

IAEA SAFETY STANDARDS SERIES

Flood Hazard for Nuclear Power Plants on Coastal and River Sites

SAFETY GUIDE

No. NS-G-3.5



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FLOOD HAZARD FOR NUCLEAR POWER PLANTS ON COASTAL AND RIVER SITES

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FOREWORD

by Mohamed ElBaradei
Director General

One of the statutory functions of the IAEA is to establish or adopt standards of safety for the protection of health, life and property in the development and application of nuclear energy for peaceful purposes, and to provide for the application of these standards to its own operations as well as to assisted operations and, at the request of the parties, to operations under any bilateral or multilateral arrangement, or, at the request of a State, to any of that State's activities in the field of nuclear energy.

The following bodies oversee the development of safety standards: the Commission on Safety Standards (CSS); the Nuclear Safety Standards Committee (NUSSC); the Radiation Safety Standards Committee (RASSC); the Transport Safety Standards Committee (TRANSSC); and the Waste Safety Standards Committee (WASSC). Member States are widely represented on these committees.

In order to ensure the broadest international consensus, safety standards are also submitted to all Member States for comment before approval by the IAEA Board of Governors (for Safety Fundamentals and Safety Requirements) or, on behalf of the Director General, by the Publications Committee (for Safety Guides).

The IAEA's safety standards are not legally binding on Member States but may be adopted by them, at their own discretion, for use in national regulations in respect of their own activities. The standards are binding on the IAEA in relation to its own operations and on States in relation to operations assisted by the IAEA. Any State wishing to enter into an agreement with the IAEA for its assistance in connection with the siting, design, construction, commissioning, operation or decommissioning of a nuclear facility or any other activities will be required to follow those parts of the safety standards that pertain to the activities to be covered by the agreement. However, it should be recalled that the final decisions and legal responsibilities in any licensing procedures rest with the States.

Although the safety standards establish an essential basis for safety, the incorporation of more detailed requirements, in accordance with national practice, may also be necessary. Moreover, there will generally be special aspects that need to be assessed on a case by case basis.

The physical protection of fissile and radioactive materials and of nuclear power plants as a whole is mentioned where appropriate but is not treated in detail; obligations of States in this respect should be addressed on the basis of the relevant instruments and publications developed under the auspices of the IAEA. Non-radiological aspects of industrial safety and environmental protection are also not explicitly considered; it is recognized that States should fulfil their international undertakings and obligations in relation to these.

The requirements and recommendations set forth in the IAEA safety standards might not be fully satisfied by some facilities built to earlier standards. Decisions on the way in which the safety standards are applied to such facilities will be taken by individual States.

The attention of States is drawn to the fact that the safety standards of the IAEA, while not legally binding, are developed with the aim of ensuring that the peaceful uses of nuclear energy and of radioactive materials are undertaken in a manner that enables States to meet their obligations under generally accepted principles of international law and rules such as those relating to environmental protection. According to one such general principle, the territory of a State must not be used in such a way as to cause damage in another State. States thus have an obligation of diligence and standard of care.

Civil nuclear activities conducted within the jurisdiction of States are, as any other activities, subject to obligations to which States may subscribe under international conventions, in addition to generally accepted principles of international law. States are expected to adopt within their national legal systems such legislation (including regulations) and other standards and measures as may be necessary to fulfil all of their international obligations effectively.

EDITORIAL NOTE

An appendix, when included, is considered to form an integral part of the standard
An appendix, when included, is considered to form an integral part of the standard and to have the same status as the main text. Annexes, footnotes and bibliographies, if included, are used to provide additional information or practical examples that might be helpful to the user.

The safety standards use the form 'shall' in making statements about requirements, responsibilities and obligations. Use of the form 'should' denotes recommendations of a desired option.

The English version of the text is the authoritative version.

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1. INTRODUCTION

BACKGROUND

1.1. This Safety Guide provides recommendations on how to meet the requirements established in the Safety Requirements publication on Site Evaluation for Nuclear Installations [1] in respect of the flood hazard to be used in site evaluation for nuclear power plants on coastal and river sites. Measures for the protection of nuclear power plant sites against floods and the strategy for monitoring sites are also discussed.

