the USA. However, additional data may be needed for some sites.

II–47. The National Oceanic and Atmospheric Administration has the responsibility of developing standards of accuracy for tsunami simulation models for the US federal government and of conducting research to support the National Tsunami Hazard Mitigation Program. The National Oceanic and Atmospheric Administration, through funding by the United States Agency for International Development, has developed an interface tool, the Community Model Interface for Tsunami (ComMIT) [II–16], which allows individuals and institutions to make use of seismic source models, tools, and National Oceanic and Atmospheric Administration results. This publicly available interface tool, when applied by an appropriately trained analyst in conjunction with high quality local bathymetric information, is a useful tool for undertaking tsunami hazard analyses at many locations both within and outside the USA. Any analyst using the tool needs to first perform the benchmark test problems provided by the National Oceanic and Atmospheric Administration.

II–48. The Nuclear Regulatory Commission intends to use the National Oceanic and Atmospheric Administration ComMIT tool, as appropriate, and will continue to work with the National Oceanic and Atmospheric Administration to enhance practices and guidance in the future. For landslide related tsunamigenic sources, alternative methods and tools are needed.

TÜRKIYE

II–49. A complete hazard evaluation due to hydrological and meteorological conditions has been performed including the hazard (high or low water) levels due to: astronomical tide, seasonal variations, storm surge, wind and wave setup, runup of wind generated waves, setup due to barometric variations, seiches, tsunami, long term sea level rise and flood.

II–50. There is no specific national guideline for the evaluation of external events for nuclear installation sites in Türkiye. Therefore, the IAEA safety standards are followed in the evaluation of all aforementioned external events.

REFERENCE TO ANNEX II

References [II–4]–[II–16] below are available either through the USNRC ADAMS system using the ML ascension number (if shown), or through the USNRC reading room. Both systems can be accessed through the USNRC web site: http://www.nrc.gov

[II–1] NUCLEAR REGULATION AUTHORITY JAPAN, SARIS Summary Report, NRA JAPAN, (2015), https://www.nra.go.jp/data/000148577.pdf.

[II–2] JAPAN SOCIETY OF CIVIL ENGINEERS, Tsunami Assessment Method for Nuclear Power Plants in Japan 2016 (2016); web page: https://committees.jsce.or.jp/ceofnp/node/140

[II–3] ATOMIC ENERGY SOCIETY OF JAPAN, Implementation standard concerning the tsunami probabilistic risk assessment of nuclear power plants, AESJ-SC-RK004:2016. (2019) (in Japanese.)

[II–4] UNITED STATES NUCLEAR REGULATORY COMMISSION, 10 CFR Part 100. Title 10, Energy, Part 100, Reactor Site Criteria, USNRC, Washington DC.

[II–5] UNITED STATES NUCLEAR REGULATORY COMMISSION, 10 CFR Part 50. Code of Federal Regulations. Title 10, Energy, Part 50, Domestic Licensing of Production and Utilization Facilities, USNRC, Washington DC.

[II–6] UNITED STATES NUCLEAR REGULATORY COMMISSION, 10 CFR Part 52. Code of Federal Regulations. Title 10, Energy, Part 52, Early Site Permits; Standard Design Certifications; and Combined License for Nuclear Power Plants, USNRC, Washington DC (2010).

[II–7] UNITED STATES NUCLEAR REGULATORY COMMISSION, Design Floods for Nuclear Power Plants, Regulatory Guide 1.59, USNRC, Washington, DC (1977).

[II–8] UNITED STATES NUCLEAR REGULATORY COMMISSION, NUREG 0-800, Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants, LWR Edition, Office of Nuclear Reactor Regulations, USNRC, Washington, DC (2007).

[II–9] GONZALEZ, F.I., et al, Scientific and Technical Issues in Tsunami Hazard Assessment of Nuclear Power Plant Sites, NOAA Technical Memorandum OAR PMEL-136, Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration, Seattle, WA (2007).

[II–10] PACIFIC NORTHWEST NATIONAL LABORATORY, Tsunami Hazard Assessment at Nuclear Power Plant Sites in the United States of America, NUREG/CR-6966, PNNL-17397 (2009). Available for download at the USNRC reading room.

[II–11] UNITED STATES NUCLEAR REGULATORY COMMISSION, Ultimate Heat Sink for Nuclear Power Plants, Regulatory Guide 1.27, Revision 2, USNRC, Washington, DC (1976).

[II–12] TEN BRINK, et al, Atlantic and Gulf of Mexico Tsunami Hazard Assessment Group, Evaluation of Tsunami Sources with the Potential to Impact the US Atlantic and Gulf Coasts: An Updated Report to the Nuclear Regulatory Commission, US Geological Survey Administrative Report ML082960196, Woods Hole, Massachusetts (2008).

[II–13] UNITED STATES NUCLEAR REGULATORY COMMISSION, Tsunami Hazard Assessment Based on Wave Generation, Propagation, and Inundation Modeling for the U.S. East Coast, NUREG/CR-7222, USNRC, Washington, DC (2016), prepared for NRC by the NOAA Pacific Marine Environmental Laboratory.

[II–14] UNITED STATES NUCLEAR REGULATORY COMMISSION, Tsunami Hazard Assessment: Best Modeling Practices and State-of-the-Art Technology, NUREG/CR-7223, USNRC, Washington, DC (2016), prepared for NRC by the University of Southern California, Department of Civil and Environmental Engineering and the University of Washington Joint Institute for the Study of the Atmosphere and Ocean.

[II–15] NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, NATIONAL GEOPHYSICAL DATA CENTER, NOAA/WDC Historical Tsunami Database at the National Geophysical Data Center: http://www.ngdc.noaa.gov/hazard/tsu_db.shtml

[II–16] NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, Community Model Interface for Tsunami (ComMIT). Download and documentation available at: http://nctr.pmel.noaa.gov/ComMIT/ .

ANNEX III TSUNAMI WARNING SYSTEMS

GOVERNANCE OF THE UNITED NATIONS ECONOMIC, SOCIAL AND CULTURAL ORGANIZATION/INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION (UNESCO-IOC) TSUNAMI WARNING SYSTEM

III–1. The United Nations Economic, Social and Cultural Organization/Intergovernmental Oceanographic Commission (UNESCO/IOC) has the mandate to implement and coordinate the activities of tsunami warning systems around the world, in all ocean and seas that could be affected by tsunamis.

III–2. The IOC assists governments to address their individual and collective problems relating to the ocean and the coast through the sharing of knowledge, information and technology and through the coordination of national programmes.

