Note:
This is a translation of the ESK recommendation entitled
“Leitlinie zum Schutz von Endlagern gegen Hochwasser”.
In case of discrepancies between the English translation and the German original, the original shall prevail.

ESK

RECOMMENDATION

Guideline on the protection of disposal facilities against flooding

CONTENTS

1 Background

Protection against damage from flooding is a basic requirement for the design of nuclear facilities. Especially safety standard KTA 2207 [KTA 04], which was designed for the safe operation of nuclear power plants in Germany and applied analogously also to facilities of the nuclear fuel cycle, has served as the basis so far. The focus of the flood guideline on disposal facilities is due to the fact that the periods to be taken as a basis for it differ significantly from the residual operating life of the nuclear power plants (until 2022) and the licensed storage periods of the storage facilities (40 years). This applies in particular to a future disposal facility for high-level radioactive waste. According to the Site Selection Act [SAG 13] and the Programme for the responsible and safe management of spent fuel and radioactive waste (National Programme) [NAP 15], this disposal facility is to be constructed from 2031 onwards and put into operation approx. 2050. Taking into account an emplacement period of about 50 to 70 years and the subsequent closure phase, it can therefore be assumed that the disposal facility will be in operation until the middle of the next century.

Due to these long periods, the ESK holds the view that the influence of climate change and new findings with regard to extreme weather conditions must also be taken into account site-specifically when determining the design water level, as current studies show that climate change will lead to a further rise in sea levels (e.g. [GER 15]) and storm surge water levels in the future as well as more frequent heavy rainfall events and increasing intensities (e.g. [GER 16]).

This guideline is essentially based on the current French rules and regulations [ASN 13] as the ESK is of the opinion that this is currently the most comprehensive approach for the determination of design water levels.

2 Protection objectives

The radiological protection objectives with which the technical design and operation of the disposal facility for high-level radioactive waste must comply are

- to avoid any unnecessary radiation exposure or contamination of man and the environment (§ 6(1) of the Radiation Protection Ordinance – StrlSchV), and
- to minimise any unnecessary radiation exposure or contamination of man and the environment, even if below the respective limit, by taking into consideration the state of the art and by taking into account all circumstances of individual cases (§ 6(2) StrlSchV).

Derived from this, the following fundamental protection objectives [in the IAEA Safety Glossary referred to as main safety functions] apply to the disposal facility with the technical equipment in the surface and underground facilities during the operating phase of the disposal facility for flood protection:

- assurance of subcriticality,
- safe removal of decay heat,
- safe confinement of radioactive material, and

- avoidance of unnecessary radiation exposure, limitation and control of radiation exposure of workers and the general public.

In addition to the protection objectives and safety functions mentioned above, the technical design and operation of disposal facilities to be constructed in the future must comply with the protection objectives of mining and the requirements for the safe operation of a mine in accordance with the Federal Mining Act.

3 Consequences of floods on disposal facilities and their relevance for compliance with the protection objectives

Flooding events can endanger the safety of a disposal facility. The following consequences of a flood on a disposal facility are conceivable without appropriate flood protection:

1 interruption of access to the disposal facility due to flooding,
2 ingress of water into surface infrastructure,
3 ingress of water into parts of buildings for storage/conditioning/repackaging of the waste,
4 ingress of water into electrical systems, e.g.
    a systems for underground power supply including lighting,
    b installations for controlling mine ventilation,
    c installations for filtering the exhaust air of the weather in case of a radiological event,
    d communications and detection equipment,
    e installations for mine water drainage,
    f systems for controlling and operating the hoisting plant,
5 ingress of water into the shaft tube, exceeding of the shaft water drainage capacity and resulting flooding of parts of the mine workings as well as possible damage to the geotechnical and geological barriers,
6 sharp rise in groundwater level,
7 extensive destruction of infrastructure.

With the exception of point 3 (ingress of water into parts of buildings for storage/conditioning/repackaging of waste), maintenance of subcriticality is not endangered.

In the case of waste containers for high-level radioactive waste, it can be assumed that the robust structure of the containers ensures that the integrity of the containers will be maintained with each of the above-mentioned consequences and thus there will be no secondary accumulation of fissile material with critical masses. This applies both to thick-walled self-shielding disposal containers and to transfer casks for thin-walled canisters for high-level radioactive waste in the case of borehole disposal. In the case of thin-walled canisters for low- and medium-level radioactive waste, it can be assumed that critical concentrations of fissile material are excluded a priori due to the very low container inventories.

The safe removal of the decay heat could be endangered if water enters into parts of the building for storage/conditioning/repackaging of the waste (point 3) if this impairs the systems for heat removal relevant to nuclear processes.

The protection objectives “safe confinement of radioactive material” and “avoidance of unnecessary radiation exposure, limitation and control of radiation exposure of workers and the general public” must also be differentiated according to the stability of the container types:

- In the case of high-level radioactive waste in self-shielding disposal containers or thin-walled canisters surrounded by transfer casks it can be assumed, as mentioned above, that the integrity of the containers will be maintained with each of the above-mentioned consequences and that the above-mentioned protection objectives will be achieved. Apart from the case that these containers are in the open state, i.e. above all when the waste is repackaged in the conditioning plant (point 3), no radionuclide releases due to flooding occur.

- In the case of low- and medium-level radioactive waste in comparatively thin-walled sheet steel or concrete containers, radionuclide releases in addition to the cases mentioned above could not be ruled out if damage to the container shells caused by flooding were to result in a loss of integrity of the containers. This could already occur in the case of storage (buffer storage hall, point 3; filling station, point 5) due to collision of the containers with each other or with other solid objects as well as under certain circumstances in the case of a surge-like ingress of the flood into the shaft tube if these containers are located close to the filling station.

For all other effects, release of radioactive substances is not to be assumed since the containment effect of the containers is maintained.

Nevertheless, in order to ensure operational safety during construction, operation and closure [BMU 10], protective measures must be taken against all the above-mentioned effects. These go beyond the mere prevention of nuclide releases.

4 Causes for flooding

Flooding can be caused by the following phenomena, which can occur individually, in combination or not at all, depending on the site location. In addition, they can be subject to a temporal change.

- **Local heavy rainfall** are larger amounts of precipitation in the form of rain, which - typically in a short period of time - fall directly onto the site of the facility.

- **Surface runoff in local catchment areas** (up to approx. 500 km^2) is the runoff of precipitation that falls in the vicinity of the facility and is discharged by smaller watercourses (streams). Especially during local heavy rainfall events, otherwise insignificant streams can overflow their banks and flood the surrounding area. In this context, an increased amount of flotsam is to be expected.

- **Surface runoff in large catchment areas** (more than 500 km^2) refers to the runoff of water in a nearby larger watercourse (river). The runoff can result from current rainfall or heavy rainfall and/or from snow melting in the catchment area.

- **Ice jam in rivers** results from the accumulation of ice floes at obstacles such as river narrowing, narrow river bends or bridges. Ice jams can become a cause of flooding in two ways: (a) The ice barrier dams the water, causing flooding of an upstream site. (b) When the ice barrier breaks, a flood wave is generated which leads to flooding downstream.