1.2. This Safety Guide is the first revision of and supersedes two Safety Guides dealing with flood hazards on river sites and on coastal sites respectively and originally issued under the IAEA's safety standards programme in 1983.¹

1.3. The two former Safety Guides have been merged in this revised version for the following reasons:

- (1) Flood hazards on river sites and on coastal sites give rise to similar actions by plant designers for the protection of both the site and the plant;
- (2) The meteorological causes of the phenomena observed on sites of both kinds are often the same and the phenomena very similar;
- (3) In many cases the effects of the marine environment and the river environment on the same site can be combined: it is therefore convenient to have a joint treatment.

1.4. New sections have been developed on the basis of a detailed review of recent years of operation of nuclear power plants around the world. These relate mainly to:

¹ INTERNATIONAL ATOMIC ENERGY AGENCY, Design Basis Flood for Nuclear Power Plants on River Sites, Safety Series No. 50-SG-S10A, IAEA, Vienna (1983); Design Basis Flood for Nuclear Power Plants on Coastal Sites, Safety Series No. 50-SG-S10B, IAEA, Vienna (1983).

- Requirements for input data in term of sufficiency and reliability, oriented towards application in States with limited historical background in the subject and therefore with different technical approaches (e.g. a deterministic approach as opposed to a probabilistic approach);
- Monitoring requirements and techniques in connection with warning systems, with all the implications in terms of reliability and the size of the area monitored, and therefore competences;
- Mechanisms for updating of the hazard analysis with reference to very fast modifications in the intrinsic properties relating to both precipitation (intensity, area and frequency) and the basin (drainage, population, water storage and artificial obstacles).

1.5. Other Safety Guides relating to site evaluation present discussion on flood related events — for earthquake induced tsunamis, flood induced effects on foundations, procedures for the site survey, and precipitation and cyclonic wind hazard — and are thus complementary to this Safety Guide [2–4].

OBJECTIVE

1.6. The purpose of the present Safety Guide is to provide recommendations relating to the evaluation of the flood hazard for a nuclear power plant on a coastal or river site so as to enable the identification of hazardous phenomena associated with flooding events initiated by natural and human induced events external to the site.

1.7. The Safety Guide presents guidelines for the analysis and quantification of flood induced effects in all the phases of the project: from the site selection phase (regional analysis, screening and ranking phases) to the definition of the design basis and from the design of measures for site protection and monitoring up to the periodic site review (see Ref. [5]).

SCOPE

1.8. This Safety Guide discusses the phenomena, both natural and human induced, that may cause floods or droughts at coastal and river sites, and gives an outline of the methods that can be used for and the critical factors involved in the evaluation of such events and of their associated effects. Possible combinations of two or more phenomena that can give rise to flooding at a site are also discussed.

1.9. The present Safety Guide discusses the hazard definition for the site and the general derivation of the design basis for the interacting effects on the nuclear power plant as a whole, to be used in a design framework or in a design assessment framework. The next step in the full determination of the design basis for a specific plant, which includes the load definition, is carried out in a design context, being intrinsically dependent on the layout and design of the plant. This additional step is therefore discussed in a Safety Guide relating to the Safety of Nuclear Power Plants: Design [6], together with the detailed loading schemes and the design procedures. Some design considerations are anticipated here in relation to site protection measures only, since they are traditionally considered part of the site evaluation process.

1.10. The installation of additional nuclear power units is under consideration for a number of nuclear power plant sites. The re-evaluation of existing sites is sensitive because of the need to reconcile an evaluated and accepted situation with a new evaluation performed by new methods on the basis of new data. This may indicate a need to upgrade the safety of the site for the older installations on the re-evaluated site. This Safety Guide does not explicitly discuss the re-evaluation of an existing nuclear power plant site, but it provides many elements that could be useful for such a re-evaluation.

1.11. This Safety Guide discusses the applicability of different methods for the evaluation of the flood hazard. Dam failures, tsunamis and other very rare events may generate a flood substantially more severe than floods due to precipitation. Generally, very few historical data are available and special techniques have to be developed. The static and dynamic effects of floods resulting from various combinations (independent and interdependent) of surface waves of differing frequency are also discussed. Consideration is also given to the effects of shoreline instabilities and erosion.

1.12. The phenomena of the lowering of water levels at coastal sites caused by offshore winds, low tides, wave effects, draw-down caused by tsunamis and drought (at the river sites also) are not discussed here as these phenomena are not expected to challenge structures and equipment but only the availability of cooling water. Although reference is made to Safety Guides [6, 7] for the relevant safety and operational aspects, the hazard evaluation may follow methods and recommendations provided in the present Safety Guide since the reference scenarios of flood and drought are often similar in nature.