III–3. The Intergovernmental Coordination Groups (ICGs) of UNESCO/IOC meet to promote, organize and coordinate regional activities for the mitigation of tsunamis, including the issuing of timely tsunami warnings. Currently, there are four tsunami warning and mitigation systems under ICG governance in the Pacific Ocean, the Indian Ocean, the Caribbean and adjacent regions, the North-Eastern Atlantic Ocean and the Mediterranean Sea and connected seas.

TSUNAMI WARNING CENTRES AND TSUNAMI WARNING MESSAGES

III–4. The main operational components of the tsunami monitoring and warning systems are:

(a) The real time seismic monitoring network;
(b) The real time sea level monitoring network;
(c) The network of tsunami warning and watch centres;
(d) The seismological warning centres.

III–5. As most of the large tsunamis are generated by earthquakes, the first information about the possible occurrence of a tsunami comes from the seismological and tsunami centres. Large seismic activity on a global and regional scale is monitored all around the world by a number of global networks. Most seismic warning centres disseminate information messages on large earthquakes in about 20 minutes. These bulletins or messages are disseminated through the Internet or other telecommunication links.

III–6. A tsunami warning centre is a centre that issues timely information messages on tsunamis. Regional tsunami warning centres monitor and provide States with tsunami related information on potential ocean wide tsunamis using global data networks. They often issue messages within 10–15 minutes of an earthquake. An example of a regional tsunami warning centre is the Pacific Tsunami Warning Centre, which provides international tsunami warnings to the Pacific basin States. Examples of subregional tsunami warning centres are the Northwest Pacific Tsunami Advisory Centre operated by the Japan Meteorological Agency and the West Coast and Alaska Tsunami Warning Centre operated by the United States National Oceanic and Atmospheric Administration National Weather Service. Since the April 2005 tsunami, the Pacific Tsunami Warning Centre and the Japan Meteorological Agency have acted as an interim regional tsunami warning centre for the Indian Ocean. Since 2006, the Pacific Tsunami Warning Centre is also acting as an interim regional tsunami warning centre for the Caribbean States. Near field tsunami warning centres monitor and provide tsunami related information on potential near field tsunamis that would strike within minutes. Near field tsunami warning centres have to issue a warning within minutes. Ref. [III–1] provides operational guidance to the users.

III–7. The current messages provided by regional warning and watch centres are described in general in Ref. [III–2]. The messages can comprise of information, watch or warning messages, and are based on the available seismological data and sea level data as evaluated by the tsunami warning centre, or on evaluations received by the tsunami warning centre from other monitoring agencies. The messages are advisory to the officially designated emergency response agencies in the Intergovernmental Oceanographic Commission Member States. The level of alert could be different from one sea to another ocean, because of the size, morphology and seismotectonic characteristics of each basin.

III–8. A tsunami warning is the highest level of alert in the case of the occurrence of a tsunami in the Pacific Ocean basin. Warnings are issued by the tsunami warning centres owing to the confirmation of a destructive tsunami wave or the threat of an imminent tsunami. Initially the warnings are based only on seismic information without confirmation of a tsunami as a means of providing the earliest possible alert to at-risk populations. Warnings initially place a restricted area in a condition for which all coastal areas in the region need to be prepared for imminent flooding. Subsequently, text products are issued at least hourly or as conditions warrant, to expand, restrict or end the warning. If a tsunami has been confirmed, the warning may be extended to a larger area. These warning messages include earthquake information, such as region, epicentre coordinates, origin time and magnitude. When a tsunami is confirmed, information on waves (amplitude, period) are added as is the estimated arrival time along the coastlines of the basin concerned. The arrival time at the nearest forecast point to the site will give an approximate time of arrival of the first wave of the tsunami at the site.

III–9. A sea level station is a system consisting of a device such as a tide gauge for measuring the height of the sea level (rise and fall), a data collection platform for acquiring, digitizing and archiving the sea level information digitally, and often a transmission system for delivering the data from the field station to a central data collection centre. The criteria for data sampling and data transmission are dependent on the application:

(a) For tsunami monitoring, 15 s or 1 min sampled data streams, available in real time, are needed.
(b) Various telecommunication transmission systems exist such as the World Meteorological Organization Global Telecommunication System or the Broadband Global Area Network (the Inmarsat satellite Internet network).

III–10. The tide gauge is the most common sensor of the sea level station implemented for monitoring and records for tides, tsunamis and storm surges. A tsunameter, a second type of sea level station, is an instrument for the early detection, measurement and real time reporting of tsunamis in the open ocean.

JAPAN

III–11. Paragraphs III–12 to III-16 present the current practice on tsunami warning system in Japan that were updated based on the lessons learned from the 2011 Great East Japan Earthquake. After the event, tsunami monitoring systems have been developed for the early tsunami warning under the responsibility of the Japanese Meteorological Agency. There are several major systems for sea level monitoring, which can detect tsunamis at early stages of their propagations.

III–12. In Japan, there are two types of tsunameter for the offshore zone setting: the observation buoy type (a tsunameter with global positioning system linked with a satellite); and the submarine cable type. The warning system for the latter is combined with the land based seismometer network. Cable type seismometers and tsunameters are deployed in the seven focal regions for the plate boundary earthquake in the Pacific coast of Japan.

Seafloor observation network for earthquakes and tsunamis along the Japan Trench (S-net)

III–13. The seafloor observation network for earthquakes and tsunamis along the Japan Trench (S-net) is operated by the National Research Institute for Earth Science and Disaster Resilience of Japan. There are 150 ocean bottom observation stations outside the axis of the Japan Trench. Pressure gauges (tsunameters), seismometers, and tiltmeters are placed at the observation stations. These stations are connected to land by bottom fibre optic cables.

Dense oceanfloor network system for earthquakes and tsunamis (DONET)

III–14. The Dense oceanfloor network system for earthquakes and tsunamis (DONET) was developed by the Japan Agency for Marine-Earth Science and Technology and is now operated by the National Research Institute for Earth Science and Disaster Resilience. The aim is monitoring of Nankai Trough earthquakes and tsunamis. There are 51 ocean bottom observation stations outside the axis of the Japan Trench. At the observation stations, both ground motion sensing and pressure sensing systems (tsunameters) are installed. The ground motion sensing system consists of a strong motion accelerometer and a broadband seismometer. There are two subsystems, DONET1, which has 22 stations, and DONET2, which has 29 stations. The total lengths of the ocean bottom cables for the two systems are approximately 300 km and 500 km, respectively.

Tide gauge stations

III–15. The Japan Meteorological Agency, Japan Coast Guard, and Geospatial Information Authority of Japan (GIA) operate 73, 20, and 25 tide gauge stations, respectively, around Japan's coastline. Some of the data at the tide gauge stations are provided to Sea Level Station Monitoring Facility of the Intergovernmental Oceanographic Commission of UNESCO.