- **Mechanically induced waves (weir wave return, backwater)** are downstream or upstream waves caused by abrupt flow changes in rivers or canals, e.g. when weirs suddenly open or close.

- **Local wind-induced waves** are waves that can form on water by local wind effects. In order for the waves to reach a size that is relevant from a safety point of view, the water must be of a minimum size, which is the case e.g. for large rivers, lakes and on the coast.

- **Sea waves** migrate over long distances after their formation and can also be a cause of flooding on coasts that are not currently affected by the generating wind field (external surge and swell). In the case of wind-induced waves, linear mass transport only takes place when they break in shallow water.

  Monster waves (also known as giant waves, rogue waves or freak waves) are exceptionally high single marine water waves. Since these only occur on the open sea and break far off the coast when entering shallow marginal seas such as the North Sea, they are not relevant to German disposal facility sites near the coast. They are therefore not considered further in this guideline.

- **Seiches** are standing waves that occur in closed or semi-closed basins, e.g. lakes, bays or harbours. Such standing waves can be caused by wind, fluctuations in atmospheric pressure or earthquakes.

- **Tsunamis** are waves at sea or on lakes that are caused by the displacement of large masses of water. In contrast to wind-induced waves, tsunamis transport water masses over long distances. Therefore, in addition to the height of the water level, the dynamic effects of tsunamis play an important role. The propagation velocities and wavelengths/periods of tsunamis are also significantly greater than those of wind waves.

  Tsunamis can be caused by a) spontaneous vertical displacement of oceanic plates (seaquakes), b) spontaneous gas emissions from volcanoes, c) an impact of large meteorites on the water-covered surface of the earth, d) slippage of unstable sediments on shelf edges or slippage of earth or rock masses on steep slopes in mountain lakes, fjords or narrow bays, and e) short-term extreme fluctuations in atmospheric pressure (meteotsunamis).

  Due to the relatively low tectonic and volcanic activity in the northern Atlantic compared to the rest of the world, tsunamis of the first two causes are not considered further in this guideline.

  The extreme primary effects of an impact of large meteorites (flooding of subcontinents, extreme firestorms, years of darkening of the atmosphere due to ejection) are disproportionate to the comparatively low safety risks emanating from a disposal facility in operation. Therefore, this type of tsunami is also not considered further in this guideline.

Meteotsunamis and tsunamis caused by landslides, however, cannot be excluded for German coastal sites and must therefore be taken into account in flood design.

- **Storm surges** are exceptionally high coastal water levels resulting from the superposition of a high tidal level (high tide, spring tide) with wind set-up and an increased local sea level due to atmospheric pressure. Typically, sea waves and local wind-induced waves come along with the water level resulting from the storm surge.

- **Failure of dams (waterway) and dykes (flood protection)**, i.e. an (artificially created) hydraulic structure along canals, coasts and rivers. A large part of the canal sewers runs in a so-called dam position where the canal water level is above the surface of the laterally adjoining terrain. In dam sections of canals, the water bed is usually lined with a canal seal to minimise water losses. In impounded rivers, there is often a natural self-sealing of the water bed due to colmation. Dykes and flood protection walls are erected along rivers and coasts to protect the areas behind them from flooding. They are not permanently exposed to water.

- **Failure of artificial water reservoirs (e.g. dams, reservoirs, weirs, water tanks)**
  Dams and reservoirs are man-made structural barriers that are constructed as part of a water-retaining structure, usually in the flow of watercourses, to create a reservoir lake. These barriers are, in the case of reservoirs, dams or, in the case of barrages and weirs, retaining walls. They are used to dam a watercourse with the aim of regulating it and/or supplying water. They generally stop the flow of water across a valley. Water tanks are built and operated for drinking water supply.

  A flood retention basin is a water-retaining structure whose main purpose is to regulate the discharge of a watercourse in the event of flooding. It dampens the outflowing flood wave by temporarily storing excessive water loads and releasing them in a controlled manner once an event has subsided. The basin is normally empty (so-called dry basin or green basin) or partially filled (permanent reservoir).

- In addition, **high groundwater levels** must also be considered. A high groundwater level can occur for various reasons. In particular, it occurs in connection with flood events in nearby large watercourses.

Table 1 provides an overview of conceivable triggers for the various causes of flooding.

Table 1: Assignment of flooding causes

	Triggers										
Flooding cause	**Precipitation**	**Snowmelt**	**Wind**	**Ice drifts**	**Earthquake**	**Seawater density decrease**	**Tides**	**Excitation of the resonance frequency of an open basin**	**Atmospheric pressure fluctuations**	**Underwater landslides**	**Artificially induced tidal waves**
Local heavy rainfall	x										
Surface runoff in local catchment areas	x	x									
Surface runoff in large catchment areas	x	x									
Ice jam in rivers				x							
Mechanically induced waves											x
Local wind-induced waves			x								
Sea waves			x								
Seiches			x		x			x	x		
Tsunamis					x				x	x	
Storm surges			x			x	x		x		
Failure of dams and dykes					x						x
Failure of artificial water reservoirs					x						x
High groundwater level	x	x									

5 Design basis

5.1 Introduction

In the following, the basic procedure for determining the design basis flood is described, which adequately takes into account the complexity of the interplay of the influencing factors relevant to a flood event. The suitability of the calculation models used in the specific application case shall be substantiated. Against this background, a four-step approach shall be applied:

The first step is to identify all potential flooding causes for the specific site. The flooding causes are largely dependent on the location. Basically, four different (typified) site locations have to be distinguished: inland location without inland waters, inland location with neighbouring large inland waters, coastal locations and locations with neighbouring artificial flood sources (e.g. reservoir lakes). A combination of the above typified site locations is possible and must be considered accordingly. For the flooding causes mentioned in Chapter 4, an assignment is to be made depending on the site location (see Chapter 5.2.1, Table 2), which serves as a basis for further considerations.

In a second step, the assessment basis for the flooding causes to be considered is to be determined. The procedure for this is explained in Chapter 5.2.

In view of the long periods of time that elapse from the determination of the site to the closure of the disposal facility, the influence of climate change must also be included in the site-specific determination of the design water level. In particular, a rise in sea water levels and storm surge water levels, but also more frequent heavy rainfall events with increasing intensity, are to be expected. The procedure for determining the influence of climate change on the site-specific design water level takes place in the third step (see Chapter 5.3).

Since the determination of design water levels is subject to uncertainties not only due to the long forecast periods, the uncertainty of the assumptions and input parameters to be made and the complex interplay of many parameters, an error analysis and an uncertainty analysis must be carried out in a fourth step in order to verify and increase the robustness of the statements made (see Chapter 5.4).