1.13. Two types of method for flood evaluation for coastal and river sites are discussed in this Safety Guide: probabilistic methods and deterministic

methods. Both approaches are discussed without details of the method, but with a strong emphasis on their applicability, constraints, reliability and suitability for use in meeting the requirements for site evaluation.

1.14. The potential transport of radioactive material by a flood and its dispersion in the environment is not treated in this Safety Guide. For a detailed analysis of such dispersion, see Ref. [7].

1.15. This Safety Guide does not deal with floods caused by any acts of sabotage on or off the site.

STRUCTURE

1.16. The structure corresponds to the logical sequence of the analyses required for the definition of the design basis flood² from the site survey stage up to the definition of the design basis and the periodic safety review on the basis of monitoring results. In particular, Section 3 deals with the preliminary investigation for site selection and Section 4 with final data collection for the site assessment up to the definition of the parameters (and probabilities, if required) for the cause of initiation of the flood (precipitation, tornadoes, earthquake and dam failures).

1.17. Sections 5 to 12 deal with the derivation of the probable maximum flood, probable maximum seiche from runoff, probable maximum storm surge and probable maximum tsunami at the site, after simulation of the effects on the site and the presentation of the possible combinations.

1.18. Section 13 deals with measures for the protection of the site from floods and flood induced events. Section 14 deals with specific mechanisms for periodic review of the flood hazard for the possible effects of modified site conditions and global warming. Section 15 deals with the monitoring of flood related initiating causes and their effects.

1.19. The annex provides examples from the experience of some States in relation to loading combinations.

² The design basis flood is the flood selected for deriving the design basis for a nuclear power plant.

2. GENERAL APPROACH TO EVALUATION OF THE FLOOD HAZARD

FLOOD SCENARIOS

2.1. The safety of nuclear power plants can be seriously affected by flooding, both for sites on rivers and for sites on the sea coast (including enclosed and semi-enclosed water bodies) or large lakes.

2.2. Floods can be associated with either 'frequent' or 'rare' events, according to the definitions provided in Refs [1, 4]. The procedures to be used for data collection and the methods to be used for hazard evaluation will depend to a large extent on the nature of the flood.

2.3. The design basis flood has to be derived from the flood hazard for the site, which is a probabilistic result derived from the analysis of all the possible flooding scenarios at the site. However, in some cases the design basis flood is evaluated via deterministic methods and no probability is attached to it. In these cases a probabilistic evaluation should always be carried out to be able to compare the contributions of different design basis scenarios to the overall plant safety (see Ref. [6]) and to evaluate the overall probability of radiological consequences of a potential plant failure.

2.4. The design basis flood is a series of parameters that maximize the challenge to plant safety as a consequence of a flood: the parameters may be associated, for example, with the maximum water level, the maximum dynamic effect on the protection or the maximum rate of increase in water level

2.5. For *coastal sites* (sea, lakes and semi-enclosed water bodies) the flood hazard is related to the most severe among the following types of flood, where applicable:

- (1) The flood resulting from the probable maximum storm surge³ (see Ref. [4] for guidance on the associated meteorological hazard);

³ A storm is a violent disturbance of the atmosphere attended by wind and usually by rain, snow, hail, sleet or thunder and lightning. A storm surge is the accumulation of water at shallow depths due to wind stress and bottom friction together with the atmospheric pressure reduction that occurs in conjunction with severe storms. The probable maximum storm surge is the hypothetical storm surge generated by either the probable maximum tropical cyclone or the probable maximum extra-tropical storm.

- (2) The flood resulting from the probable maximum tsunami⁴ resulting from an earthquake (see Ref. [2] for guidance on the seismic hazard), and also from landslides (including landslides under the sea), undersea volcanoes and falling ice⁵;
- (3) The flood resulting from the probable maximum seiche⁶;
- (4) The flood resulting from wind and wave effects, to be considered independently or in combination with the above mentioned flood mechanisms.

2.6. A conservatively high reference water level⁷ should be considered for each of these cases to allow, where applicable, for tides, sea level anomalies⁸ and changes in lake levels and flood levels on rivers. Detailed recommendations on the approach to be followed are provided in Section 4.