Nationwide ocean wave information network for ports and harbours (NOWPHAS)

III–16. The Nationwide ocean. wave information network for ports and harbours (NOWPHAS) is operated by the Ministry of Land, Infrastructure, Transport and Tourism. There are 78 monitoring stations. The main purpose is the monitoring of coastal waves, but some monitoring stations located offshore measure sea levels using GPS buoys.

REFERENCES TO ANNEX III

[III–1] UNITED NATIONS ECONOMIC, SOCIAL AND CULTURAL ORGANIZATION INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION, Operational User's

Guide for the Pacific Tsunami Warning and Mitigation System (PTWS), Technical Series No. 87, UNESCO/IOC, Paris (2009).

[III–2] UNITED NATIONS ECONOMIC, SOCIAL AND CULTURAL ORGANIZATION INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION, Tsunami Glossary, Technical Series No. 85, UNESCO/IOC, Paris (2008).

ANNEX IV CLIMATE CHANGE PARAMETERS RELEVANT TO SITE EVALUATION FOR NUCLEAR INSTALLATIONS

IV–1. This annex provides information on climate parameters relevant to site evaluation for nuclear installations: in particular, air temperature, sea level rise, and precipitation. It includes information on past climate trends and future climate projections, along with explanations of climate models and datasets that could be beneficial in the site evaluation process.

IV–2. The information provided in this annex primarily consists of global and, in some cases, regional averages, and does not include extreme values of parameters. Global averages conceal wide geographical variability. More relevant estimates (especially for climate extremes and indices) can be assessed using the Intergovernmental Panel on Climate Change multi-model climate simulations and downscaled information, with due consideration of the following:

(a) Climate change projection models are gradually becoming more reliable due to advancements in technology and modelling. These models are to be used as complementary approaches for hazard evaluation alongside statistical extrapolations of historical observational or reanalysis climate data. This approach is especially important given that the characteristics of extreme events are changing due to climate change, making historical data less representative of future extreme events.
(b) Projections of climate change are scenario dependent, and obtaining improved projections involves improved understanding of sources of uncertainty. Confidence in projections is higher for some variables (e.g. temperature) than for others (e.g. precipitation), and for larger spatial scales, as well as longer time averaging periods.
(c) Estimates of local impacts are hampered by uncertainties and the use of tools to evaluate their consequences with regard to regional projections of climate change, in particular for precipitation.
(d) Understanding of low probability, high impact events, which is needed for risk based approaches to decision making, is generally limited in climate modelling. However, some climate change models are better at reflecting extremes than others. The High Resolution Model Intercomparison Project is an example of a project designed to improve the representation of extremes in climate models up to the middle of the century in certain cases. This project focuses on increasing the spatial resolution of climate models to better capture small scale processes and phenomena.

IV–3. Periodically updated climate change information will allow for:

(a) Better identification of which types of change are already occurring and which types of change are likely to occur where and when.
(b) Improved estimates of orders of magnitude of expected changes (for temperature-related parameters first), with related uncertainties. For example, several studies have shown that the return periods of very extreme events, could be significantly reduced by a factor of about 1000 if the estimate is done using values corresponding to the end of the 21st century. As an example, the high temperatures in Western Europe during the 2003 summer were estimated with a return period of 2000–3000 years in current climate conditions, while they may be just 2–3 years if estimated on the basis of values and uncertainties by the end of 21st century.

(c) Early detection of emerging climate trends that may diverge from initial projections, enabling proactive safety measures.
(d) Enhanced robustness of hazard assessments through iterative data integration, helping reduce uncertainty margins.
(e) Stronger alignment with safety review processes such as the Periodic Safety Review, by supporting reassessment of design margins based on the most recent climate signals.

ASSESSMENT REPORTS OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

IV–4. Nearly all States have produced an assessment of past climate change in their territories, generally covering the 20th century, or part of it. The sixth (2023) assessment report of the Intergovernmental Panel on Climate Change contained an analysis of extreme climate parameters worldwide [IV–1].

IV–5. Several tens of national research centres have developed and are running their own global and/or regional climate models, of differing complexity. Generally, these centres have implemented a dedicated web site and generated publications by means of which prospective users may find out how to use the climate simulations, especially for purposes of adaptation. A list of some of these models is provided in Table IV-1. These models represent a diverse range of global climate dynamics and are widely recognized and frequently used in the climate research community. For comprehensive and accurate studies, it is important to also consider results from other models and choose the best combination of models based on the specific needs of the project. These models adhere to the Coupled Model Intercomparison Project[74] standards, ensuring consistency in model output and facilitating comparison and analysis across different models. This project is organized by the World Climate Research Programme[75].

Table IV–1. LIST OF SEVERAL CLIMATE PROJECTION MODELS BASED ON THEIR WIDE RECOGNITION AND FREQUENT USE

Institution	Model	CMIP5 version	CMIP6 version	Webpage
Commonwealth Scientific and Industrial Research Organisation (CSIRO, Australia)	Australian Community Climate and Earth System Simulator (ACCESS)	ACCESS1.0 / ACCESS1.3	ACCESS-ESM1.5	http://www.csiro.au/en/research/natural-environment/climate/csiro-ess/access
Beijing Climate Center (BCC, China)	Beijing Climate Center Climate System Model (BCC-CSM)	BCC-CSM1.1 / BCC-CSM1.1(m)	BCC-CSM2-MR	http://bcc.cma.gov.cn
Canadian Centre for Climate Modelling and Analysis (CCCma, Canada)	Canadian Earth System Model (CanESM)	CanESM2	CanESM5	http://climate-modelling.canada.ca/climatemodeldata/cgcm4/CanESM2/index.shtml