5.2 Design basis dependent on the location of the site

5.2.1 Determination of the possible causes of flooding at the specific site

Since the flood hazard depends strongly on the regional (e.g. prevailing meteorological conditions) and local (topography of the site environment) conditions, it has to be examined site-specifically which flooding causes have to be investigated in detail with regard to possible safety-relevant impacts on the site. In order to facilitate focussing on relevant flooding causes in the site hazard analysis, this guideline distinguishes between four possible site locations. For each location, the flooding causes to be considered are listed below. Since not all site locations are mutually exclusive, the flooding causes of several site locations may have to be considered for the site to be investigated. This applies in particular to the site location “near artificial flood sources”, which may additionally apply to each of the three other site locations. For river sites with tidal influence, both the flooding causes for “large inland waters” and the flooding causes for “coast” are to be considered. Furthermore, it must be examined which combinations of different flooding causes, taking into account their frequency, can make a relevant contribution to site hazards. In Table 2, the flooding causes are assigned to the respective location.

Table 2: Assignment of flooding causes to the location of the site

	Site location[1]			
Flooding cause	**Inland without inland waters**	**Inland with large inland waters**	**Coast**	**Near artificial flood sources**
Local heavy rainfall	x	x	x	x
Surface runoff in local catchment areas	x	x	x	x
Surface runoff in large catchment areas		x		
Ice jam in rivers		x		
Mechanically induced waves				x
Local wind-induced waves		x	x	
Sea waves			x	
Seiches		x	x	
Tsunamis		x	x	
Storm surges			x	
Failure of dams and dykes		x	x	x
Failure of artificial water reservoirs				x
High groundwater level	x	x	x	x

[1] For disposal facility sites, several site locations may be applicable; this applies in particular to the site location “near artificial flood sources”.

As a rule, it can be assumed that the flooding causes “local heavy rainfall”, “surface runoff in local catchment areas" and “high groundwater level” can occur at all sites. However, here too it must be tested whether all causes of flooding are actually given. For example, it is not necessary that a site is located in the immediate vicinity of a local receiving water (stream, see case “surface runoff in local catchment areas”). This has to be examined accordingly in each individual case.

The other flooding causes to be considered are only relevant if the site is located either on a large inland body of water, the coast and/or in the vicinity of artificial flood sources (dams, dykes, artificial water reservoirs).

In the case of the location of a disposal facility near to the mouth of a river into a tidal sea (estuary), the combination of flooding causes for large inland waters and the coast are to be taken into account.

5.2.2 Definition of the design basis

5.2.2.1 Local heavy rainfall

Heavy rainfall events are characterised by maximum precipitation heights depending on the duration of precipitation and exceedance frequency. For the design of disposal facilities, precipitation durations of five minutes and one hour have to be considered. For these, an exceedance frequency of 10^{-4}/a is to be assumed.

For the calculations, values from weather stations are to be used whose location is representative for the conditions at the site.

The discharge rates are to be calculated using a suitable precipitation-runoff model based on accurate site data.

The dewatering systems existing at the site (sewerage, drainage systems) can also be considered if their availability is ensured. The following must be taken into account:

- During normal operation, dewatering systems have flow rates that already use part of their capacity. Flows from rain must therefore be drained additionally through the dewatering system.

- When discharging into existing sewer systems, the entire dewatering system must be considered in terms of capacity and condition (e.g. leakage, roughness).

- In the case of sewer/rainwater drainage systems that drain into basins or watercourses whose water level is influenced by local rainfall, the water level there is to be taken into account.

- For sewer/rainwater drainage systems draining directly into watercourses whose flow rate is independent of the local weather situation, the average discharge rate or average water level of the watercourse is to be used.

- In the case of sewer/rainwater drainage systems leading to tidal seas, the 10-yearly maximum tidal level is to be used.

Soil and/or flotsam can also be mobilised with the heavy rainfall event. In the area of the installation, such places must be examined and identified where soil and flotsam can be deposited. Any resulting accumulation of rainwater at the facility site is to be taken into account.

5.2.2.2 Surface runoff in local catchment areas

Precipitation falling in the vicinity of the facility and discharged by smaller watercourses near the facility site can lead to flooding of the facility. Decisive for the design of the facility are the maximum water level at the facility site and the flow velocity of the flood at the facility site.

In order to determine the maximum water level and the flow velocity, the flood runoff in a receiving watercourse (stream, pond, ditch, etc.) fed by a local catchment area (up to approx. 500 km^2) is to be estimated with an instantaneous 10,000-year discharge rate. If this discharge rate cannot be determined by extrapolation of water level measurements, it must be determined by appropriate precipitation-runoff modelling.

For precipitation-runoff modelling, the hydrological and hydrogeological characteristics of the catchment area must be taken into account.

The following is also to be considered:

- If necessary, the hydrological conditions of the watercourse at its estuary into the next larger receiving water are to be considered. Any flood levels of the river are to be taken into account into which the receiving water, which drains the local catchment area, flows.

- If the receiving water flows into a watercourse which is not affected by the weather conditions prevailing in the local catchment area, the average discharge rate of the watercourse at the estuary is to be applied.

- If the receiving water draining the local catchment area flows directly into a tidal sea, the 10-year tidal peak can be used to determine the peak discharge rate.

With the discharge from the local catchment area, soil and/or flotsam can also be mobilised through the watercourse. In the area of the facility, such places must be checked and identified where soil and flotsam can be deposited. Any resulting accumulation of rainwater at the facility site is to be taken into account.

5.2.2.3 Surface runoff in large catchment areas

Catchment areas with an area of more than 500 km^2 are referred to as large. For flood protection in these catchment areas, the water level reached in the area of the facility components to be protected and protective structures is decisive. This is to be determined with the aid of hydraulic models from the discharge (volume flow, typically in m^3/s) resulting from rainfall or snowmelt in the watercourse concerned. An exceedance frequency of $10^{-4}/a$ is to be assumed for the design of disposal facilities. The determination of a discharge with a corresponding exceedance frequency is to be carried out – if reliable data are available – preferably by evaluating water level measurements.

- Evaluation of level measurements: The measurement data (water levels) of a representative level in the vicinity of the site (or several levels, if necessary) are to be converted into corresponding discharges. From this discharge data series, a discharge with an exceedance frequency of $10^{-4}/a$ is to be determined by means of suitable statistical methods. If significant amounts of snow are to be expected in the catchment area, several separate data populations may have to be considered in the statistical evaluation of the data (e.g. separation of the water level data according to seasons in order to take into account purely rain-related discharges and discharges resulting from rain on an existing snow cover).

If no reliable water level measurement data are available, discharge must also be determined from the precipitation in the catchment area.

- Evaluation of precipitation data in the catchment area: A precipitation event with an exceedance frequency of 10^{-4}/a is to be determined by statistical evaluation of the precipitation measurement data of relevant weather stations in the catchment area of the river under consideration. Based on suitable precipitation-runoff relationships, a resulting runoff at the site must be calculated from the precipitation. Different possible boundary conditions in the catchment area (e.g. existing snow cover or already saturated soil) are to be taken into account.