2.7. For *river sites* the flood hazard is associated with one or more of the following scenarios:

- (1) The flood resulting from off-site precipitation⁹ with waters routed to the site (see Ref. [4] for guidance on the precipitation hazard);

⁴ A tsunami is a wave train generated by impulsive disturbances of a water surface due not to meteorological but to geophysical phenomena such as submarine earthquakes, volcanic eruptions, submarine slumps, landslide or ice blocks falling into a body of water. The probable maximum tsunami is the hypothetical tsunami having that combination of characteristics which will make it the most severe, in terms of flooding, that can reasonably be expected to occur at the site.

⁵ Ocean impacts may also be the cause of a tsunami. The impact of an asteroid or comet on an ocean may be a significant cause of major tsunamis that affect populations quite different from the populations affected by tsunamis caused by geological events. Such an event may be considered in the analysis of beyond design basis events.

⁶ A seiche is an oscillation of an enclosed or semi-enclosed body of water in response to an atmospheric, oceanographic or seismic disturbing force. The probable maximum seiche is the hypothetical seiche which results in the most adverse flooding at the site that can reasonably be considered possible.

⁷ The reference water level is a conservatively estimated reference water level used for purposes of flood evaluation, either high or low (for the evaluation of flooding or of the minimum water level, respectively), including, as appropriate, components such as the tide, river flow and surface runoff but not including increases in the water level resulting from surges, seiches, tsunamis and wind waves.

⁸ A sea level anomaly is an anomalous departure of the water surface elevation from the predicted height of the astronomical tide.

⁹ Flooding caused by on-site precipitation is discussed in Ref. [4].

- (2) The flood resulting from snowmelt [4], seasonal floods [4] or floods relating to volcanism;
- (3) The flood resulting from the failure of artificial or natural structures for water control, due to either seismic or hydrological causes or the faulty operation of these structures, identified as the probable maximum dam break;
- (4) The flood resulting from the obstruction of a river channel (downstream or upstream) by landslides, ice, jams caused by logs or debris, or lava or ash from volcanic activity (this is also included in the probable maximum dam break);
- (5) The flood resulting from large waves induced by volcanoes, landslides or avalanches in water basins or by waterspouts;
- (6) The flood resulting from changes in a natural channel;
- (7) The flood resulting from wind waves on large rivers or estuaries;
- (8) The flood resulting from increasing groundwater levels, which may be caused by an earthquake (see also Refs [2, 3]).

2.8. It should be borne in mind that, in spite of the accepted terminology for the probable maximum storm surge, probable maximum tsunami, probable maximum seiche and probable maximum dam break, such events cannot always be characterized in a purely probabilistic framework. However, the terminology emphasizes that an estimate should always be made of the probability of exceedance associated with the design basis scenarios, even when they are investigated by means of deterministic approaches.

2.9. In this Safety Guide, recommendations are made for selecting the event with the worst effects on the site due to flooding, which may be different from the event with the most extreme values of a single flood parameter.

2.10. Combinations of two or more dependent events should be carefully analysed with account taken of the dependence or independence of the events. For example, on a river site exceptional spring runoff floods may cause the collapse of an ice jam resulting in higher water levels at the site and the possible obstruction of water intakes by ice floes. On a coastal site a tsunami or a storm surge may occur at the time of an exceptionally high tide. Special attention should be paid to sites on estuaries for which flood scenarios may show aspects of both coastal and river sites.

2.11. Special attention should be paid to flooding induced by rising of the groundwater level as a consequence of the influence of the sea or of a river, and also of other phenomena such as earthquakes or volcanism.

EXPECTED MAIN EFFECTS OF FLOODING ON NUCLEAR POWER PLANT SITES

2.12. The effects of flooding on a nuclear power plant site may have a major bearing on the safety of the plant and may lead to a postulated initiating event (PIE) that is to be included in the plant safety analysis. The presence of water in many areas of the plant may be a common cause of failure for safety related systems, such as the emergency power supply systems or the electric switchyard, with the associated possibility of losing the external connection to the electrical power grid, the decay heat removal system and other vital systems. Details are provided in Ref. [6].

2.13. Considerable damage can also be caused to safety related structures, systems and components by the infiltration of water into internal areas of the plant, induced by high flood levels caused by the rise of the water table. Water pressure on walls and foundations may challenge their structural capacity. Deficiencies in the site drainage systems and in non-waterproof structures may also cause flooding of the site. This has happened in many cases in the past, with consequent large scale damage documented, and the possibility should be considered in the hazard evaluation and in the design of measures for site protection.