[74] https://wcrp-cmip.org/
[75] https://www.wcrp-climate.org/

National Center for Atmospheric Research (NCAR, USA)	Community Earth System Model (CESM)	CESM1(BGC) / CESM1(CAM5)	CESM2 / CESM2-WACCM	https://www.cesm.ucar.edu/models/cesm2/
China Meteorological Administration (CMA, China)	Flexible Global Ocean-Atmosphere-Land System Model (FGOALS)	FGOALS-g2	FGOALS-f3-L / FGOALS-g3	http://nmc.cma.gov.cn
Geophysical Fluid Dynamics Laboratory (GFDL, USA)	Geophysical Fluid Dynamics Laboratory Climate Model (GFDL)	GFDL-CM3 / GFDL-ESM2G / GFDL-ESM2M	GFDL-CM4 / GFDL-ESM4	https://www.gfdl.noaa.gov/climate-modeling/
NASA Goddard Institute for Space Studies (NASA GISS, USA)	Goddard Institute for Space Studies Model (GISS)	GISS-E2-H / GISS-E2-R	GISS-E2-1-G / GISS-E2-1-H	https://data.giss.nasa.gov/modelE/
Met Office Hadley Centre (MOHC, UK)	Hadley Centre Global Environment Model (HadGEM)	HadGEM2-ES / HadGEM2-CC / HadGEM2-AO	HadGEM3-GC31-LL / HadGEM3-GC31-MM	https://www.metoffice.gov.uk/research/approach/modelling-systems/unified-model/climate-models/hadgem3
Institute of Numerical Mathematics (INM, Russia)	Institute of Numerical Mathematics Coupled Model (INM-CM)	INM-CM4	INM-CM4-8 / INM-CM5-0	http://www.inmcm.ru
Institut Pierre-Simon Laplace (IPSL, France)	Institut Pierre-Simon Laplace Coupled Model (IPSL-CM)	IPSL-CM5A-LR / IPSL-CM5A-MR / IPSL-CM5B-LR	IPSL-CM6A-LR	https://cmc.ipsl.fr
Atmosphere and Ocean Research Institute (AORI, Japan)	Model for Interdisciplinary Research on Climate (MIROC)	MIROC5 / MIROC-ESM / MIROC-ESM-CHEM	MIROC6 / MIROC-ES2L	http://www.jamstec.go.jp/e/about/press_release/20120423/
Max Planck Institute for Meteorology (MPI-M, Germany)	Max Planck Institute Earth System Model (MPI-ESM)	MPI-ESM-LR / MPI-ESM-MR / MPI-ESM-P	MPI-ESM1-2-HR / MPI-ESM1-2-LR	https://www.mpimet.mpg.de/en/science/models/mpi-esm/
Meteorological Research Institute (MRI, Japan)	Meteorological Research Institute Coupled General Circulation Model (MRI-CGCM)	MRI-CGCM3	MRI-ESM2-0	https://www.mri-jma.go.jp/Dep/cl/cl4/eng/
Norwegian Climate Centre (NCC, Norway)	Norwegian Earth System Model (NorESM)	NorESM1-M / NorESM1-ME	NorESM2-LM / NorESM2-MM	https://www.norceresearch.no/en/projects/norwegian-earth-system-model

National Taiwan University (NTU, Taiwan)	Taiwan Earth System Model (TaiESM)	N/A	TaiESM1	https://www.as.ntu.edu.tw/EN/Research/Research-Highlight/taiwan-earth-system-model-taiesm1

IV–6. The Coupled Model Intercomparison Project[76] encompasses contributions from many different climate modelling groups around the world: consequently, the horizontal resolution of models can vary from 50 km to 250 km. The outputs are extensively used in major climate assessments, such as the Intergovernmental Panel on Climate Change reports, to inform global climate policies and decision-making. The scenarios used are called ‘representatives concentration pathways’ and describe different greenhouse gas concentration trajectories based on varying assumptions about economic growth, energy use, and policy interventions. In a further refinement, scenarios are called ‘shared socioeconomic pathways’ and combine different socio-economic pathways with various levels of climate change mitigation, resulting in a broader and more integrated approach.

IV–7. Global coordination for assessing global and regional climate change for the forthcoming decades and centuries is the responsibility of the Intergovernmental Panel on Climate Change. In preparing the Panel’s assessment reports, the following sources of information were used to help determine how well climate models simulate extremes:

(a) Observational datasets from global networks of weather stations, satellites, and other monitoring systems. These datasets provide historical records of extreme weather events such as heatwaves, heavy rainfall, droughts, and storms. Climate models simulate these events, and their ability to reproduce observed extremes is a critical validation metric.
(b) Climate indices developed by expert teams[77]. Projected changes in these indices are indicators of changes in future climate extremes.
(c) Expert assessment and peer review, as well as peer-reviewed scientific publications.

IV–8. The Assessment Reports published by Intergovernmental Panel on Climate Change reflect the state of knowledge [IV–1]. These reports include observed and multi-model projected changes in climate parameters and indices, covering both the averages and the extremes, globally and regionally. Assessment Reports are available at the Intergovernmental Panel on Climate Change website[78].

IV–9. Downscaling techniques using both dynamical and statistical methods have been developed in order to adapt large scale information to specific conditions prevailing at smaller scales. Regional Climate Models and empirical statistical downscaling, such as Coordinated Regional Climate Downscaling Experiment[79] can provide information on much smaller horizontal scales (e.g. 12–25 km, depending on the region) support more detailed impact and adaptation assessment and planning for specific regions and sectors.

[76] https://wcrp-cmip.org/cmip-data-access/
[77] For example, the World Meteorological Organization, World Climate Research Programme.
[78] https://www.ipcc.ch/reports/
[79] https://cordex.org/data-access/

IV–10. At the national scale, the essential climate-related activities, including modelling, simulations and downscaling, are conducted by some national meteorological and hydrological services. Operating organizations are encouraged to establish a collaboration framework with the national meteorological and hydrological services to communicate their needs and receive the necessary support.

IV–11. Within the context of site evaluation for nuclear installations, it is important to take into account the principal conclusions of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [IV–1]:

(a) Human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming.
(b) Global greenhouse gas emissions have continued to increase, with unequal historical and ongoing contributions arising from unsustainable energy use, land use and land-use change, lifestyles and patterns of consumption and production across regions, between and within countries, and among individuals. With every increment of global warming, regional changes in mean climate and extremes become more widespread and pronounced.
(c) Climate change has caused widespread adverse impacts and related losses and damages to nature and people that are unequally distributed across systems, regions and sectors. Economic damages from climate change have been detected in climate-exposed sectors, including energy.
(d) Effectiveness of adaptation in reducing climate risks is proven and documented for specific contexts, sectors and regions. Adaptation options such as disaster risk management, early warning systems, climate services and social safety nets have broad applicability across multiple sectors.

WORLD METEOROLOGICAL ORGANIZATION

IV–12. The World Meteorological Organization issues annual statements on the status of the global and regional climate conditions and trends observed worldwide and in different regions to provide credible scientific information on climate and its variability[80]. These reports consolidate data and analyses from national meteorological and hydrological services, as well as international climate monitoring agencies.

IV–13. Analyses of weather, water and climate extreme events have been greatly facilitated by technical publications and regional climate change workshops organised by the World Meteorological Organization. An archive of globally verified and certified and openly accessible records of extremes can be found in the WMO World Weather and Climate Extreme Records[81]. Extreme events in a changing climate are becoming more intense and frequent, with longer duration, larger geographical extent, and shorter onset time. WMO guidelines on “Analysis of Extremes in a Changing Climate in Support of Informed Decisions for Adaptation” (WMO-No 1500)[82] provides an overall guidance on how to incorporate a changing climate into assessments and estimates of extremes.

[80] https://wmo.int/publication-series/state-of-global-climate
[81] https://wmo.asu.edu/content/world-meteorological-organization-global-weather-climate-extremes-archive
[82]https://library.wmo.int/idurl/4/48826

IV–14. The World Meteorological Organization guidelines on Meteorological and Hydrological Aspects of Siting and Operation of Nuclear Power Plants [IV–2] provides a wide range of analytical methods to calculate extreme events based on historical weather, water and climate data. Historical data might not be representative of future hydrometeorological events in a changing climate; consequently, it is advisable to incorporate climate change models alongside extrapolation methods on historical records to accurately predict extreme events, leveraging the increasing reliability of these models.

IV–15. Every year, the World Meteorological Organization issues the Global Annual to Decadal Climate Update[83], which provides a climate prediction for the next 5 years. For longer term predictions, extending up to decades ahead, climate projection models need to be consulted.

SUMMARY OF CURRENT STATUS AND FUTURE CLIMATE CHANGE TRENDS

Current status

IV–16. Past climate data shows that climate change is already affecting many weather and climate extremes in every region across the globe. Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones. Hot extremes (including heatwaves) have become more frequent and more intense across most land regions since the 1950s, while cold extremes (including cold waves) have become less frequent and less severe.

Temperature

IV–17. The long-term increase in global temperature is due to increased concentrations of greenhouse gases in the atmosphere. A clear warming trend has emerged in all regions in the latter half of the twentieth century (See Fig. IV–1). In the period 1961–2023, Europe and Asia warmed faster than the global land and ocean average with a higher rate of temperature increase compared to other regions.

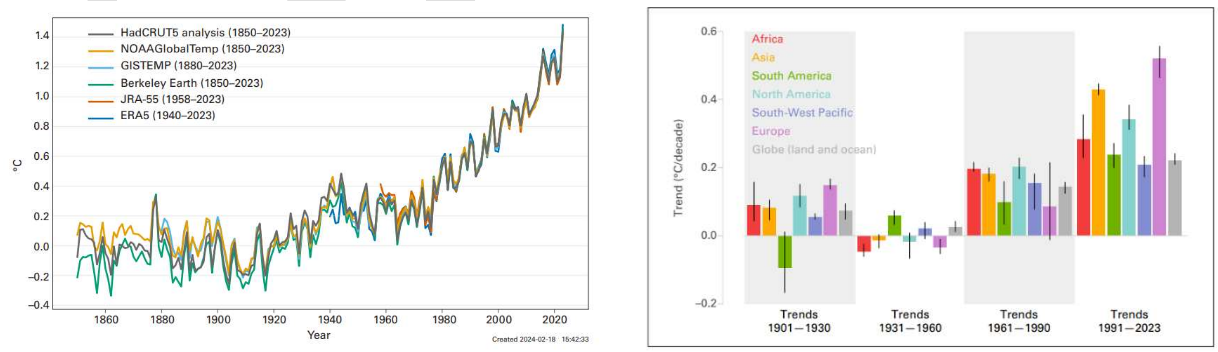

FIG. IV-1. Trends in global mean temperature anomalies (relative to 1850-1900).

[83] https://hadleyserver.metoffice.gov.uk/wmolc/

IV–18. Ocean warming rate show a particularly strong increase in the 21st century. Although ocean heat content has increased strongly through the entire water column, the rate of warming has not been the same everywhere. The strongest warming in the upper 2000m occurred in the Southern Ocean, North Atlantic and South Atlantic (See Fig. IV–2).

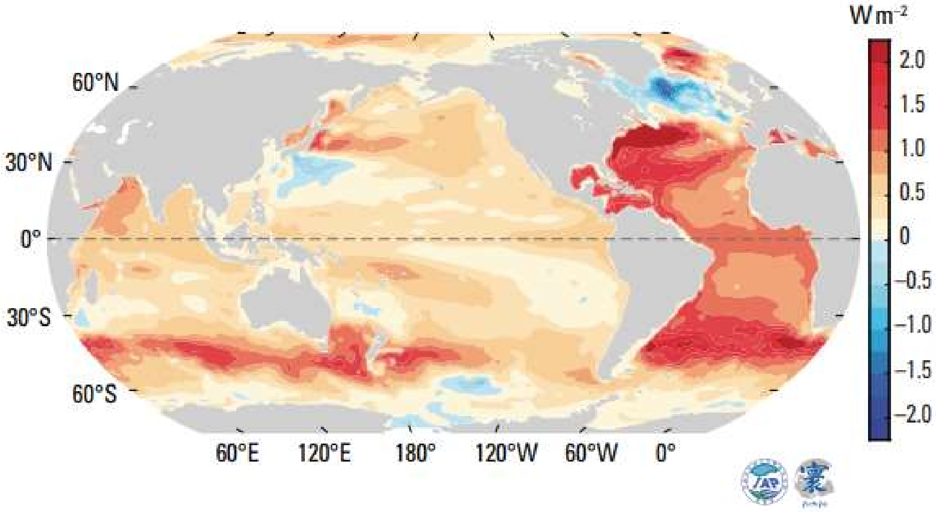

FIG. IV-2. Observed Ocean Heat Content from 1958 to 2023 (upper 2000 m).

Sea Level

IV–19. The global mean sea level has shown a consistent upward trend. Over the period 2014–2023, the rate of sea level rise has more than doubled compared to the rate observed in 1993–2002 (See Fig. IV–3).