On the basis of the runoff determined with an exceedance frequency of 10^{-4}/a, the resulting water level in the area of the facility components to be protected and protective structures is to be determined using hydrological and hydraulic models. For this purpose, a sufficiently large area has to be modelled in order to determine the topographical and hydraulic properties of the site. The spatial resolution of the model must allow the consideration of essential hydraulic structures such as dams and bridges. In the model, the boundary conditions resulting from an extreme runoff event (e.g. dam failures, accumulation of flotsam at narrow places or opening of retention areas) have to be considered. If, due to such site-specific boundary conditions, the water level resulting from a runoff event with an exceedance frequency of 10^{-4}/a is lower than the water level due to a more frequent runoff without flooding of retention areas, the design is to be based on the event with the higher water level.

In addition to the maximum water level, the expected temporal development of the flood event at the site is also to be determined or estimated conservatively. Information on the duration is required in particular for the planning of measures for the supply of operating materials and for the exchange of personnel (if the water level is to be assumed to make the site an island) and for the assessment of the reliability of flood protection measures (e.g. with regard to the load on dykes and waterproofing).

Furthermore, the following aspects are to be considered in connection with surface runoff from large catchment areas:

- the impact of flotsam or ice drifts on protective structures,
- the flow direction and velocity of the water on the facility site, if it is not free of water during the flood event to be postulated,
- the groundwater rise resulting from the flood, also behind protective structures, as well as any seepage water[1],
- the buoyancy resulting directly from the flood or from the rise in groundwater,
- the possibility of washout, erosion and subsidence,
- the possible failure of the facility’s operational and public sewer systems.

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[1] Water that is pressed to the land side by water-bearing soil layers under the dyke due to level differences during floods and exits from the soil there is referred to as “seepage water” or “rushing-out water”. In addition to unwanted water ingress into areas actually protected by the dyke, seepage water can also impair the stability of the dyke by washing away the subsoil.

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5.2.2.4 Ice jam in rivers

If water temperatures remain low for a long time, drift ice can form in a river. If the transport of ice crystals and ice floes is impeded, ice jam may form which, due to further accumulation of ice floes, turns into an ice dam (significant narrowing of the discharge cross-section by frozen drift ice over the entire width of the river). The narrowing of the discharge cross-section may result in rapid accumulation of water upstream of the ice dam with the risk of flooding sites upstream. In addition, if the ice dam breaks, a flood wave can occur, which represents a flood hazard for downstream sites. The damaging effect of the flood wave is intensified by the presence of drift ice.

Since ice dam formations are rare events resulting from the interaction between hydro-meteorological influences and ice mechanics, their assessment using probabilistic methods is not yet possible satisfactorily. A methodology that allows a quantitative prognosis for the formation or breakage of an ice dam, including the resulting water levels, will not be available in the foreseeable future due to the complex interrelationships. Therefore, the design of a disposal facility cannot be based on an ice flood with a given exceedance frequency and a corresponding water level. Regardless of the water level which cannot be determined in advance, a disposal facility is to be protected against flooding due to ice jam in accordance with Chapter 6. This must be ensured by appropriate administrative measures.

5.2.2.5 Mechanically induced waves (weir wave return, backwater)

Flood protection against mechanically induced waves is to be based on the maximum water level that can be reached by waves due to abrupt changes in the flow rate at hydraulic structures in adjacent watercourses. When determining the water level in the area of the facility components to be protected and protective structures as well as its temporal development, the most unfavourable initial conditions with regard to the water flow in the watercourse (water level and flow rate) at the beginning of the event are to be assumed.

When identifying possible sources of mechanically induced waves, ship locks, weirs and other hydraulic structures with hydraulic functions both downstream and upstream of the site are to be considered. The length of the river section to be considered depends on the size of the hydraulic structures and the wave propagation conditions resulting from the geometry of the river bed.

5.2.2.6 Local wind-induced waves

The design basis wind for determining the local wind waves is defined as 10,000-year wind speed averaged over ten minutes and at a height of ten metres. It is calculated by means of statistical surveys of extreme wind forces independent of the wind direction. If the local topography can influence the wind speed at the site, this is to be considered.

If the local wind-induced waves cause the protective structures to be overflown, the amount of water flowing over these structures is to be calculated. Taking into account the wind direction, this amount of water is determined for each individual fetch. The choice of physical methods used to calculate the amount of overflow water must be justified (scope of validity, increase in results, etc.).

The method used to include the wind in the exceedance flow rates must also be justified (e.g. application of an increase coefficient to an overflow rate if this flow rate is determined by empirical formula and the effect of the wind is not taken into account).

5.2.2.7 Sea waves

The wave conditions on a coast are characterised by two different wave types. Ocean waves, generated by winds on the ocean that propagate beyond the zone of origin, and local wind waves (see Chapter 5.2.2.6) that are generated near the coast. The latter are significantly influenced by the morphology of the coast. Depending on the exposure and the nature of the site, it is possible to simplify the analyses depending on the dominance of the two wave types. The maximum wave height should be calculated either on the basis of ocean waves or local wind waves.

The areas where local wind waves can develop are determined by the local geometry of the coastal water body. All areas are to be considered which have a sufficient extent for the development of significant local wind waves. In this respect, it is to be postulated that the design basis wind can generate local wind waves in each of these areas.

The influence of ocean currents on the formation of local wind waves is to be taken into account. Thus, the local wind waves can be strengthened or weakened by prevailing currents. If the wave steepness meets the wave breaking conditions, the wave heights at the surf edge are determined for the local design basis wind waves.

The 10,000-year ocean wave used for the design must be determined at a sufficient distance from the coast so that its characteristics are not influenced by the physical phenomena occurring in shallow coastal waters, in particular the surf. For this purpose, long-term series of measurements on wave heights are to be extrapolated using appropriate methods. If the wave steepness meets the wave breaking conditions, the wave heights at the surf edge are determined for the local design basis ocean waves.

The calculation of ocean wave propagation is performed with models that take into account the dominant physical phenomena of coastal wave propagation and the existence of coastal and harbour structures. Where necessary, the penetration of the wave into a harbour basin or into the water inlet or outlet channels as well as the interaction of the wave with the coastal structures is considered. Wave propagation is simulated for stationary and unfavourable boundary conditions.

5.2.2.8 Seiches

The risk of seiches is to be determined on the basis of experience, e.g. with regard to the water level. If this risk cannot be excluded at sites close to the shore, this phenomenon must be considered when calculating the design water level. The design water level must be increased by the value corresponding to the calculated height of a maximum annual seiche (statistical or empirical determination, depending on available data).

5.2.2.9 Tsunamis

In the past, meteotsunamis have occurred in the North Sea and Baltic Sea. They are therefore to be taken into account when designing a disposal facility near the coast. Similarly, at least for the German North Sea coast, the risk of a tsunami caused by sediment slides is considered to be non-negligible. The same applies to tsunamis caused by landslides or rock slides from steep slopes into mountain lakes. These types of tsunamis are therefore also to considered when designing a disposal facility on the coast or lakes surrounded by steep slopes.