2.14. The dynamic effect of the water can be damaging to the structure and the foundations of the plant as well as the many systems and components located outside the plant. In such cases there could also be major erosion at the site boundary, which should be studied and taken into consideration.

2.15. A flood may transport ice floes in very cold weather or debris of all types which may physically damage structures, obstruct water intakes or damage the water drainage system.

2.16. Flooding may also affect the communication and transport networks around the plant site. The effects may jeopardize the implementation of safety related measures by operators and the emergency planning by making escape routes impassable and isolating the plant site in a possible emergency, with consequent difficulties in communication and supply. A flood that makes the road network around the plant impassable could also cause an emergency.

2.17. Flooding can also contribute to the dispersion of radioactive material to the environment in an accident [7]. Such an effect should be considered in the

definition of the reference probability level to be used in the evaluation of the design basis flood on the basis of the flood hazard.

2.18. Other information on the causes and effects of flood induced phenomena may be found in other Safety Guides relating, respectively, to earthquakes [2], wind and snow [4], groundwater flow [3], and dispersion in air, water and groundwater [7].

METHODS FOR EVALUATION OF THE DESIGN BASIS FLOOD

2.19. Different methods are used in flood hazard evaluation according to the site evaluation phases defined in the Requirements [1]: site selection, site assessment, the pre-operational phase and the operational phase (including periodic safety review). The different aspects of flood hazard evaluation in the different phases are considered explicitly in this Safety Guide. To this end, a quality assurance programme should be established and implemented to cover items, services and processes that affect safety and that are within the scope of this Safety Guide. The quality assurance programme should be implemented to ensure that data collection, data processing, field and laboratory work, studies, evaluations and analyses and all activities that are necessary to follow the recommendations of this Safety Guide are correctly performed.

Deterministic methods

2.20. Deterministic methods¹⁰ are based on the use of models to describe the system; these models may be empirical or based on physical relationships. For a given input or set of initial and boundary conditions, the model will generate a single value or a set of values to describe the state of the system. To obtain conservative estimates, appropriate extreme or conservative values of the input parameters should be used.

2.21. In general, deterministic methods may provide rational limits to the statistical extrapolation by means of the concept of the ‘physical limit’: an upper limit to the flooding level, irrespective of the probability of its occurrence. Deterministic methods may perform an important function, also

¹⁰ A deterministic method is a method for which most of the parameters used and their values are mathematically definable and may be explained in terms of physical relationships.

providing a useful alternative validation of the results of the probabilistic methods.

2.22. Deterministic methods necessitate the consideration of specific features of the region and the application of engineering judgement. Where deterministic methods are applied to derive the storm generating the probable maximum storm surge, this storm should be used as input to the surge and wave models for the evaluation of the design basis.

Probabilistic methods

2.23. Probabilistic methods are based on time series¹¹ analysis and synthesis. They combine deterministic and statistical analysis, and they synthesize a time (or space) series of stochastic variables¹² and the effects of a limited number of data. It is assumed that the series represents both definable causes and an unknown number of stochastic causes, and that the stochastic causes are reasonably independent. With these methods, jumps, trends and outliers of the data set can be adequately taken into account. It is emphasized that the data used in probabilistic evaluations are based on actual measurements or variables. As with deterministic methods, probabilistic methods should be used in conjunction with engineering judgement; when it is feasible, they should be checked by the use in parallel of a simplified deterministic analysis.

Use of deterministic and probabilistic methods

2.24. In general, deterministic and probabilistic methods should be seen not as competitive but rather as complementary. For example, if a surge is generated by a tropical cyclone, the evaluation is usually carried out by deterministic methods with account taken of the more symmetrical characteristics of the generating storm. Surges generated by extra-tropical storms have been evaluated mainly by stochastic methods since such storms are usually very

¹¹ A time series in this context is a chronological tabulation of data measured continuously or at stated time intervals (e.g. mean daily flow, maximum annual flood and daily water level at 08:00).

¹² A stochastic variable (as used in hydrology) is a variable whose value is basically of a probabilistic nature, but that may include a non-random dependence on time (or space). In a stochastic time series, one term in the series may be significantly related to neighbouring terms, and this possibility is taken into account in the analysis and synthesis of the series.

extensive, asymmetrical and difficult to model. Deterministic methods should be used as a complementary method for evaluating these surges.