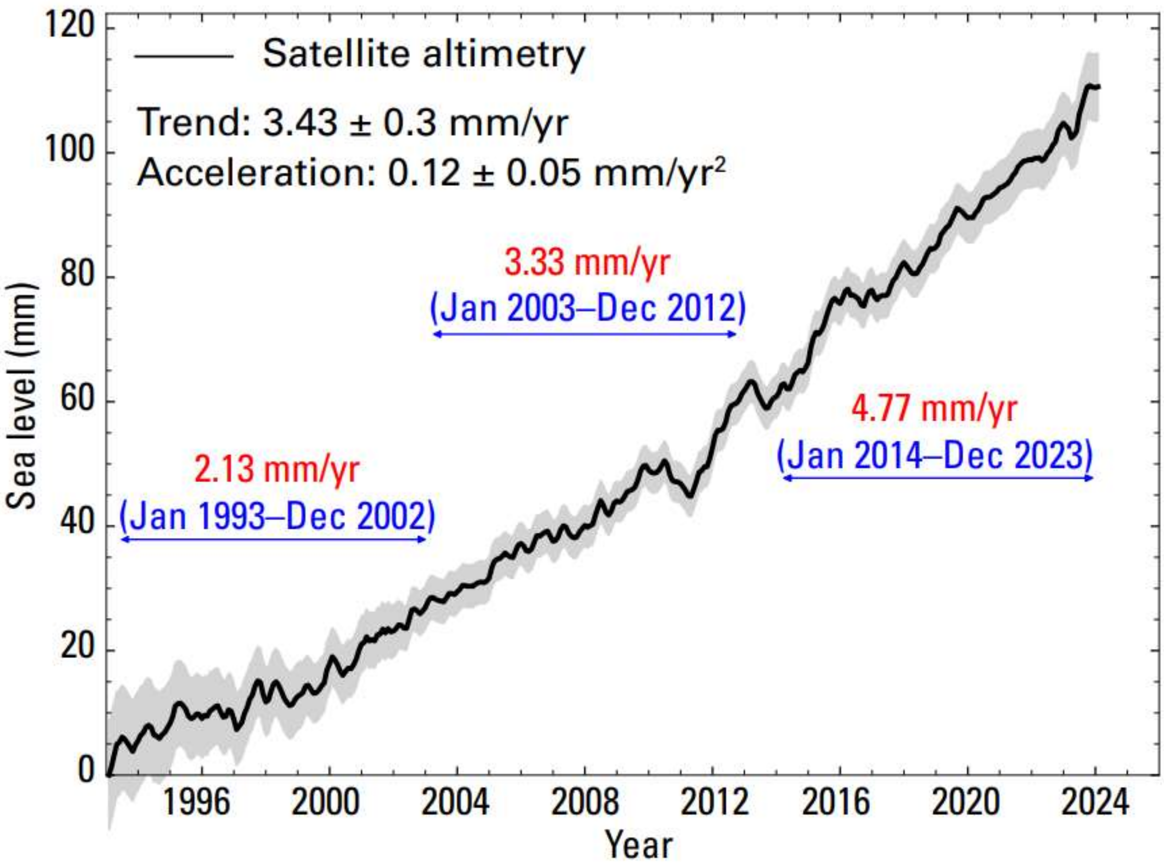

FIG. IV-3. Trend of global mean sea level between 1993-2023.

IV–20. The rate of sea-level rise is not the same everywhere. The observed non-uniform regional and sub-regional trends in sea level are essentially due to non-uniform ocean thermal expansion in conjunction with salinity changes in some regions.

River Flow

IV–21. Between the 1950s and 2010s, stream flows showed decreasing trends in parts of western and central Africa, eastern Asia, southern Europe, western North America and eastern Australia, and increasing trends in northern Asia, northern Europe, and northern and eastern North America. The spatial differences in annual mean streamflow trends around the world are influenced by climatic factors, particularly changes in precipitation and evaporation.

Future trends

IV–22. Limiting human induced global warming to a specific level means limiting cumulative CO_2 emissions, reaching at least net zero CO_2 emissions, along with strong reductions in other greenhouse gas emissions. Future emissions cause future additional warming, with total warming dominated by past and future CO_2 emissions. Many changes due to past and future greenhouse gas emissions are irreversible for centuries to millennia, especially changes in the ocean, ice sheets and global sea level.

IV–23. Global warming will continue to increase in the near term, mainly due to future cumulative CO_2 emissions. The central estimates of reaching the 1.5°C level are at the latest in the early 2030s. Global warming of 2°C is extremely likely to be exceeded during the 21st century in scenarios in which greenhouse gas emissions peak after mid-century. Table IV–2 shows changes in global surface temperature, which are assessed based on multiple lines of evidence, for selected 20-year time periods and the five illustrative emissions scenarios considered [IV-3].

TABLE IV–2. CHANGE IN GLOBAL SURFACE TEMPERATURE FOR THE FIVE ILLLUSTRATIVE EMISSIONS SCENARIOS IN REF. [IV–3]

	Near-term, 2021—2040		Mid-term, 2041—2060		Long term, 2081—2100	
Scenario	Best estimate (°C)	Very likely range (°C)	Best estimate (°C)	Very likely range (°C)	Best estimate (°C)	Very likely range (°C)
SSP1-1.9	1.5	1.2 to 1.7	1.6	1.2 to 2.0	1.4	1.0 to 1.8
SSP1-2.6	1.5	1.2 to 1.8	1.7	1.3 to 2.2	1.8	1.3 to 2.4
SSP2-4.5	1.5	1.2 to 1.8	2.0	1.6 to 2.5	2.7	2.1 to 3.5
SSP3-7.0	1.5	1.2 to 1.8	2.1	1.7 to 2.6	3.6	2.8 to 4.6
SSP5-8.5	1.6	1.2 to 1.9	2.4	1.9 to 3.0	4.4	3.3 to 5.7

IV–24. It is virtually certain that global mean sea level will continue to rise over the 21st century. A global mean sea level rise above the likely range — approaching 2 m by 2100 and 5 m by 2150 under a very high greenhouse gas emissions scenario — cannot be ruled out due to deep uncertainty associated with ice-sheet processes. The likely global mean sea level rise by 2100 is 0.28–0.55 m under a very low emissions scenario, and 0.63–1.01 m under a very high emissions scenario.

IV–25. Every region is projected to increasingly experience concurrent and multiple changes in climatic impact drivers, including intensification of tropical cyclones and/or extratropical storms (medium confidence) and increases in aridity and fire weather (medium to high confidence). Compound heatwaves and droughts will likely become more frequent, including concurrent events across multiple locations. Fig . IV-4 provides a qualitative illustration of the impact of climate change to a region's hazard profile in terms of intensity, magnitude, frequency, duration, timing and special extent. The difference between the historical climate (blue) and future climate (red) shows the changing aspects of climate change that stakeholders will have to manage.

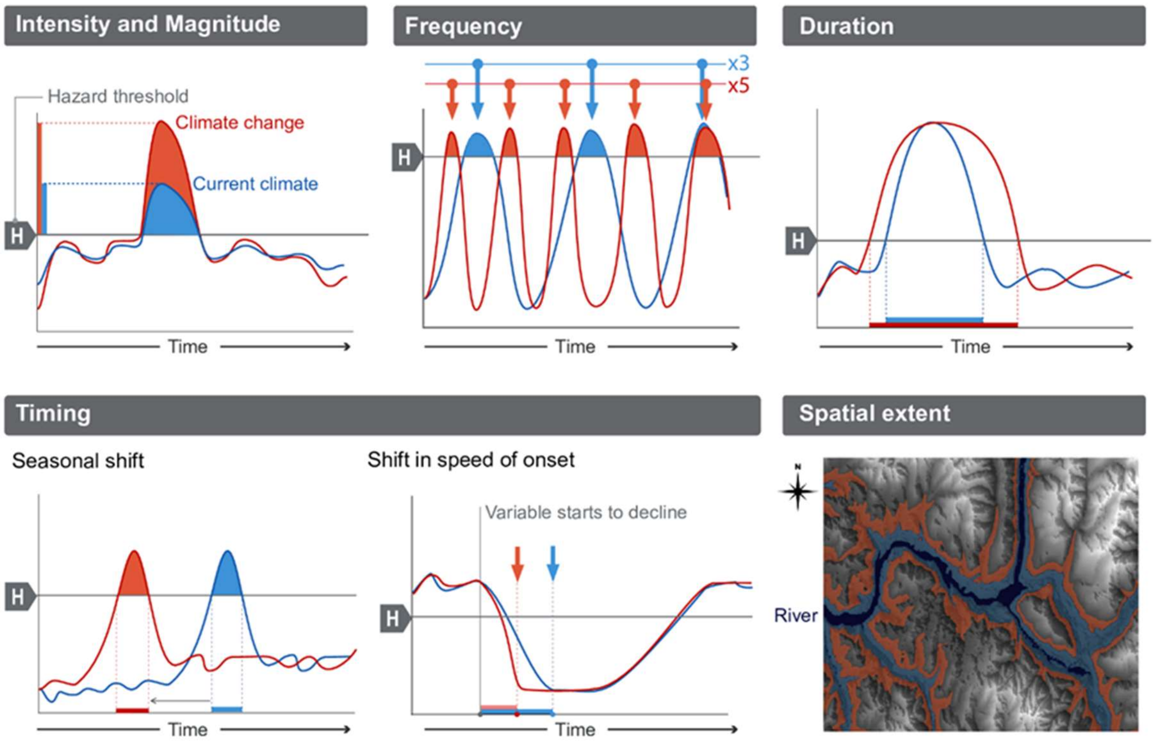

FIG. IV-1. Qualitative illustration of the impact of climate change on the characterization of climate hazards.

IV–26. Changes in several climatic impact drivers would be more widespread at 2°C compared to 1.5°C global warming and even more widespread and/or pronounced for higher warming levels. There is a specific combination of changes each region will experience. Many regions are projected to experience an increase in the probability of compound events with higher global warming. In particular, concurrent heatwaves and droughts are likely to become more frequent. Also, heavy precipitation and associated flooding are projected to intensify and be more frequent in most regions in Africa and Asia, North America and Europe.

REFERENCES TO ANNEX IV

[IV-1] Intergovernmental Panel on Climate Change (IPCC) ,2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, 184 pp., doi: 10.59327/IPCC/AR6-9789291691647. Source: https://www.ipcc.ch/reports/

[IV-2] World Meteorological Organization, Guidelines on Meteorological and Hydrological Aspects of Siting and Operation of Nuclear Power Plants, WMO-No. 550, source: https://library.wmo.int/idurl/4/57042

[IV-3] Intergovernmental Panel on Climate Change (IPCC) 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T.

Waterfield, O. Yelekçi, R. Yu, and B. Zh (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896.

ANNEX V
COMBINATIONS OF EXTREME EVENTS TO DETERMINE DESIGN BASIS EVENTS AND BEYOND DESIGN BASIS EVENTS FOR COASTAL SITES BASED ON MEMBER STATE EXPERIENCE

EXAMPLES OF POSSIBLE COMBINATIONS OF HYRDOLOGICAL AND METEOROLOGICAL EVENTS CAUSING FLOODS

V–1. A suitable combination of hydrological and meteorological events that can cause floods depends on the specific characteristics of the site and involves considerable engineering judgement. The following is an example of a set of combinations of hydrological and meteorological events that can cause floods, for use in determining the design conditions for flood defence for a nuclear power plant located at a coastal site, where the following water level constituents (external events) are of importance:

(a) Astronomical tide;
(b) Seasonal variations;
(c) Storm surge;
(d) Wave setup and runup;
(e) Wind setup;
(f) Barometric effects;
(g) Tsunami;
(h) Tropical cyclone;
(i) Sea level rise;
(j) Flood level from land side.

V–2. The characteristics of these events are different in different regions across the world. The probability of occurrence of each event needs to be determined in accordance with the region and site characteristics and the respective cases (design basis events and beyond design basis events). The combination of these events for design basis events and beyond design basis events needs to be determined by considering their correlation and possibility of their combined occurrences, in accordance with the general characteristics of the site region and catalogues of historical events. Table V-1 shows an example of possible combinations of these events, with associated probabilities, for the Eastern Mediterranean.

TABLE V-1. EXAMPLE OF POSSIBLE COMBINATIONS OF EXTERNAL EVENTS FOR DESIGN BASIS EVENT AND BEYOND DESIGN BASIS EVENT CONDITIONS

■ recommended, □ optional.

Constituent (External Event)	Probability	DBE	Probability	BDBE
Astronomical tide, Seasonal variations	1	■	1	■
Storm surge Wave setup and runup Wind setup Barometric effects	1×10^{-1}	■	1×10^{-2}	■
Seiche	1	□	1	■
Tsunami	1×10^{-4}	■	1×10^{-4}	■
Tropical cyclone	1×10^{-0}	□	1×10^{-1}	□
Sea level rise	1	■	1	■
Flood Level (precipitation and release of impound water)	1×10^{-1}	□	1×10^{-2}	□

ANNEX VI PROBABLE MAXIMUM PRECIPITATION

VI–1. For deterministic watershed scale flood modelling, the largest credible rainstorm for a watershed of interest (often referred to as the probable maximum precipitation, probable maximum precipitation), is estimated and used as input for a hydrologic model of the watershed. The probable maximum precipitation cannot be considered as having a specific probability or return period. The duration and area size of the probable maximum precipitation used is selected in consultation with hydrologists. For example, the rise time of the flood hydrograph to peak (time of the arrival of the peak flow) from storms over different parts of the basin will inform the selection of probable maximum precipitation duration. In addition, for large watersheds, it may be necessary to estimate the probable maximum precipitation for sub-watersheds. The selection of sub-watersheds will be determined by the physical characteristics and stream-gauging station locations. For regions where storm characteristics and flooding vary significantly with season, probable maximum precipitation estimates for each season need to be considered (e.g. warm vs cold season, rainy vs dry season, hurricane vs non-hurricane season).

VI–2. In theory, the probable maximum precipitation is the physical upper limit for precipitation of a given duration over a particular watershed area under given climatic conditions. However, in practice the probable maximum precipitation is an approximation based on the operations performed on the available rainfall data in the particular probable maximum precipitation method used. The operations performed do not account completely for the physical complexity of precipitation processes and rainfall data is limited in quantity, as well as temporal and spatial resolution.

VI–3. There are two main approaches for developing probable maximum precipitation estimates (generalized or indirect approach and basin specific or direct approach) with several variations of each approach. The most significant variation within each approach is regarding details of methods for non-orographic regions versus methods for orographic regions and methods for mid-latitude regions versus methods for tropical regions. Paragraphs VI–4 to VI–11 describe the basic steps of each approach assuming that they are applied in a mid-latitude non-orographic region. Considerations for orographic influences and tropical regions are discussed in paras VI–12 to VI–21.

DIRECT APPROACH

VI–4. The direct or basin specific approach is applied to a specific watershed area and involves the direct estimation of probable maximum precipitation with a given duration in the selected watershed. The main steps in the direct estimation approach include storm model development and storm maximization.

VI–5. The storm model reflects the characteristics of major storms that can occur in the selected watershed. Where there is sufficient observed data for the watershed (i.e. at least several decades), the storm model may be the largest observed storm in the watershed (i.e. a local storm model). The storm model may also be developed by transposing an extreme storm from an adjacent watershed into the target watershed, with adjustments based on differences in topographic conditions (i.e. a transposition storm model). Another approach is to combine two or more storms that have occurred in the watershed, based on synoptic meteorology principles (i.e. a combination storm model).

VI–6. Next, the storm model precipitation is maximized by applying a moisture factor and, possibly, a dynamic factor to take into account the precipitation efficiency of the storm. When the storm model is a ‘high-efficiency storm’ (i.e. micrometeorological processes resulted in high precipitation efficiency), only moisture maximization is performed, otherwise both the moisture factor and the dynamic factor are applied.[84]

GENERALIZED APPROACH

VI–7. The generalized or indirect probable maximum precipitation estimation approach is applied to develop estimates of various durations and areas at selected points (usually a grid of points) within a large, meteorologically homogeneous region. This approach generally needs a large dataset of historical storm rainfall observations. The main steps in the generalized approach include: (1) major storm catalogue development; (2) moisture maximization; (3) transposition; and (4) envelopment.

VI–8. First, the historical storm rainfall observations are reviewed to identify a set of major storms that have occurred in the region. A basic assumption is that these major storms represent events for which the dynamics (i.e. convergence) and micrometeorological processes (i.e. precipitation efficiency) approached maximum values, but might or might not have experienced maximum moisture inflow.

VI–9. Next, the rainfall observations for each major storm are adjusted to take into account the fact that the storm might not have experienced maximum moisture inflow. This is accomplished by applying a moisture maximization factor, which is the ratio of estimated 100 year average return interval precipitable water for the area and season during which the storm occurred to that actually observed during the storm.

VI–10. During the transposition step the rainfall distribution map for moisture-maximized storms is transferred from the location where the storm was centred to other points within the meteorologically homogeneous region. This will often involve adjustments to the transposed storm rainfall, based on differences in topographic conditions between the transposition point and the storm occurrence area.

VI–11. In the envelopment step, the Depth-Area-Duration curves resulting from transposition of multiple storms to a given point are examined and an enveloping curve is developed. This maximizes the precipitation for various areas and durations.

CONSIDERATIONS FOR OROGRAPHIC REGIONS

VI–12. Orographic regions are those regions where topographic effects (e.g. flow over mountains) has a significant effect on rainfall distribution. In such regions, precipitation can be divided into that resulting from the movement of weather systems (i.e. convergence component) and that resulting from orographic effects (i.e. orographic component). Both components need to be estimated. The orographic separation method separately estimates each precipitation component, then combines them. The convergence component can be

[84] The moisture factor is the ratio of the estimated 100 year average return interval precipitable water for the area and season during which the storm occurred to that actually observed during the storm. The dynamic factor is usually taken as the estimated 100 year average return interval precipitation efficiency (for storms in the region) to the precipitation efficiency of the model storm. Precipitation efficiency is typically taken to be the ratio of the observed precipitation to the observed precipitable water inflow.

estimated using the basic steps described above, but certain considerations and adjustments may need to be applied to estimate the orographic component and properly combine it with the convergence component.

VI–13. Transposition of storms in mountainous regions needs to be done with caution. Orographic influences on precipitation can be significant and precipitation patterns are often closely associated with the orographic features where the storm occurred.

VI–14. Observations of precipitation in mountainous topography exhibit a general increase in precipitation with elevation. Observations also show that precipitation increases on windward slopes due to forced lifting of moist air while precipitation decreases on leeward slopes. The size of these effects varies with moist airflow speed and direction and with mountain barrier extent, height, steepness and regularity. Initiation of showers and thunderstorms in foothill regions, resulting from triggering of convective activity in the unstable moist air mass is often observed. Where storm winds move parallel to narrow valleys, there may be forced horizontal convergence with associated uplift and increased rainfall.

VI–15. Orographic rainfall can be estimated using single-layer or multi-layer laminar flow models. These models take into account the wind acceleration, forced lifting, and subsequent cooling and precipitation in a simplified fashion, considering the two-dimension flow of air in a vertical plane normal the mountain. Depending on the scale of the problem, the analysis can be applied to a single ridge or to an entire mountain chain. Airflow at ground level moves parallel to the surface. The slope of the flow streamlines above a given horizontal location decreases with height, eventually becoming horizontal. Assuming that temperature decreases with altitude along the streamlines at the moist adiabatic rate, the rainfall rate can be derived from the specific humidity and atmospheric pressure at the inflow and outflow boundaries (or at the inflow and outflow of each stream tube in the multi-layer version of the model).

CONSIDERATIONS FOR TROPICAL REGIONS

VI–16. For the humid tropics (i.e. within approximately 30 degrees of the equator), the basic steps in probable maximum precipitation estimation procedures for mid-latitude regions can be used, but certain considerations and adjustments may need to be applied.

VI–17. Because of the sparse nature of rainfall stations in many of the humid tropical regions, it is often necessary to supplement direct rainfall observations with indirect measurements from satellites.

VI–18. Tropical region storm meteorological conditions are different from those in temperate mid-latitudes. For example, sea surface temperatures play a more important role in moisture availability and large storm formation. Thus, sea surface temperature conditions are more appropriate input for moisture maximization of tropical regions storms than surface dewpoints used for mid-latitude storms.

VI–19. The variation of storm types and moisture availability in tropical regions is generally less than that of mid-latitude regions, so a given number of tropical region storms will have experienced a narrower range of storm types and moisture conditions than an equivalent number of mid-latitude storms. So a wider transposition region may be needed in order to provide a realistic sampling of storm types and moisture conditions.

VI–20. The dynamic features of major storms (e.g. tropical cyclones, inter-tropical convergence zone thunderstorms) may be different than those in mid-latitude regions.

STATISTICAL PROBABLE MAXIMUM PRECIPITATION APPROACH

VI–21. Statistical probable maximum precipitation estimation methods may be useful where observed point precipitation time series for appropriate durations are available, but meteorological data used in other methods (such as dew points) are not. For example, the Hershfield method is a widely used statistical approach. This method uses point precipitation times series for fixed durations to arrive at a point probable maximum precipitation estimate.

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