The height of tsunamis that have occurred in the past and their impact on the disposal facility site or a topographically comparable region are to be used as a design basis.

Soil and/or flotsam can also be mobilised with tsunami waves. This is to be considered when designing the protective measures according to Chapter 6.

5.2.2.10 Storm surges

The storm surge design basis sea level is composed of

- the highest level of theoretical tides, and
- of a 10,000-year storm surge.

The design basis storm surge is the 10,000-year sea level rise above the level of the calculated theoretical tides. The theoretical tides are calculated from predictable changes in sea level, mainly determined by astronomical tides caused by the gravitational effect of the sun and moon (spring tide). Storm surges are significantly influenced by weather conditions (atmospheric pressure fluctuations) and the impact of the wind on the sea surface (wind set-up). Statistical analyses must be used to determine data on extreme storm surges during a tidal flood. The selection of the corresponding observation series is to be carried out with regard to the scope of the data set (data series as long as possible), the reliability of the values (in particular for the strongest storm surge) and the representative character of the data for this site. It is to be ensured that the determined design basis event covers all historically documented storm surge events.

Soil and/or flotsam can also be mobilised with the storm surge. This is to be considered when designing the protective measures according to Chapter 6.

5.2.2.11 Failure of dams (waterway) and dykes (flood protection)

The reason for the failure of dams/dykes is, for example, an extreme rise in water levels, slope failure or an erosion channel. In the case of reservoir dams, flooding can cause the colmation layer to rupture and the colmatised area to be overflown, which generally only reaches the mean water level. Leaks in the seals can be caused, for example, by ship collision. In all the cases mentioned, uncontrolled runoff of water into the surrounding areas occurs.

The consequences of a dam failure in canals or a dyke failure are to be identified using appropriate simulation models from which flooding heights, flow velocities and spatial and temporal distribution of the water can be determined. The resulting flooding heights at the disposal facility site are the design basis.

Soil and/or flotsam can also be mobilised due to a dam or dyke failure. This is to be considered when designing the protective measures according to Chapter 6.

5.2.2.12 Failure of artificial water reservoirs (e.g. dams, reservoirs, weirs, water tanks)

The water dammed by a dam upstream of the facility can flood the site in the event of a dam failure. The design of the facility is based on the maximum water level reached at the site (design basis) and the flow velocity of the water running off in an uncontrolled manner. The latter is essentially determined by the topography of the terrain between the dam and the facility.

Various models are available for a dam failure prognosis. The simulation of the initiated flood wave is used to determine flooding heights, flow velocities as well as the spatial and temporal distribution of the water.

For the design of the maximum possible water discharge at a specific site, the accumulated water volume or the design basis flood for which a facility is designed as well as the topography of the runoff area is to be taken as a basis and calculated by means of an appropriate simulation model.

Soil and/or flotsam can also be mobilised due to the failure of artificial water reservoirs. This is to be taken into account when designing the protective measures according to Chapter 6.

5.2.2.13 High groundwater level

A strongly increased groundwater recharge due to flooding, caused by local heavy rainfall or increased surface runoff (e.g. river flooding), can lead to a usually delayed rise in the groundwater level. The speed of this groundwater rise is largely determined by the soil type and the layer structure. Technical measures, such as the discontinuation of groundwater management measures or the targeted flooding of former mining regions, can also lead to a rise in groundwater levels.

The maximum groundwater level is to be determined as the design water level. The design water level must be determined on the basis of maximum available long-term observation data on the groundwater level and groundwater recharge resulting from natural flooding causes with a probability of 10^{-4}/a and simulated using site-specific hydrogeological models. Alternatively, the existing data can be extrapolated to a 10,000-yearly maximum groundwater level in the sense of extreme value statistics.

In connection with rising groundwater, the following aspects are to be considered:

- resulting buoyancy forces on foundations and all facility components laid underground which can lead to failure of the supporting structure,
- additional static water pressure on underground facility components, and
- water ingress into underground facility components.

5.2.2.14 Combinations of flooding causes

In addition to individual flooding causes, possible combinations of different flooding causes are also to be taken into account when designing a disposal facility. Such combinations are to be assumed if there is a causal relationship between the causes or if their coincidental simultaneous occurrence is safety-relevant due to the probability and the possible extent of damage. A causal relationship is given if there are common triggers (correlation) or if one cause is triggered by another (consequence). Table 3 shows the conceivable causes of flooding with a causal relationship. For the specific site, it is to be examined whether the respective causality can occur.

- Causes of flooding with a common trigger: Floods are usually not isolated events but result from phenomena that cause several impacts at the same time. In addition to the combination of different types of impacts (e.g. flooding and strong winds), possible intensification effects and interactions of two or more simultaneous flooding causes are also to be considered for flood protection. For example, a cyclone at a coastal site can lead both to heavy precipitation on the facility site and at the same time to a storm surge. When combining the causes of flooding, the respective design basis events are to be applied as a matter of principle. Deviation from this is permitted if reliable information on the correlation behaviour of the flooding causes under consideration is available.

- Cause of flooding as a consequence of an already occurring flooding: Further causes of flooding may occur as a consequence of a cause of flooding (e.g. failure of dams and dykes due to surface runoff in a large catchment area). When assessing which combinations must be postulated, the boundary conditions for the occurrence of the various consequential causes (e.g. minimum duration of the primary flooding, necessary flow velocity) are to be taken into account. For the combination, the design basis event is to be postulated for the primary flooding cause. For the consequential cause, the strength of the consequence resulting from the design basis event of the primary flooding cause is to be applied.

- Flooding causes occurring at the same time by coincidence: Flooding causes without causal relationship can also occur at the same time by coincidence. It is therefore to be investigated whether such combinations can result in safety-related effects that go beyond the effects of the individual impacts (at the design basis level). For this investigation, all possible combinations of flooding causes at the site with an annual event combination of 10^{-4}/a are to be considered that fulfil the following two conditions: (a) The combination has not already been considered on the basis of a causal relationship. (b) At least one of the impacts is of longer duration (of the order of several days) in order to be sufficiently likely to occur simultaneously within one year.

For the design of flood protection, two possible effects of a simultaneous occurrence of different flooding causes are to be considered:

- The combination of both flooding causes leads to a higher water level in the area of the facility components to be protected and protective structures. In this case, the water level resulting from the combination is to be determined (e.g. storm surge and local wind-induced waves).

- The causes of flooding have different effects on the site and therefore require different protective measures. In this case, the interactions of the protective measures are to be taken into account (e.g. obstruction of the terrain drainage by flooding occurring outside the dyke).

Combinations of flooding causes with other external hazards are not considered in this guideline.

Table 3: Causes of flooding with causal relationship

Causes of flooding with a common trigger (triggers are not mentioned in the Table) are marked with a G in the upper right half of the Table. Flooding causes that occur as triggers for a consequential cause are indicated in the lower left half of the Table by arrows whose direction indicates the respective consequential cause.