2.25. In general, the flood hazard should be compared critically with recorded and historical data and the design basis flood should be set at a value not less than a recorded occurrence plus a substantial margin that should be related to the length of the period over which measurements were made and the local situation. This should only be done provided that there has been no significant change in the basin either upstream or downstream of the site.

2.26. A dam failure or tsunami, where applicable, may generate a flood substantially more severe than any due to natural meteorological phenomena. For these cases the site specific methods outlined in the subsections should be used to estimate the order of magnitude of the flood hazard.

2.27. In both deterministic and probabilistic cases, a reference probability of exceedance value for the initiating event and for the site flood should be defined and attached to the design basis flood. The definition of such a value should be closely connected with the conditional probability that such an event (or accidental sequence) would have serious radiological consequences¹³.

2.28. In all cases the margin of uncertainty in the result should be determined. This may be done by testing the degree to which predictions are affected by varying the values of relevant parameters and by evaluating the effect of the overall level of uncertainty in these parameters. Different methods should be used to check the conservativeness of the chosen safety level.

¹³ The reference probability of exceedance value for the initiating event and for the site flood is defined in different ways in different States. The probability of occurrence of an event generating the design basis flood can be taken to be one or more orders of magnitude greater than the probability associated with the design basis flood, to provide the necessary target for probabilistic methods and reasonable equivalent thresholds for deterministic methods. Moreover, the selection of the probability level for the design basis flood should guarantee that a sufficient margin of safety remains to protect the plant against serious radiological consequences. For example, if the probabilistic limit for a serious radiological accident is $1 \times 10^{-7}/a$, then the probability of occurrence of a design basis flood may be $1 \times 10^{-4}/a$ provided that in the event of flooding the margin of safety for (i.e. conditional probability of) a serious radiological accident remains smaller than $1 \times 10^{-3}/a$.

2.29. Both deterministic and probabilistic methods suffer in general from constraints that limit their applicability and necessitate an evaluation of their reliability. For example, with deterministic methods it is not possible to express the level of safety quantitatively, and with probabilistic methods there is a lack of confidence in the results of the extrapolation to very low probabilities of exceedance. In addition, the use of deterministic methods requires data for the region which, in some parts of the world, may not be available. Similarly, the use of probabilistic methods requires measurements which may not be available. The quality and extent of available historical series of data should be considered as reference criteria in the choice of the type of method.

3. PRELIMINARY INVESTIGATIONS

GENERAL

3.1. The potential for flooding is one of the site characteristics that should be evaluated during both the regional analysis of the site selection phase for a nuclear power plant development project and the site assessment phase, according to the general procedures set out in Ref. [1].

3.2. As the most suitable protection against flooding, the plant should be constructed at a level where it will not be affected by floods. The preliminary evaluation of the flood level is therefore extremely important and should be given due attention in selecting a site.

3.3. At the stage of site selection, it may be evident in certain cases that there is no potential for flooding, because of location or elevation for example. In this case the preliminary assessment should be sufficiently well documented to demonstrate either that the plant would not be affected by any potential flooding or that the potential for flooding is insignificant and has a negligible affect on safety.

3.4. It is not usually practicable to make detailed flood analyses at the site selection stage, and empirical and approximate methods are generally used to estimate roughly the extreme flood. The choice of method will depend on the data available and the characteristics of the region. The results of the

evaluation should be compared critically with any data measured or otherwise recorded.

3.5. The reference sites discussed in this Safety Guide pertain to two main categories:

- (1) Sites vulnerable to coastal flooding are those located in open coastal regions, and on semi-enclosed bodies of water and enclosed bodies of water of such an extent that the hydrological response cannot be compared with that of a small lake. Open coastal regions are those areas of land directly exposed to and having a shore on a major body of water. Semi-enclosed bodies of water are lagoons, river estuaries, gulfs, fjords and rias. Enclosed bodies of water are lakes and reservoirs.
- (2) Sites vulnerable to river flooding are those located on river coastal regions or in general in river basins.

3.6. The different natures of flood generating phenomena should be considered in data collection and processing. Floods exhibit major differences in their characters and causes associated with their nature:

- (1) *Frequent phenomena.* For frequent phenomena, flood related variables such as water level, amount of precipitation and wind speed characterize the marine, meteorological or climatological environment. The extreme values of these variables can be derived by statistical analysis of routine measurements over a network of fixed stations by international, national, local or private oceanographic, hydrographic or meteorological services.
- (2) *Rare phenomena.* Rare phenomena are phenomena such as tsunamis or dam breaks which occur infrequently. At any particular station, the instruments used for routinely measuring variables would rarely have registered characteristics of these phenomena, and generally therefore modelling is used extensively and comparisons with sites elsewhere are made. The intensity values of rare phenomena may be expressed in terms of either a qualitative characteristic such as damage or a quantitative physical parameter.

COASTAL SITES

3.7. For a regional analysis where the region includes a coast, a preliminary study of coastal floods should be performed. At the preliminary phase of site selection the most important flood causing events, in particular surges,

tsunamis, seiches and waves, should be determined, together with the reference level components. If the potential for coastal floods is significant and it is decided to consider coastal floods in the regional analysis, then approximate methods such as those mentioned below should be used to identify areas affected by surges, seiches and tsunamis and the appropriate components of the reference water levels:

- (a) The parts of the coast most frequently subjected to surges, tsunamis and severe wind waves should be determined from maps prepared for land use planning and flood emergencies. Although the return time of the events considered for drawing these maps is usually short (e.g. 30–50 years), they can nevertheless be very useful in a preliminary screening.
- (b) Aerial photographs and satellite imagery may also be helpful in determining areas subject to flooding.
- (c) If detailed determinations of the probable maximum storm surge or probable maximum tsunami have been made for the region, envelope curves should be prepared for the part of the coast being studied and the magnitude of the results should be evaluated, with account taken of the effects of waves and tides. It may be useful to plot extreme surges or tsunamis of known mean return time (e.g. 100, 50 or 20 years) derived from historical data on the same graph together with estimated values of probable maximum storm surge or probable maximum tsunami.

3.8. For site assessment at the feasibility and verification stages (i.e. the evaluation of the suitability of a site to host a plant), first the large scale and long term weather pattern of the area should be established, then a preliminary evaluation of the important flood causing events for the proposed site should be undertaken.

3.9. A more detailed study than that conducted in the regional survey of the meteorological extremes for the region should be carried out. Recommendations and guidance on methods and parameters are provided in Ref. [4].

3.10. The potential for storm surges at a site should be assessed on the basis of meteorological and hydrological information. If there is found to be a potential for storm surges, a preliminary estimate of the storm surges at the site should be made. Case studies of actual severe storms in the region should be used to identify the following characteristics of the critical storm that would produce surges at the site with a sufficiently low probability of being exceeded (see also Ref. [4]):

- minimum central pressure and associated peripheral pressure,
- maximum sustained wind speed and its direction,
- wind fetch¹⁴,
- duration of storm and associated winds,
- direction and speed of movement of the storm,
- the storm track and particularly the point at which the storm track is closest to or crosses the coast.

3.11. A preliminary estimate of the height of the probable maximum storm surge should then be made by using the values of parameters representing the characteristics listed as inputs to empirical relationships. Whenever possible, these results should be compared with historical records of storm surges to check the suitability of the method used. A method that results in a calculated extreme event that is lower in magnitude than any event that was recorded is unacceptable.

3.12. Information on tsunamis should be collected if the site is located in a region that is affected by tsunamis. Although it is estimated that 80% of all tsunamis occur in the Pacific Ocean, destructive events of this type also occur in the Atlantic Ocean, the Indian Ocean, the Caribbean Sea, the Mediterranean Sea and their adjoining bodies of water. Catalogues of records of tsunamis should be carefully analysed.

3.13. The potential for offshore seismic or volcanic activity, and the vulnerability of the site to tsunamis emanating from both local and distant areas should be investigated even though no such waves from these areas may have been recorded over historical time.

3.14. Probabilistic or simplified deterministic methods for evaluating tsunamis are appropriate for use at this stage. With information gained from the list of known and suspected tsunamis, the procedure includes the review of all hydrographs for a specific gauge station in the region of the site to determine whether there is evidence of tsunami activity.

3.15. For part of the list of known and suspected tsunamis, arrival times and the height of the maximum tsunami wave, from trough to crest, with the tide

¹⁴ The fetch is the extent of sea water over which the wind under consideration blows, measured in the direction of the wind.

subtracted, can be extracted from the records. A plot of the maximum tsunami waves against the mean return time should be used as a basis for predicting the extreme tsunami wave to be expected at the gauge station. The correlation between the tsunami response at the gauge station and that at the site should be investigated by means of a study of the coastal features. Since the maximum tsunami heights on the hydrographs may differ significantly from observed runups¹⁵ at adjacent shore locations, comparisons between known flood levels at the sites and those at the gauge stations should be carried out whenever possible.

3.16. Preliminary estimates should be made of the height and range of the extreme wave for a coastal site. They should be based on collected historical data for maximum wave heights along the coast, modified as necessary by the use of data on the bathymetry of the seabed facing the site. If historical wave data are not available, wave parameters should be estimated on the basis of wind and fetch data by using wave forecasting curves.

3.17. A preliminary estimate of a conservative reference water level to be considered jointly with the characteristics of the surge, seiche, tsunami or wave should be made at this stage. For coastal sites the astronomical tide height is an important component of the reference water level.

RIVER SITES

3.18. For the regional analysis of river floods and the systematic survey of large areas, the following approximate methods should be used:

- (a) If detailed determinations of the flood hazard have previously been made in the region, envelope curves should be prepared for similar basins in the same region and the magnitude of the flood hazard should be estimated. The drainage area should be plotted against the peak flow, or more elaborate procedures based on the envelope of available data may be preferred. It may be useful to plot curves of floods of known mean return time (e.g. 100, 50 or 20 years) and flood hazard curves on the same graph.

¹⁵ The runup is the rush of water up a beach or structure on the breaking of a wave. The height of the runup is the vertical height above the still water level that the rush of water reaches.

- (b) For the rapid estimation of flood hazard, a multiple regression analysis should be made of the drainage area, the rainfall index, soil conditions and urbanization.
- (c) Envelope curves of historical flood peaks in the region versus the drainage area should be produced for estimating the flood hazard.
- (d) For some areas, studies of the relationship between floods of known mean return time and the flood hazard have been made or if not they should be made. Such information may provide rough approximations of the flood hazard required.
- (e) By using aerial photographs and satellite images, areas that are subject to flood hazards should be identified and approximate checks should be performed of the relationship between the flow and level of the flood and the extent of the flooded areas.

3.19. The following approximate methods should be used for site assessment purposes, according to the availability of data:

- (a) Empirical curves extrapolated to low probabilities should be used for site screening purposes in cases for which flow records over 30 or more years are available, as a first indication of the level of protection necessary. When an approximate value of the flood flow has been obtained, the peak water level should be estimated by means of Manning type formulas on the basis of the average river channel bottom slope, the river cross-sectional areas and conservative friction factors.
- (b) Empirical formulas should be used for drainage basins of a few hundred hectares in area in which runoff characteristics are not influenced by the presence and operation of water control structures.
- (c) A simple and approximate procedure that should be used, if necessary, for evaluating the effects of dam failures is to assume that all relevant upstream dams fail at such times as to produce the maximum potential flood. Constructions and obstructions downstream from the dam and from the site should be taken into consideration.
- (d) Frequency curves and relationships between flows and levels should be extrapolated and historical data should be used to check and possibly to improve on the results.

STABILITY OF THE SHORELINE AND RIVERBANK

3.20. A preliminary investigation should be undertaken to determine whether there is a potential for instability of the shoreline or riverbank since erosion

over the lifetime of the nuclear power plant could affect items important to safety. Erosion maps and tidal current maps, aerial photographs and satellite images are very useful and should be used where possible for studying erosion over large areas. Information on the importance of erosion in historical times should be used at this stage.

EFFECTS OF ICE

3.21. For sites in the higher latitudes, information on regional ice conditions should be considered at this preliminary stage.

OTHER POTENTIAL CAUSES OF FLOODING

3.22. Preliminary historical data should be collected at this stage about landslides, avalanches, volcanoes and the modification of the river channel.

4. DATA COLLECTION AND SITE CONFIRMATION

GENERAL

4.1. After the site selection phase, if it is established that there is a potential for flooding or for serious erosion at a site, a detailed study should be undertaken to detect the reference mechanism for site flooding and, therefore, to define the relevant design basis flood for the plant. A similar study should be carried out within the framework of a safety assessment of the plant. In this latter option, the data from the site monitoring system which has been in operation since the preliminary phase of site evaluation should have the highest priority.

4.2. The data should be presented on maps of the appropriate scale, on graphs or in tables. In some cases, where the existing network for collecting meteorological and hydrological data in the basin is inadequate, supplementary observation stations should be installed and operated. Although the time available for collecting supplementary data is usually relatively short, the information that can thus be obtained may be important.