	Local heavy rainfall	Surface runoff in local catchment areas	Surface runoff in large catchment areas	Ice jam in rivers	Mechanically induced waves	Local wind-induced waves	Sea waves	Seiches	Tsunamis	Storm surges	Failure of dams and dykes	Failure of artificial water reservoirs	High groundwater level
Local heavy rainfall	■	G	G			G				G	G		
Surface runoff in local catchment areas		■	G			G				G	G		
Surface runoff in large catchment areas			■	G	G						G	G	G
Ice jam in rivers				■							G		
Mechanically induced waves					■								
Local wind-induced waves						■	G			G	G		
Sea waves							■			G	G		
Seiches					⇦			■	G				
Tsunamis								⇧	■				
Storm surges										■			G
Failure of dams and dykes			⇦	⇦					⇦	⇦	■	G	
Failure of artificial water reservoirs			⇦									■	
High groundwater level			⇦										■

5.3 Consideration of climate change

In view of the long periods of time that elapse from the decision on the site and the closure of the disposal facility, the likely consequences of climate change must be taken into account when determining the design water level, even if these are naturally subject to uncertainties. The climate-dependent design water level of the various flooding causes depends on the climate change-dependent triggers listed in Table 4.

Table 4: Triggers of flooding causes dependent on climate change

	Trigger						
Flooding cause	**Precipitation**	**Snowmelt**	**Wind**	**Ice drifts**	**Seawater density decrease**	**Atmospheric pressure fluctuations**	**Underwater landslides**
Local heavy rainfall	x						
Surface runoff in local catchment areas	x	x					
Surface runoff in large catchment areas	x	x					
Ice jam in rivers				x			
Mechanically induced waves							
Local wind-induced waves			x				
Sea waves			x				
Seiches			x			x	
Tsunamis						x	x[1]
Storm surges			x		x	x	
Failure of dams and dykes							
Failure of artificial water reservoirs							
High groundwater level	x	x					

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[1] The warming of seawater caused by climate change can lead to increased spontaneous outgassing of submarine methane hydrate. The associated reduction in the stability of sediment masses near to shelf edges can lead to increased landslides and resulting tsunamis (Storegga effect).

5.3.1 Application of climate change factors

Calculating the respective design water levels adapted to climate change is very time-consuming due to the use of regional climate scenarios and corresponding water balance models using extreme climate value statistics. Therefore, the following simplified approach may be used during phases 1 and 2 ([SAG 13]: § 13 and 14). For precautionary reasons, the increased design water levels resulting from climate change can be taken into account via a general surcharge – climate change factor – to the currently valid design value (see [TRA 11], [KLI 13]).

In order to adapt to climate change, this has to be taken into account as follows:

1. A climate adaptation factor of 1.2 is applied to the intensities of flooding causes (e.g. design water levels) to be used in accordance with Chapter 5.2.

2. A detailed analysis may be used in individual cases to justify deviating from the factor 1.2. This is feasible if, for the respective area, the possible change has already been included by regional climate change factors adapted to the specific area on the basis of regional climate scenarios with extreme value statistics.

3. Future new findings regarding climate change will be considered in the revisions of this guideline.

5.3.2 Design on the basis of climate prediction calculations

Following underground exploration during the site selection procedure, but at the latest within the framework of the licensing procedure for the selected disposal facility site, the project implementer or the applicant has to define the flood design basis for the surface facilities of the disposal facility on the basis of the results of computer-based climate prediction calculations.

Based on one or more global climate models, regional climate models are to be developed in accordance with the state of the art in science and technology. The results of climate modelling serve to add corresponding corrections to flood design bases according to Chapter 5.2, insofar as the flooding causes are subject to a change due to climate change (see Table 4). When selecting the climate scenarios that form the basis for the climate prediction calculations, those are to be selected that are internationally recognised (IPCC[2]) and contain probable economic, ecological and social boundary conditions at the time of modelling. The selection of the postulated climate scenarios is to be justified.

Climate prediction calculations are to be carried out until the end of the phase of sealing and closure of the disposal facility. The results are used for the initial design of the surface structures against flooding. The disposal facility must be designed against flooding causes resulting from these climate calculations from the start of operation. As far as results of regional climate modelling are already available, they can be used if their suitability for the respective site can be demonstrated.

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[2] IPCC = International Panel on Climate Change (www.ipcc.ch)

In the regionalisation of global climate models, several procedures are to be applied in parallel and the results have to be compared with regard to the adequacy for the given disposal facility site. The selection of the most probable result is to be justified. In the case of result scattering, mean values are to be used for the design, since 10,000-year and thus strongly conservative events are already used for the design basis flood.

The primary result parameter in climate prediction calculations for flooding causes at inland locations is the climate-induced change in precipitation intensities. In the case of the flooding causes “local heavy rainfall”, “surface runoff in local catchment areas”, “surface runoff in large-scale catchment areas” and “high groundwater level”, the design margins shall be determined from hydrological modelling.

In the case of coastal sites, for the protection against the flooding causes “sea waves”, “local wind-induced waves”, "seiches” and “storm surge” the change of the global sea level is to be taken as the basis for additional design margins due to climate change. In the case of the cause “storm surge”, it is to be determined whether a future change in the coastal wind intensity is to be expected due to climate change.

The causes “local wind-induced waves” and “seiches” in inland areas must be dealt with analogously.

Within the framework of the mandatory periodic optimisation of the disposal facility concept, the results of the modelling are to be checked for their up-to-dateness with regard to the progressing state of the art in science and technology. This concerns the consideration of progress in computer-based climate predictions, the adequacy of climate scenarios and hydrological models. If necessary, further modelling with updated boundary conditions has to be carried out and, based on this, the design of the surface facility components or the planning of the design reserves has to be adapted accordingly.

5.4 Dealing with uncertainties

The uncertainties associated with the respective data, methods and assumptions are to be determined in all steps to determine the site hazard and thus the design basis. On this basis, the effects of the uncertainties on the overall result of the analyses are to be quantified or, if this is not possible, qualitatively assessed.

With regard to the approach to explicitly consider uncertainties, it is necessary to distinguish between aleatoric uncertainties resulting from the natural scattering of data and epistemic uncertainties due to a lack of knowledge, e.g. of the underlying physical processes.

- Aleatoric uncertainties are generally considered sufficiently by applying established statistical methods.

- Epistemic uncertainties often become evident by the fact that there are different models for a process or that assumptions have to be made. The quantification or qualitative assessment of the effects of these uncertainties on the overall result of the site hazard assessment must be carried out, for example, by sensitivity analyses or by a logical tree. If parts of the hazard assessment are based on expert opinions (expert judgement), a structured, comprehensible process is to be chosen for the opinion survey to ensure that the current scientific knowledge is optimally used.

Information on how the uncertainties can be taken into account in the various steps of the site hazard analyses is given in Annex I.

6 Protective measures

In order to prevent the emergence of possible consequences of a flood for a disposal facility described in Chapter 3 from arising in the first place, to prevent them or to minimise them accordingly, appropriate protective measures are to be provided.

A three-level protection concept is to be pursued. This means that the initial objective is to exclude or minimise as far as possible the risk of potential flooding by selecting the disposal facility site, in particular the location of the surface facilities (Level 1). If this is not sufficiently possible, the second level is to exclude or reduce possible hazards through structural measures. In particular, a hazard to the shaft(s) must reliably be prevented by appropriate measures if flooding of the site cannot be completely ruled out. In addition to these two measures, which are already to be considered in the site selection and design/construction of the disposal facility (selection of disposal facility site and structural measures), temporary measures are described on Level 3 of the protection concept on which they are based in order to support the effects of the protective measures described above.

The first step is therefore to select the site of the disposal facility, if possible, in such a way that a potential flood would result in no or only a low hazard to the disposal facility. However, since the disposal facility site is determined by the criteria described in the Site Selection Act [SAG 13], which primarily focus on the long-term safety of the disposal facility, conflicts of objectives may arise here. When selecting the disposal facility site, it should be aimed at, in accordance with the protection concept on which this guideline is based, that the surface facilities of the disposal facility are constructed neither in a depression nor in the immediate vicinity of a river, at a mountain slope or below a dam.

At Level 2 of the underlying protection concept, the objective is to exclude or reduce possible hazards by structural measures. The following protective measures are therefore to be provided for the consequences of a flood for a disposal facility as described in Chapter 3:

- Since flooding of the shaft is to be prevented in any case, structural precautions are to be taken for beyond-design-basis events so that the shaft can be sealed against water ingress. These measures apply to all other shafts if they cannot be separated from the underground emplacement area by dam structures (see below) to be erected at short notice. The shaft sump of the transport shaft for emplacement is to be designed for the case of water ingress and equipped with appropriately powerful pumps.

- The deepest galleries are to be drifted bottom-up. In addition, dam structures are to be provided which, in the case of beyond-design-basis events, enable the temporary sealing of the galleries leading away from the filling station as well as the connections to other mine parts / to the ventilation shaft.

- If necessary, the facility site is to be protected against unplanned entry of water by a dyke or similar flood protection structures.

- If, due to the location of the disposal facility site, there is a risk of flooding due to ice dam formation, appropriate countermeasures are to be taken (e.g. use of air bubble systems, securing endangered dyke sections, ice blasting, etc.). In order to be able to initiate these measures in good time, in addition to contact with the competent authorities, constant monitoring of the water level and ice conditions at previously identified critical points of the river is required if corresponding meteorological conditions exist.

- A suitable sewer system and collecting basins of sufficient size are to be provided for the targeted drainage of the floodwater flowing off the surface in particular after heavy rainfall events.

- In order to prevent the ingress of water into the buildings, appropriate protective devices are to be provided at the buildings or the building openings are to be installed at an appropriate height. For a conditioning/packaging plant, collecting devices are to be provided in the event that water enters and becomes contaminated despite these precautions.

- Measures are to be taken to protect the electrical equipment in accordance with the relevant regulations.

- Facilities are to be provided for evacuating personnel from the mine.

- Depending on the topography of the disposal facility site, the access roads to the disposal facility are to be built at higher levels and designed against flooding accordingly. At the same time, rooms must be provided to allow staff to stay at the disposal facility for several days and, if necessary, boats must be available for staff turnover.

- The corresponding foundation measures and the static calculation of the foundations of the structures must take into account the changes in soil mechanical properties due to a disproportionately rising flood.

- In the case of predictions of severe weather events which, despite the precautions described above, could endanger the disposal facility by flooding, appropriate measures are to be taken. These are primarily organisational measures such as taking facilities or parts thereof out of service – in particular the conditioning/packaging plant prior to predicted severe weather – as well as corresponding planning for flooding within the framework of the alarm and hazard prevention plan (e.g. increased patrols by the security staff) and integration into the municipal disaster control planning.

At Level 3 of the underlying protection concept, the objective target is to take further measures if the described protection measures are not sufficient. The organisational measures mentioned are to be implemented and monitored. As further measures, mobile pumps and temporary sealing devices as well as a corresponding emergency power supply is to be provided in case electrical systems fail despite the described protective measures or individual parts of the building are flooded.

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Annex I Consideration of the uncertainties in the different steps of the site hazard analyses

In the following, the uncertainties of the individual steps of the site hazard assessment are discussed with regard to the possibility of their consideration and, where applicable, reduction. As a final step before the determination of the design basis, the plausibility of the result of the site hazard assessment is to be determined by a comparison with documented events in the region (taking into account the transferability of the historical boundary conditions) and, if available, with estimates of the maximum possible flooding events (in the sense of a probable maximum flood).

- **Data basis:** The uncertainties associated with the provision of the data required for the site hazard assessment mainly result from the limitations of the available measurements and observations as well as from the measurement uncertainty of the individual data points themselves. Level measurements and meteorological measurement data are generally only available for periods ranging from a few decades to about 150 years. In addition, these time series may have gaps and erroneous data points.

    - Measurement uncertainty: The measurement uncertainty contains a random and a systematic part. The random component (scattering) can be treated as classical aleatoric uncertainty with the usual statistical methods. Systematic errors can result, for example, from incorrect calibration of the measuring instruments, unsuitable measuring instruments or unsuitable measuring methods. If such errors are detected, the proceeding as described under “Correction of erroneous data” is to be applied.

    - Limitation of the data sets: In itself, the limitation of the data sets does not represent an uncertainty to be explicitly considered. However, the relatively short time periods for which measurement data are available are one of the major sources of uncertainty in extrapolating the data series to rare events (with exceedance frequencies of e.g. 10^{-4}/a). Measures are therefore to be taken to improve the site-specific data basis, thus reducing the scattering in extrapolation. This can be done, for example, by using data from the wider vicinity of the site and from suitable other regions. In this respect, care must be taken to ensure that the conditions there are transferable to the site. Furthermore, documented historical information (e.g. flood marks) can also be included in the evaluation if suitable statistical methods (e.g. peak over threshold) are applied. It may also be possible to use palaeo-data (e.g. sediment deposits) to estimate the intensity of very rare events. In this case, the uncertainties resulting from the assumptions made are to be taken into account.

    - Assumptions for filling gaps: Depending on the statistical methods used, it may be necessary to fill gaps in the data sets with appropriate values. The procedures chosen for this purpose and the assumptions made are to be comprehensibly justified. The sensitivity of the results to different possible substitute values is to be tested. The uncertainties resulting from a plausible variation of the substitute values are to be considered when determining the overall result of the site hazard analysis.

    - Correction of erroneous data: Obviously erroneous measured values in data series are either corrected or deleted. Correction requires knowledge of the cause of the error. The meta data of the measuring station may provide indications as to the possible cause (e.g. indication of replacement of a measuring instrument in the event of a jump in the data series). If the cause cannot be determined, it is advisable to delete the data concerned. In both cases, the uncertainties are to be considered as in the case of incomplete data sets.

- **Determination of the design basis:** Apart from individual causes of flooding for which the design basis is determined deterministically, the design is to be based on rare events with an exceedance frequency of 10^{-4}/a. Since the available data are limited to significantly shorter periods of time, extrapolation by means of extreme value statistics is required. In this statistical evaluation, trends in the data, the choice of the extrapolation procedure, the choice of the method for adjusting the parameters of the extrapolation function and, if applicable, assumptions regarding maximum values to be applied are sources of uncertainties.

  - Trends: Trends in the data sets may not only result from climate change, but also, for example, from changes in land use or hydraulic engineering measures. Regardless of the cause, trends are to be taken into account as far as they can be identified. This is usually done by separating the trend from the remaining part of data. The detrended share is then subjected to the extreme value statistical evaluation and then recombined with the trend. The uncertainty that results from this is the trend model to be applied since the assumptions made in this regard do not necessarily have to correspond to reality. These uncertainties are to be taken into account by means of a sensitivity analysis or by considering different trend models.

  - Extrapolation procedure: Various extrapolation functions can be used to extrapolate the measurement data, which lead to different results with regard to the intensity of rare events. However, the "correct" extrapolation function for a flooding cause cannot generally be derived from the underlying physical processes. Therefore, an uncertainty remains with respect to the choice of the extrapolation function, even if certain extrapolation functions are used particularly frequently for certain phenomena (e.g. Pearson III distribution for flood runoff). In order to take account of this uncertainty with regard to scientifically justifiable extrapolations, several different extrapolation functions are to be used. The number and concrete choice of the extrapolation functions used is to be comprehensibly justified. The different results of the extrapolations are to be evaluated by means of a sensitivity analysis with regard to their impact on the result of the site hazard analysis or considered as branches of a logical tree when determining the design basis.

  - Parameter adjustment: In addition to the choice of the extrapolation function, another uncertainty results from the method with which this is adapted to the data. Several established methods are available for determining the function parameters of the extrapolation function, e.g. the maximum likelihood method, moment method or least squares method. Each of these methods has its specific advantages and disadvantages. Nevertheless, there is in principle a choice whose impact on the overall result are to be taken into account. As with the extrapolation functions themselves, this consideration can be done by a sensitivity analysis or within the framework of a logical tree.

- Maximum values: Some extrapolation functions have an upper limit, which also corresponds to the expected behaviour of most natural phenomena. The corresponding maximum value usually results from the adaptation of the extrapolation function to the data. In principle, however, it is also possible to specify boundary conditions for the parameters of the extrapolation function so that a certain maximum value is not exceeded. If this option is used, the choice of the maximum value is to be comprehensibly justified. In addition, the impact on the result of the site hazard analysis is to be quantified (sensitivity analysis) or, if this is not possible, evaluated qualitatively (branching in the logical tree).

For flooding causes, such as tsunamis, where the design basis is determined deterministically, a sensitivity analysis is to be carried out with regard to the assumptions used in the determination.

- **Consideration of hazard combinations:** In connection with hazard combinations, two essential sources of uncertainty come into play: (1) the selection of the considered hazard combinations themselves and (2) the determination of the intensity of the individual hazards to be applied. While the uncertainties with regard to the individual hazards have to be considered analogously to the requirements defined above, there is currently no established procedure for the consideration of the uncertainties resulting from the selection of the (not) considered combinations.

- **Consideration of climate change:** According to this guideline, consideration of climate change takes place in two steps: For the first site assessment, the design impacts determined on the basis of the available data are increased by general climate change factors. As part of a detailed site investigation, the design impacts are then already to be determined taking into account regional climate models.

  With regard to the consideration of climate change with general climate change factors, the same applies as written at the beginning of Chapter 5.4 under the keyword “epistemic uncertainties” on expert opinions. A more detailed consideration of uncertainties is not required in this step.

  When determining the design impacts using climate projections and regional climate models, the approaches described above for the consideration of aleatoric and epistemic uncertainties are applied with regard to the initial data and climate models. This means that aleatoric uncertainties are dealt with by classical statistical means, while epistemic uncertainties, such as the choice of global climate models and the regional climate models linked to them, as well as the uncertainties associated with the climate models themselves, are taken into account by sensitivity analyses or logical trees. Uncertainties in global and, in particular, regional climate models result, among other things, from

  - not or not comprehensively known physical processes, e.g. feedback of clouds and ice surfaces,
  - the calibration of the models with the currently available observation data,
  - the limited spatial grid resolution and the resulting neglect of small-scale processes, and
  - simplifications that are necessary to limit the computing time.

  With regard to the representative concentration pathways (RCPs), i.e. the four postulated future concentration patterns of climate-relevant gases in the atmosphere, which serve as a starting point for the climate projections, the uncertainty due to the choice of a particular RCP can also be taken into account by means of a logical tree. With regard to the determination of the four RCP sensitivity analyses themselves, however, the uncertainty cannot be quantified since these are postulated concentration patterns.

Annex II Information material on tsunamis

The following **historical events** in which a sediment slide triggered a tsunami are to be mentioned:

- In June 1858, a tsunami hit the coasts of the North Sea. There are eyewitness accounts from Sylt, Helgoland and Wangerooge. The tsunami must have originated southwest in the Atlantic Ocean. The most probable cause is suspected to have been an undersea slope slide in which several cubic kilometres of rock fell onto the seabed.

- The best known tsunami disaster from the North Sea occurred 7,000 – 8,000 years ago. (Storegga event). The continental slope off Norway slipped down over a length of 800 kilometres. More than 5,000 cubic kilometres of material began to move, triggering a violent tsunami that struck England, Scotland and Norway.

Tsunamis can also occur in lakes; e.g. in the Swiss lakes.

Evidence of historical and prehistoric rock avalanches and landslides that triggered flood waves has been found in the sediments of numerous Swiss lakes. These are chaotically mixed sediments that differ from normal sediments. Since their age can be determined, they can be retrospectively assigned to an event. The height of the flood wave can be calculated using numerical models and compared with historical reports.

In German lakes, flood waves cannot be ruled out either.

To quantify the size of a tsunami, sea level recording takes place in the deep ocean off the coast. There, at water depths of several thousand metres, a tsunami wave is several hundred km/h fast, but only a few to some tens of centimetres high and approximately one hundred kilometres long. Not before it reaches the coast or shallower waters, does a tsunami wave develop into a massive wall of water several metres high. Being able to detect the very slight sea level rise in the deep ocean reliably and precisely requires the use of bottom pressure sensors. These instruments are installed on the seafloor where they measure any sea level changes in the water column above. In this process, the weight of any additional water leads to minute pressure increases at the seafloor which are reliably recorded by the high-precision PACT bottom units. Pressure fluctuations due to the considerably shorter, but also higher waves of swell average out due to the operating depth of the bottom pressure sensors. Similar to a fax machine, an acoustic modem uses a sequence of sounds – the so-called telegram – to transmit information to a second modem which is connected to a buoy near the sea surface, sending the data via satellite to the warning centre. (Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung)