Guidelines on Meteorological and Hydrological Aspects of Siting and Operation of Nuclear Power Plants

2020 edition
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EDITORIAL NOTE

The following typographical practice has been followed: Standard practices and procedures have been printed in **bold**. Recommended practices and procedures have been printed in regular font. Notes have been printed in smaller type.

METEOTERM, the WMO terminology database, may be consulted at [http://public.wmo.int/en/resources/meteoterm](http://public.wmo.int/en/resources/meteoterm).

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1. INTRODUCTION

The WMO Disaster Risk Reduction Programme uses the United Nations Office for Disaster Risk Reduction (UNDRR) definition of hazard: “A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation” (UNDRR, 2017). Meteorological and hydrological hazards result from natural processes or phenomena of atmospheric, hydrological or oceanographic nature. They include latent conditions that may represent future threats, and which can have different origins.

Meteorological hazards are produced by rarely occurring or extreme meteorological phenomena and conditions. Hydrological hazards are associated with flooding events, including related phenomena such as storm surges, and low-water-level conditions. Hazards that could affect the safety of nuclear installations must therefore be properly considered in the selection and evaluation of sites, in the design of new nuclear installations, and in the operational and decommissioning stages of existing installations.

The International Atomic Energy Agency (IAEA) publication *Meteorological and Hydrological Hazards in Site Evaluation of Nuclear Installations* (IAEA, 2011) is intended to assist IAEA Member States in meeting the requirements for nuclear installations with regard to the assessment of meteorological and hydrological hazards, as established in *Site Evaluation for Nuclear Installations* (IAEA, 2016a). *Meteorological and Hydrological Hazards in Site Evaluation of Nuclear Installations* (IAEA, 2011) identifies, in general terms, the meteorological and hydrological hazards that must be taken into account for nuclear installations.

This publication, *WMO Guidelines on Meteorological and Hydrological Aspects of Siting and Operation of Nuclear Power Plants*, is a counterpart, to assist National Meteorological and Hydrological Services (NMHSs) in addressing the technical aspects for implementing the guidance provided in *Meteorological and Hydrological Hazards in Site Evaluation of Nuclear Installations* (IAEA, 2011). It provides scientific and technical guidance on the access to, and analysis, interpretation and use of, meteorological and hydrological information on hazards, including the relevant aspects of climate variability and change, to support the assessment of the associated impacts. It also supports compliance with the requirements in *Site Evaluation for Nuclear Installations* (IAEA, 2016a).

This publication aims to provide practitioners in meteorological, hydrological and climatological sciences with guidance on how to utilize global resources and state-of-the-art practices in the development of information that can be used in the assessment of site-specific hazards and the capabilities of sites in responding to any emergency that may occur at a nuclear installation.

In accordance with *Meteorological and Hydrological Hazards in Site Evaluation of Nuclear Installations* (IAEA, 2011), the meteorological and hydrological hazards dealt with in these Guidelines are those caused by external events, defined as events unconnected with the operation of a facility or the conduct of an activity that could have an effect on the safety of the facility or activity. The concept of “external to the installation” is intended to include more than the area immediately surrounding a proposed site area, as the region where the site is planned or located may contain features that pose a hazard to the installation.

The present publication supersedes Technical Note No. 170, *Meteorological and Hydrological Aspects of Siting and Operation of Nuclear Power Plant, Volume I: Meteorological Aspects* (WMO, 1985) and *Volume II: Hydrological Aspects* (WMO, 1981). It has been changed to provide technical guidance needed by Members to implement the intent and safety objectives of IAEA publications on this subject, relating to nuclear installation sites.

The structure of the information provided in this publication is similar to that of *Meteorological and Hydrological Hazards in Site Evaluation of Nuclear Installations* (IAEA, 2011). Chapter 2 provides the necessary information for meteorological and hydrological assessment. Chapter 3 covers the assessment of meteorological hazards. Chapter 4 addresses the assessment of hydrological hazards. Chapter 5 is on the design-basis parameters related to meteorological and hydrological
hazards. Chapter 6 covers the measures for site protection. Chapter 7 discusses the changes in
hazards with time. Chapter 8 deals with monitoring, forecasting and warning systems for the
protection of installations. The three annexes provide further details on atmospheric transport,
dispersion and deposition, the WMO Coastal Inundation Forecasting Initiatives and an example
of an integrated approach for emergency support.

ORGANIZATIONAL ROLES

The WMO Convention affirms the vital importance of the mission of NMHSs in observing and
understanding weather and climate and in providing meteorological, hydrological and related
services in support of relevant national needs that should include the following areas:

(a) Protecting life and property;
(b) Safeguarding the environment;
(c) Contributing to sustainable development;
(d) Promoting long-term observation and collection of meteorological, hydrological and
climatological data, including related environmental data;
(e) Promoting endogenous capacity-building;
(f) Meeting international commitments;
(g) Contributing to international cooperation.

NMHSs are a fundamental part of national infrastructure and play an important role in
supporting the vital functions of governments. They undertake activities directed at improving
the understanding of weather, climate, hydrology and the environment over land and sea. They
undertake monitoring of weather-, climate-, water- and environmental-related phenomena,
provide forecasts, and supply weather, climate, water and related environmental services to a
range of users to respond to relevant national, regional and global needs. NMHSs play a central
role in the Global Framework for Climate Services (GFCS), which is an initiative led by the United
Nations and spearheaded by WMO.

These Guidelines are a publication jointly sponsored by WMO and IAEA, which have a
long-standing history of collaboration. WMO, including its NMHSs, provides scientific and
technical guidance on the access to, and analysis, interpretation and use of, meteorological and
hydrological information on hazards. This includes the relevant aspects of climate variability and
change, to support assessment of the associated impacts on the safety of nuclear installations as
well as the planning and risk management efforts concerned.

WMO is also one of the international organizations that co-sponsor the IAEA-led Joint Radiation
Emergency Management Plan of the International Organizations (IAEA, 2017). The Joint Plan is
intended to support and underpin the efforts of national governments and ensure a coordinated
and harmonized international response to radiation incidents and emergencies.
2. NECESSARY INFORMATION – METEOROLOGICAL AND HYDROLOGICAL ASSESSMENT

2.1 GENERIC SPECIFICATIONS

2.1.1 Introduction

The need for meteorological and hydrological information, including on potential coastal flooding, is dictated by the broad requirement of data and knowledge for the successful design, planning, construction, operation and decommissioning of a nuclear power plant (NPP), which may cover a period of up to 100 years. Data and information will be necessary for the site and local specific details, plus what may be appropriate for the more general conditions in the adjacent area. The ultimate objective is to consider and identify meteorological and hydrological characteristics in the context of risks and impacts, which must relate to high- and low-magnitude extreme events, as well as the more general climatological and hydrological environment. All phases of the siting, design, construction, operation and decommissioning of an NPP have certain meteorological and hydrological implications that have to be envisaged as early as possible in the planning of the installation, because they will influence site selection, design solutions, operational and decommissioning strategies and so forth.

It should be noted that throughout this publication, the term “hydrology” is used to refer to the complete hydrological cycle. This is in accordance with the International Glossary of Hydrology (WMO and United Nations Educational, Scientific and Cultural Organization, 2012), where hydrology is defined as the “Science that deals with the waters above and below the land surfaces of the Earth; their occurrence, circulation and distribution, both in time and space; their biological, chemical and physical properties; and their interaction with their environment, including their relation to living beings.”

Some parts of the hydrological (water) cycle may be defined and considered as distinct process entities. Thus, the atmospheric aspects of the water cycle, involving rainfall and the behaviour of water vapour, particularly with regard to evapotranspiration is often defined as hydrometeorology because this is a field where hydrological and meteorological studies and observations overlap. Similarly, the behaviour and characteristics of subsurface structures (soils and rocks) may be considered as hydrogeology (also sometimes referred to as geohydrology when dealing with landslides). In this and subsequent sections, the more specific definitions may be applied only when this is particularly relevant; otherwise, the word hydrology can be assumed to have its wider meaning.

The safety of an NPP is related in several ways to the atmospheric and hydrological conditions at the site and in its surrounding geographical setting, which can be a complex mixture of human settlement, activity and natural (ecological) conditions. Adequate solution of the meteorological (and climatological) and hydrological issues and problems generated by the potential impacts associated with the NPP requires comprehensive information on local and regional conditions, including possible trends related to human and social activity.

Shortfalls in data may become apparent at any stage of the existence of the NPP, and should be rectified if feasible. Thus, for example, at the design stage, it may be necessary to augment the observation network and upgrade the instrumentation and data transfer arrangements. Principal and important changes may be the change from manual recording to electronic monitoring and recording instruments, and the introduction of remote-sensing and automatic electronic data transfer. Changes in legislation that cover, for example, atmospheric pollution or water quality may require redefinition of the network and observation techniques, particularly with respect to more stringent environmental or water quality criteria of design safety legislation.

All NPPs require copious and reliable water supplies, so they must be near to rivers, lakes or coasts, thus giving the potential for enhanced impacts from meteorological and
hydrometeorological hazards. The *Nuclear Technology Review 2018* (IAEA, 2018) gives information on the number of existing and planned NPP as well as the types of reactors. The following sections in this publication examine the necessary meteorological and hydrological parameters required for the assessment of siting (location) for NPP installations.

2.1.2 **Meteorological assessment**

2.1.2.1 **General**

The objectives of using meteorological information before and during operation of an NPP (IAEA, 2016a) are to:

- Assess the effects of the environment on the NPP
- Assess the effects of the NPP on the environment in case of release of radioactive material (IAEA, 2001, 2002)

The need for considering meteorological information at the early stage of a site selection process is obvious, noting that radiological safety and building regulations aim at preventing damage to the structures, systems and components (SSCs) of the future plant caused by extreme meteorological phenomena. The objective is to have all the weather parameters and procedures relative to normal and emergency situations determined before operations start.

In most cases, the site of the potential NPP will not be previously equipped with meteorological instruments. A standard automatic weather station and an instrumented tower/mast or a boundary-layer profiler should be installed at the site. An analysis of the meteorological data should be conducted to determine standard weather parameters as well as vertical profiles of winds and temperatures in the atmospheric boundary layer and atmospheric dispersion conditions. A continuous series of at least 1 but preferably 3 years of measurements can then be correlated with data from a nearby official station (usually run by an NMHS) for which more robust statistics exist over a longer period of time.

It is important to note also that fine mesh numerical mesoscale models with spatial resolution adequate to resolve the characteristics of the surface (elevation, land cover, roughness, soil properties and so forth) can provide simulations of local meteorological parameters at regional and local scales (see section 2.4). They are an additional source for the evaluation of the foreseen site, although not a substitute to observational data.

During normal operation, real-time meteorological information and forecasts are used to check that none of the meteorological and hydrological thresholds established in the early phase are or will be exceeded in the near future, and to test the validity of procedures launched in an emergency situation.

During emergency operation involving potential or actual release to the atmosphere, guidance and advice from national authorities and IAEA can be based on dispersion/deposition model computations for which in situ observations are important inputs.

It is therefore highly recommended that the NPP operator establish, as early as possible, a cooperation programme with the NMHS.

The statement by WMO on the role and operation of NMHSs (WMO, 2015a) declares that:

The NMHSs own and operate most of the infrastructure that is needed for providing the weather, climate, water and related environmental services for the protection of life and property, economic planning and development, and for the sustainable exploitation and management of natural resources. Most NMHSs:
(a) Develop and distribute forecasts, warnings and alerts for safety of life and property and to support efforts to reduce the impacts of weather, climate, water and related environmental natural hazards;

(b) Provide essential data, information and products necessary for designing/planning, developing and managing infrastructure, settlements and other essential sectors such as agriculture, water resources, energy and transport for improving the well-being of societies;

(c) Maintain a continuous, regularly updated, reliable and comprehensive historical record of their national weather, climate, water and related environmental data;

(d) Provide relevant advice on weather, climate, water and related environmental issues for decision-making;

(e) Advance science and technology related to weather, climate and water, in addition to developing and improving their own operations and services through research and development;

(f) Participate in the development, implementation and operation of national multi-hazard early warning systems, including those involving seismology, volcanic ash monitoring, transboundary pollution and ocean-related phenomena such as tsunamis;

(g) Fulfil relevant international commitments, including those under the WMO Convention, and further national interests through participation in the appropriate international programmes and activities;

(h) Establish and operate observing station networks that gather observations of the Earth–atmosphere–ocean system in real time to support the provision of weather, climate, water and related environmental services and research activities, including the assessment and projection of climate change;

(i) Establish and operate telecommunications networks for the rapid exchange of observations, data and services;

(j) Acquire and operate data-processing and forecasting systems to provide real-time weather, climate, water and related environmental services, including warnings and alerts to the public and sectors such as agriculture, water resources, energy, health, shipping, aviation, national defence and environment;

(k) Acquire and operate a product dissemination system for efficient and effective delivery of information and services to users to enable planning, preparedness and decision-making for socioeconomic development.

Governments have appointed their own NMHSs to provide the above services. It is internationally agreed that NMHSs must follow WMO standard procedures and recommended good practices, described in the WMO Technical Regulations, Manuals and Guides. WMO is the United Nations system’s authoritative voice on the state and behaviour of the Earth’s atmosphere, its interaction with the oceans, the climate it produces and the resulting distribution of water resources (see https://www.wmo.int/pages/index_en.html).

WMO is sponsoring and/or co-sponsoring various operational and research programmes, including the Intergovernmental Panel on Climate Change (IPCC), which is the leading international body for the assessment of climate change (see https://www.ipcc.ch/).

For meteorological activities related to NPPs, NMHSs are the best partners to provide:
Guidance for meteorological observations and measurements based on the Guide to Instruments and Methods of Observation (WMO, 2018a; hereafter referred to as the CIMO Guide): for example, types of appropriate instruments, rules for siting and exposure, frequency of measurements, averaging times, calibration and maintenance.

Guidance for real-time data collection, archiving and processing, and historical data, according to best practices described in the Guide to Climatological Practices (WMO, 2018b): for example, from real time and/or climatological databases, provision of time series of relevant parameters (temperature, pressure and humidity, wind speed and direction, precipitation and snowpack). Other examples include phenomena (lightning, tropical cyclones, tornados, waterspouts, duststorms, hail and freezing precipitation) listed in Meteorological and Hydrological Hazards in Site Evaluation of Nuclear Installations (IAEA, 2011); homogenized reference time series; statistical data including 30 or 10 year climate normals; extremes; and frequency of occurrence of phenomena.

Guidance for accessing climate forecast products and multi-hazard early warnings, climate predictions and projections, as described in the Manual on the Global Data-processing and Forecasting System (WMO, 2017a).

It should also be noted that Regional Specialized Meteorological Centres (RSMCs) have been appointed to provide atmospheric transport modelling products for environmental emergency response and/or backtracking (listed in the Manual on the Global Data-processing and Forecasting System (WMO, 2017a), Part III).

An NPP operator may wish to: (a) ask its NMHS to include its meteorological data into the standard quality control procedures in place there and (b) offer its meteorological data to NMHSs for inclusion in the data assimilation suite, to improve the analysis around the NPP site. The operator may also wish to benefit from the availability of off-site meteorological data, to have good knowledge of the NPP wider environment. The NPP operator can also benefit from additional services such as access to remote-sensing data (networks of weather radars and profilers operated by NMHSs) and satellite data from national or regional space agencies.

Climate change is introducing a new challenge for long-term planning. It is considered that historical data are no longer sufficient to make decisions because the climate may change significantly at the NPP site over its lifetime of the order of one century. These Guidelines provide information on new sources of climate model data valid for the next 30–100 years, for different socioeconomic scenarios. The IPCC Fifth Assessment Report (AR5) summarizes the expected impacts (IPCC, 2014a, 2014b, 2014c); see also section 7.1 below. Some guidance is given to derive appropriate statistical data, especially the return periods of extremes in a changing climate, which may need a re-evaluation of parameters established during the design phase.

2.1.2.2 Atmospheric transport and dispersion

Evaluation of transport and dispersion in the atmosphere of radioactive material discharged from an NPP under normal operational or accidental conditions is a requirement for design and licensing. Dispersion of Radioactive Material in Air and Water and Consideration of Population Distribution in Site Evaluation for Nuclear Power Plants (IAEA, 2002) discusses the meteorological parameters needed to determine the atmospheric dispersion characteristics at an NPP. A few key points include:

- The atmosphere is a major exposure pathway by which radioactive material that is either routinely discharged under authorization or accidentally released from an NPP could be dispersed in the environment and transported to locations where it may reach the public.

- A meteorological investigation should be carried out to evaluate regional and site-specific meteorological parameters. These data should be collected from appropriate elevations above ground (section 2.2) and with the use of meteorological analyses (section 2.4).
The type and extent of acquired meteorological data should allow for a reliable assessment of atmospheric dispersion parameters and statistical analyses to assist with radiation exposure calculations (see section 3.5).

Table 1 summarizes the range of meteorological data required and the purposes for which they are necessary for NPP operation. Table 2 gives a similar table for hydrological observations and applications.

### Table 1. Types of meteorological data required for NPP operation

<table>
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<tr>
<th>Purpose</th>
<th>Features</th>
<th>Required data and elements</th>
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<tbody>
<tr>
<td>Normal NPP operation</td>
<td>Continuous improvement of knowledge of climatological statistics at the site</td>
<td>Synoptic, mesoscale and local meteorological information Precipitation Temperature Humidity Snowpack Wind speed and direction Rare or other meteorological phenomena Extremes Forecasts and warnings</td>
</tr>
<tr>
<td>Prevention of damage to NPP SSCs</td>
<td>Precipitation Temperature Humidity Wind speed Synoptic, mesoscale and local meteorological information Forecasts and warnings Rare or other meteorological phenomena</td>
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<tr>
<td>Assessment of routine (small) releases as part of normal operations</td>
<td>Wind speed and direction Precipitation Dispersion/deposition conditions (stability or turbulence indicator, inversion conditions) from tower/mast or profiler Simple Gaussian plume model</td>
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<tr>
<td>Emergency preparedness</td>
<td>Boundary-layer wind and temperature profiles Synoptic, mesoscale and local meteorological information Forecasts and warnings Simple (Gaussian) plume model Advanced three-dimensional (3D) transport-dispersion-deposition model coupled with an operational meteorological model Lessons learned from previous operations</td>
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<tr>
<td>Meteorological effects on cooling towers (plume length, fog, downwash and reduction of sunshine duration)</td>
<td>Wind speed and direction Humidity Sunshine recorders</td>
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<td>Regular updates of design-basis parameters</td>
<td>Return periods of extremes taking into account observed or expected climate change</td>
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<tr>
<td>Purpose</td>
<td>Features</td>
<td>Required data and elements</td>
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</tr>
<tr>
<td>Emergency NPP operation</td>
<td>Need for the immediate assessment of potential/real spread of a release (operators, national agencies, IAEA and RSMCs)</td>
<td>Current and predicted atmospheric state and dispersion/deposition conditions (stability or turbulence indicator, inversion conditions) from a tower/mast or ground-based remote-sensing profiler. Meteorological conditions at the site including vertical profiles. Meteorological nowcasting information to provide wind and precipitation information with forecast lead times of the order of a few hours. Simple Gaussian plume model. Advanced 3D transport-dispersion-deposition model coupled with an operational meteorological model. Lessons learned from previous operations. Radar data to determine precipitation areas and potential for wet deposition.</td>
</tr>
</tbody>
</table>

Post-emergency analysis (for example, United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 2013; WMO, 2013a; Draxler et al., 2015) | Advanced 3D transport-dispersion-deposition model coupled with an operational meteorological model. Operational analyses for the duration of the whole event. Observed concentrations, deposition and doses for validation of model results. |

2.1.3 **Hydrological assessment**

The following hydrological and water resource problems require consideration and solution when selecting a site or designing an NPP:

(a) Water supply;

(b) Flooding (due to hydrologic and coastal surge forcing);

(c) Droughts and low flows;

(d) Effects on water use upstream and downstream (quantity and quality aspects);

(e) Effects on future regional water resources;

(f) Operational and decommissioning conditions.

It is imperative for the meteorological, hydrological and coastal hazards assessments to be of a comprehensive nature and to provide information to define and develop:

(a) Long-term characterization at the site and in the regional or catchment context;

(b) Specific design criteria;

(c) The necessary models for design and management applications;
(d) Support for the operational requirements at the NPP;
(e) Sufficient data for forecasting and warning, and for emergency situations.

As a minimum, hydrological data should be sufficiently detailed to identify means, variability, specified extremes, long-term trends and characteristics at a range of time intervals, for example, depth duration of rainfall, exceedance probability of river levels and discharges. Chapter 4 discusses, in more detail, the types of data required for the assessment of various hydrological hazards. Additionally, meteorological information and models must be sufficiently detailed to represent expected long-term coastal flooding hazards at a site if this is relevant.

Table 2 identifies the components of the hydrological observation network for various applications. Most of the data items are common to hydrological and meteorological network operations, but instrument location and density may be inadequate for site-specific investigations and direct hydrological observations. Sections 2.2, 2.4 and 2.8 provide more information on the instrumentation and operation of hydrological observations and the range of data processing and analyses for hydrological studies. The Guide to Hydrological Practices (WMO, 2008a, 2009a) provides full information.

The siting and design phases of NPPs have to take into account routine and emergency conditions. During routine operation, the staff responsible for hydrological and water resource matters have to carry out the following activities:

(a) Monitoring or obtaining monitoring data on the conditions of dams and other significant structures in the relevant river basins and on the available water supply;
(b) Forecasting future supply;
(c) Reservoir operation;
(d) Forecasting and/or monitoring:
   (i) Water levels and water quality in water supply sources;
   (ii) Sedimentation and/or erosion and ice conditions;
   (iii) Water quality in water bodies receiving untreated and/or treated wastewater from the NPP;
   (iv) Changes in quality of water used for irradiated fuel storage;
   (v) Water consumption of the plant;
(e) Collection, storage and safe disposal of waterborne waste (radioactive and non-radioactive);
(f) Maintenance in good functioning order of water-related safety features;
(g) Ensuring availability of water for the ultimate heat sink;
(h) Investigation of reports on corrosion and/or mineral/biological deposits in various water conveyance and storage installations.

The hydrological/water resource staff will also be responsible for initiating all measures for correcting deficiencies observed in any of the above areas and for checking that such measures have been implemented as expeditiously as necessary, to maintain the NPP operation within acceptable limits of risk.

During emergency operation, situations may be of two types: emergencies of hydrological origin and others of non-hydrological nature, but which may have an external hydrological impact.
Emergencies of hydrological origin range from extreme flood events to reductions of flow, and both situations require consideration of surface water and groundwater. The hydrological/water resource staff, because of their knowledge and understanding of river and catchment behaviour, may be called on to deal with extremes caused by non-hydrological origins, for example, river blockage by landslips, ship collisions or operational actions upstream. The same staff may also be required to assist in ensuring safe operation of the NPP, to assess the effects on water quality downstream and to assist in supply measures to ensure the continuous safe operation of water supply to users downstream if water sources have been contaminated, and also in any hydrological/water resource aspects of decontamination operations.

### Table 2. Types of hydrological data required for NPP operation

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Features</th>
<th>Required data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrological characterization</td>
<td>Catchment/watershed planning</td>
<td>Precipitation, Temperature, Humidity, Wind speed, Water level, Discharge</td>
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<tr>
<td></td>
<td>General water balance</td>
<td>Snow data (if applicable), Glacial data (if applicable)</td>
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<tr>
<td></td>
<td></td>
<td>Hydrographic data, Land use/land cover, Elevation data, Soil characteristics, Surficial geology</td>
</tr>
<tr>
<td>Flood management and control</td>
<td>Structures (dams and river training*)</td>
<td>Precipitation, Temperature, Humidity, Wind speed and direction, Water level, Discharge</td>
</tr>
<tr>
<td>Flood forecasting and warning</td>
<td></td>
<td>Precipitation, Temperature, Solar radiation, Evapotranspiration, Synoptic information, Water level, Discharge, Soil moisture data, Snowpack data (if applicable), River ice data (if applicable), Warning and flooding thresholds, Forecasts and alerts</td>
</tr>
<tr>
<td>Flood-plain zoning/flood frequency estimation</td>
<td></td>
<td>Precipitation, Evapotranspiration, Water level, Flow rate, Hydrographic network, High-resolution flood-plain digital elevation model (DEM)</td>
</tr>
<tr>
<td>Coastal inundation</td>
<td></td>
<td>Wind speed, Wind direction, Sea-level data near the river mouth, Synoptic information, Forecasts and alerts, High-resolution flood-plain/coastal DEM</td>
</tr>
<tr>
<td>Purpose</td>
<td>Features</td>
<td>Required data</td>
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<td>-------------------------</td>
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<td>-------------------------------------------------------------------------------</td>
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<tr>
<td>Groundwater</td>
<td>Recharge</td>
<td>Groundwater level, Precipitation, Temperature, Humidity, Wind speed, Medium/long-range forecasts, Groundwater chemistry, Soil and aquifer characteristics</td>
</tr>
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<td></td>
<td>Groundwater flooding</td>
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<td></td>
<td>Spill containment</td>
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<tr>
<td>Navigation</td>
<td>Canal systems</td>
<td>Precipitation, Medium/long-range forecasts</td>
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<tr>
<td></td>
<td>Dredging</td>
<td>Hydrographic data, Sedimentation data</td>
</tr>
<tr>
<td>Power generation</td>
<td>Hydropower</td>
<td>Precipitation, Temperature, Humidity, Wind speed, Medium/long-range forecasts</td>
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<tr>
<td></td>
<td>Cooling water</td>
<td></td>
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<tr>
<td>Water supply</td>
<td>Potable water</td>
<td>Precipitation, Temperature, Humidity, Wind speed, Medium/long-range forecasts</td>
</tr>
<tr>
<td></td>
<td>Industrial processing</td>
<td>State of climate (for example, El Niño versus La Niña phases in the El Niño–Southern Oscillation (ENSO)), Drought monitoring, Snowpack data (where applicable)</td>
</tr>
<tr>
<td>Water quality</td>
<td>Pollution control</td>
<td>Precipitation, Temperature, Humidity, Wind speed, Forecasts and alerts, Key water quality parameters, sampling data</td>
</tr>
<tr>
<td></td>
<td>Dilution</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Salinity and sedimentation</td>
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<tr>
<td>Fisheries and conservation</td>
<td>Hydroecology</td>
<td>Precipitation, Temperature, Humidity, Wind speed, Medium/long-range forecasts, Water quality, Water temperature</td>
</tr>
<tr>
<td></td>
<td>Hydromorphology</td>
<td></td>
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</tbody>
</table>

* Engineering works built in or along a river, to direct the flow, or to lead it into a prescribed channel or to increase the water depth for navigation and other uses (WMO and United Nations Educational, Scientific and Cultural Organization, 2012).

For hydrological activities related to NPPs, the National Hydrological Service (NHS) is the most appropriate source of information, assistance and guidance. Note that in many countries, the NHS is a separate body from the NMHS, and may also operate under a different lead ministry or department.

The NHS has the role of gathering hydrological and some hydrometeorological data (the latter including evaporation), as well as water quality data. Water quality includes the biological and conservation aspects of water bodies, and may be termed hydroecological. The data networks are normally catchment (watershed) based, whereas meteorological networks are geared to more general geographic distribution. The NHS network may have a specific focus, with water resources being the most frequent concern, but the location of the State or region may require emphasis on groundwater, flooding, power generation and irrigation.
The operators of an NPP facility will need access to data in near real time for most applications in operation, whether routine or emergency. This requires a high level of automation of recording and transmission facilities; if this does not exist, then the network requires redesign or upgrade. The suitability or otherwise of existing observations must be ascertained, for the operation of any NPP, for river discharge and flood measurement, forecast and warning. Station metadata for the existing networks must be collated as far as possible, to include: location information (geographic coordinates, elevation and gauge datum), site conditions (including accessibility arrangements), record length, holder of data, type of record (electronic or paper), type of instrument, physical condition and so forth.

Water quality and aquatic environmental considerations are complex, and closely related to the hydrological environment. Water quality criteria cover chemical, biological and physical variables, and environmental controls are based on biological measures. National government bodies have overall responsibility for the administration of legislation and its enforcement. The detail of legislation, the criteria used and institutional capacity of the responsible agencies will vary from country to country, and even from region to region. However, there are supranational guidelines on water quality, biodiversity and so forth that have been built up over the years with United Nations agencies – for example, the World Health Organization (WHO) water quality standards (WHO, 2011).

All of the above need to be carefully examined, to take into account the most up-to-date policy and regulation. For example, the European Union Water Framework Directive (European Union, 2015) has greatly modified criteria for effluent and receiving water with regard to physical, chemical, radiological and biological properties, to which all European Union member countries are obliged to comply and incorporate into their national legislation.

2.2 **OBSERVATIONS**

2.2.1 **General considerations**

The meteorological observations at a planned(existing NPP site serve several purposes, such as assessing the suitability of the site for an NPP, in support of routine and emergency operation of the NPP, and for the issuance of warnings and deployment of emergency response activities. Tables 1 and 2 above identified the components of the meteorological and hydrological observation network for various applications.

Traditional observing techniques, based on meteorological sensors set on a tower/mast and acoustic sounders (SODAR – sonic detection and ranging), as well as more modern approaches, based on integration of remote-sensing observations and modelling, are considered below. It should be noted that the qualifications of the staff operating traditional instruments or remote-sensing instruments (such as radars and lidars) are different, with staff for the latter requiring more expertise. Section 2.2.2 provides more specific guidance on the observing systems and is concluded by a comparison of the performances and limitations of various available profiling systems.

Meteorological observations collected at the NPP site and in the region should be used to feed numerical weather prediction (NWP) analyses (see section 2.4). In the case of an emergency with a potential of release of radioactive material to the atmosphere, this information can then be used as input for atmospheric transport, dispersion and deposition modelling (ATDM; see sections 3.5 and 8.5). Annex 3 presents an example of an integrated observation-NWP-ATDM approach for emergency support. Similarly, meteorological and hydrological observations (and in some applications, NWP output) should be used to feed hydrological models used for short-term flood forecasting, seasonal water supply predictions, and surface water and groundwater contaminant fate and transport modelling for site selection, planning and emergency response.
2.2.2 Meteorological observations and instruments

2.2.2.1 Generalities

The results of a meteorological investigation are essential to confirm the suitability of a site for an NPP. Accordingly, a detailed meteorological investigation should be carried out in the region of the future NPP. It should be planned by a knowledgeable and experienced person (meteorologist) with expertise in meteorological measurements, traceability assurance, and data collection and transmission. This person should be familiar with the requirements for the positioning of meteorological sensors to ensure the representativeness of those measurements. The whole establishment process of the meteorological measurements, starting from calibration in the laboratory, through on-site installation and to data collection, should be monitored by the person involved in the planning activities or by a meteorological project leader. After establishment, the regulatory body should approve and inspect the measurements.

Meteorological data are gathered from the NMHS, but also from other organizations. WMO OSCAR (Observing Systems Capability and Review Tool; https://www.wmo-sat.info/oscar/) can be used to identify observing stations that could provide data suitable for site analysis and for NPP operation.

During the local meteorological investigation and also later during normal NPP operation, it is necessary that a person be responsible for the regular maintenance, technical inspection and calibration of meteorological instruments and auxiliary equipment, and the traceability assurance of the measurement results.

Dispersion of Radioactive Material in Air and Water and Consideration of Population Distribution in Site Evaluation for Nuclear Power Plants (IAEA, 2002) contains some advice on how the sensors should be positioned in relation to terrain features, to obtain data representative of the site conditions for later use in meteorological studies of atmospheric dispersion. This information is assumed to be known here, as well as the required characteristics of the instrumentation system to be used. The CIMO Guide describes best practices in the field of meteorological measurements and observations, providing details of measuring methods and various types of instruments, as well as their installation, maintenance, calibration and data acquisition.

It is extremely worthwhile to use best-quality equipment with regard to sensors, sensor holders, shielding, towers/masts, and data acquisition and transmission devices, to minimize downtimes and ensure high-quality and continuous data availability. Preference should be given to equipment that has been sufficiently tested and which withstands long-term operation in difficult conditions. The equipment should be chosen in such a way as to be capable of measuring the meteorological parameters achieving the required measurement uncertainty over the whole range expected to be encountered by these parameters at the site (climatological extremes). In addition, the equipment (sensors, mounting, masts and so forth) must also be able to withstand extreme meteorological events that can occur on the site to ensure the system will still be able to provide accurate measurements during and after severe weather events to support emergency response activities.

A programme for meteorological investigation should be designed to collect and evaluate data continuously during normal operation of an NPP, and when an emergency arises, enable evaluation of the radiation exposure of the public and the radiological impact on the environment for assessment against each regulatory objective.

Meteorological instrumentation and systems should be maintained, serviced and calibrated on a regular basis.

2.2.2.2  **Siting of the meteorological measurement system**

The site for a new meteorological station must be carefully selected to ensure that it is representative of the area and positioned far enough from any obstacles (including the NPP itself) to minimize their effect on measurements. The Siting Classification for Surface Observing Stations on Land (CIMO Guide, Part I, Chapter 1, Annex 1.B, and International Organization for Standardization (ISO) standard ISO 19289:2015 (ISO, 2015a)) provides guidelines on the classification of surface observing sites on land to indicate their representativeness for the measurement of different variables. As described in *Dispersion of Radioactive Material in Air and Water and Consideration of Population Distribution in Site Evaluation for Nuclear Power Plants* (IAEA, 2002), meteorological equipment should be installed in such a way as to obtain relevant data representative of the dispersion conditions at release points. Equipment should be properly exposed and open to the environment.

2.2.2.3  **Meteorological instrumented towers and masts**

Special instrumented towers and masts are used for many purposes, especially for estimation of the diffusion of atmospheric pollution. For some purposes, the height of the tower must be up to 100 m, and for air-pollution monitoring and control projects, it should exceed the height of the important sources of pollution by at least 50 m. The tower height is usually limited by practical reasons. Measurements should be made at several (at least two or three) levels, the lowest of which should be at the level of the standard meteorological screen, close to the tower or mast (CIMO Guide, Part I, Chapter 5). The number of measuring levels depends upon the task and the height of the tower or mast. The use of just two levels provides no information on the shape of the vertical profile of meteorological variables and is therefore limiting.

The site of the tower/mast should be chosen to minimize the influence of structures and natural obstacles on the meteorological measurements. It is important that the structure of the tower or mast should not affect the sensors and their measurements appreciably.

In planning for the tower or mast, and equipment, the following should be taken into consideration:

(a) The tower/mast dimensions must allow space for climbing and installation work.

(b) The tower/mast should be equipped with landings beneath the sensor levels, to facilitate installation and maintenance work.

(c) The tower/mast must be of an open type and the positions and dimensions of cable bearers must be chosen carefully, to minimize turbulent wake effects on the wind sensors. The positioning of a junction box at a height similar to that of a wind or temperature sensor must be avoided.

(d) For open structures, booms (stationary or retractable) should be at least 2 m long, and preferably long enough to keep the sensors at least 10 tower diameters removed from the tower or mast. For solid structures, or where the required booms would not be practicable, a double system is required at each level, with booms on opposite sides of the tower or mast extending for at least three times the structure diameter.

(e) Flexibility in the sensor bracket and sensor connection system is preferred to facilitate sensor-level alterations.

(f) At sites with harsh environments, the sensors must be protected against falling ice by special shields.

(g) Sensors with moving parts should be heated at sites with icing and hoar frost conditions.

(h) Junction boxes at moist sites or at low-signal levels (for example, bridge-coupled temperature sensors) should have internal heating.
(i) The tower/mast and the guy-wires must be satisfactorily earthed for protection against lightning.

(j) The junction box at the tower/mast base or at the data-logger site must be equipped with lightning-surge dissipaters (for example, vacuum lighting protectors and/or solid-state transient suppressors).

(k) The presence of the tower/mast affects downwind thermometers and anemometers; therefore, the use of two sets of those sensors 180° apart should be appropriate.

It is also necessary to observe legislation concerning electrical installations and the protection of workers. Good planning advice may be obtained from the department of the telecommunications administration that deals with erecting masts.

Tower measuring equipment requires periodical checks by highly qualified instrument maintenance staff, who should pay special attention to the state and performance of sensors and recorders and the connecting cables, sockets and plugs exposed to outdoor weather conditions.

2.2.2.4 **Sensors**

For description of the meteorological conditions, data on the following should be obtained concurrently (IAEA, 2002):

1. Wind velocity (wind directions and speeds);
2. Precipitation;
3. Air temperature;
4. Humidity;
5. Air pressure;
6. Specific indicators of atmospheric turbulence.

The CIMO Guide provides detailed descriptions of sensors suitable for measuring these parameters.

The CIMO Guide, Part I, Chapter 1, Annex 1.E, which is regularly updated, provides operational measurement uncertainty requirements for these parameters.

1. **Wind velocity**

Wind velocity is a 3D vector quantity with small-scale random fluctuations in space and time. However, generally for meteorological purposes, it is considered mainly as a two-dimensional (2D) vector quantity representing wind direction and wind speed. The CIMO Guide, Part I, Chapter 5, gives a detailed description of wind velocity instruments, and their exposure, maintenance and calibration. The wind velocity sensors most commonly used for measurements on towers or masts are sonic, cup and propeller sensors with wind vanes, or hot-wire anemometers.

Sonic anemometers measure the time between emission and reception of an ultrasonic pulse travelling over a fixed distance. They have no moving parts; therefore, they have high durability and little accuracy deterioration. Sonic anemometers can be 2D or 3D sensors, and can be used for turbulence studies during good weather conditions (without precipitation).

Cup and propeller anemometers consist of two sub-assemblies: the rotor and the signal generator. The angular velocity of the cup or propeller rotor is directly proportional to the wind speed, or, more precisely, in the case of the propeller rotor, to the component of the wind...
speed parallel to the axis of rotation. A wind vane measuring wind direction is usually used as a separate sensor jointly with a cup anemometer, or can be integrated as a part of a propeller anemometer.

Hot-wire anemometers measure the cooling of thin, heated wires. They are sensitive instruments and can be used for short-time turbulence studies during good weather conditions (without precipitation). Operationally, they are rather unreliable, because of excessive fragility and because their calibration can change quickly in unclean or wet surroundings.

There are also remote wind-sensing techniques (CIMO Guide, Part I, Chapter 5) such as:

- Acoustic sounders – SODARs. These operate on the principle of scattering of acoustic waves by the atmosphere. Different types of acoustic sounders have been developed, but the two most common types considered for operational use are the monostatic SODAR and the monostatic Doppler SODAR. The maximum height that can be reached by acoustic sounders is dependent on system parameters, but also varies with atmospheric conditions. Low-cost systems can routinely reach heights of 600 m or more with vertical resolutions of a few tens of metres.

- Radar wind profilers. These are very high and ultra-high-frequency Doppler radars designed for measuring wind profiles in all weather conditions. These radars detect signals backscattered from radio refractive index irregularities associated with turbulent eddies with scales of one half of the radar wavelength (the Bragg condition). Profilers are able to operate unattended and make continuous measurements of the wind up to a few kilometres above the surface directly above the site.

- Wind lidars. Lidars are active remote sensors using lasers as emitters. They emit short pulses of light into the atmosphere. The emitted radiation encounters diffusion by atmospheric particles and molecules along the line of sight. Part of the radiation is scattered backward and collected by an optoelectronic device into the lidar reception system. The optical signal is then translated into a voltage over time and distance by multiplication of the speed of light. The wind lidar enables users to measure wind speed and direction profiles using the Doppler effect on small particles.

- Radiosounding systems (CIMO Guide, Part I, Chapter 12). These usually comprise a radiosonde (consisting of the sensors with references, an electronic transducer and the radio transmitter), carried by balloons and ground station equipment to receive and encode the radiosonde signal. Radiosounding systems usually enable measurements of wind, air temperature, humidity and pressure at different levels up to a height of 35 km.

- Rawinsonde and pilot-balloon techniques using optical theodolites (CIMO Guide, Part I, Chapter 13).

2. Precipitation

Precipitation is defined as the liquid or solid products of the condensation of water vapour falling from clouds or deposited from air onto the ground. It includes rain, hail, snow, dew, rime, hoar frost and fog precipitation. Precipitation can be measured as a total amount of precipitation that reaches the ground in a stated period, or as an amount of precipitation collected per unit time interval, known as precipitation intensity.

The CIMO Guide, Part I, Chapter 6, gives a detailed description of precipitation instruments, and their exposure, maintenance and calibration. For automated systems, at least two types of precipitation sensors are frequently used: weighing-recording gauge and tipping-bucket gauge.

In weighing-recording instruments, the weight of a container, together with the precipitation accumulated therein, is recorded continuously, either by means of a spring mechanism or with a system of balance weights. All precipitation, liquid and solid, is recorded as it falls. This type of gauge requires regular, manual emptying. Care should be taken to minimize evaporation losses,
by adding enough oil or other evaporation suppressants inside the container. The advantage of these instruments is the significantly reduced need for maintenance due to lack of any moving mechanical parts in the weighing mechanism, so only elastic deformation occurs.

The tipping-bucket raingauge uses a metallic or plastic twin bucket balance to measure the incoming water in portions of equal weight. When one bucket is full, its centre of mass is outside the pivot and the balance tips, dumping the collected water and bringing the other bucket into position to collect. The bucket compartments are shaped in such a way that the water is emptied from the lower one. The output from the sensor is generally a reed switch or micro switch. The contact closures from the switch are counted by a digital counter. Some tipping-bucket sensors are also equipped with heaters for measurements during winter conditions. To reduce loss of the collected precipitation from evaporation, it is necessary to equip the heaters with proportional temperature control.

Radars can provide remote-sensing measurements or continuous monitoring of precipitation. Meteorological weather radars are primarily designed for detecting spatial occurrence of precipitation and associated weather phenomena. They can provide an estimate of precipitation over a large area. Appropriately installed, calibrated and maintained modern radars are relatively stable and, in principle, do not produce significant measurement errors due to the stability of the hardware. However, maintenance and calibration of radars are still a considerable challenge and require highly qualified personnel. External physical factors, such as ground clutter effects, bright band, anomalous propagation, attenuation and propagation effects, beam effects and target composition, create artefacts in the data that must be removed during scientific data processing for use in quantitative applications.


3. Air temperature

Air temperature is most commonly measured by electrical resistance, semiconductor or thermocouple thermometers in screens, with or without aspiration. The CIMO Guide, Part I, Chapter 2, gives a detailed description of temperature sensors, and their exposure, maintenance and calibration.

Resistance thermometers should have the same physical and chemical properties throughout the temperature measurement range, and should be robust enough to avoid any external influences such as humidity, corrosion or physical deformations. Pure platinum best satisfies these requirements; therefore, platinum thermometers are widely used as operational sensors. Practical thermometers are artificially aged before use and are commonly made from platinum alloys, nickel and occasionally tungsten for meteorological purposes. They are usually hermetically sealed in a ceramic sheath.

Mixtures of sintered metallic oxides are suitable for making practical semiconductor thermometers (thermistors), which usually take the form of small discs, rods or spheres and are often coated in glass.

The least frequently used electrical thermometers for meteorological applications are thermocouples. They are made by welding or soldering together wires of the metals concerned. These junctions can be made small and with negligible heat capacity.

Thermometers of any type should be placed in a radiation shield or screen, designed in a way to provide an enclosure with an internal temperature that is uniform and the same as that of the outside air. The radiation shield or screen should completely surround the thermometer and exclude radiant heat, precipitation and other phenomena that might influence the measurement, and it should be naturally or artificially ventilated.

Vertical temperature profiles can be obtained from:
- Radio acoustic sounding systems. The technique consists of tracking a short high-intensity acoustic pulse that is transmitted vertically into the atmosphere by means of a collocated microwave Doppler radar. By measuring the acoustic pulse propagation speed, the virtual temperature can be calculated as it is proportional to the square of the pulse propagation.

- Microwave radiometers. Surface ground-based passive microwave radiometers measure the microwave thermal emission by oxygen in a spectral band near 60 GHz, enabling determination of the vertical temperature profiles of the lower atmosphere.

The CIMO Guide, Part II, Chapter 5, gives a detailed description of these ground-based remote-sensing systems.

4. **Humidity**

Atmospheric humidity is most commonly measured by relative humidity, which represents the ratio, in per cent, of the observed vapour pressure to the saturation vapour pressure with respect to water at the same temperature and pressure. The old psychrometric measurement method has been replaced by electronic hygrometers based on change in capacitance or resistance, and the chilled-mirror dewpoint hygrometer. The CIMO Guide, Part I, Chapter 4, gives detailed descriptions of humidity instruments, and their exposure, maintenance and calibration.

The dewpoint (or frost point) hygrometer is used to measure the temperature at which moist air, when cooled, reaches saturation and a deposit of dew (or ice) can be detected, normally optically on a solid surface that is usually a mirror. The most widely used sensors employ a small polished metal reflecting surface that is cooled electrically using a Peltier-effect device.

Vertical profiles of humidity can also be obtained by lidars or radiosondes.

5. **Air pressure**

The most widely used instruments for air (or atmospheric) pressure are electronic barometers, as they can be used in different applications and configurations considering low power consumption. The CIMO Guide, Part I, Chapter 3, gives a detailed description of atmospheric pressure sensors, and their exposure, maintenance and calibration.

Most barometers with recent designs make use of transducers that transform the sensor response into a pressure-related electrical quantity in the form of either analogue or digital signals. Digital piezoresistive barometers utilize the piezoelectric (piezoresistive) effect with a common configuration featuring four measuring resistors placed onto the flexible surface of a monolithic silicon substratum interconnected to form a Wheatstone bridge circuit. In digital piezoresistive barometers, axially loaded crystalline quartz elements are used. They are a type of absolute pressure transducer. Another variation of the pressure-measuring method is based on the displacement of the aneroid capsule that is measured by capacitive displacement detectors, potentiometric displacement detectors, strain gauges placed at strategic points on the sensor or force-balanced servo systems that keep the sensor dimensions constant regardless of pressure.

There are also cylindrical resonator barometers that use a sensing element which is a thin-walled cylinder of nickel alloy. This is electromagnetically maintained in a “hoop” mode of vibration. The pressure is sensed by the variation it produces in the natural resonant frequency of the vibrating cylinder whose wall movement is sensed by a pick-up coil.

Vertical profiles of air pressure can also be obtained using radiosondes.

6. **Specific indicators of atmospheric turbulence**

Direct indicators of atmospheric turbulence are fluctuations in meteorological conditions. Depending upon the model, turbulence should be indicated by using one or more of the following measurement data:

- Fluctuations in wind direction
- Air temperature and temperature lapse rate
- Wind speed and solar radiation or sky cover (daytime), and net radiation levels or sky cover (night-time)
- Vertical profiles of wind speed and air temperature

All these data can be obtained using the aforementioned measurement instruments and techniques.

2.2.2.5 **Data loggers and recorders**

The data logging and display system should be planned in a way to achieve (together with sensors) a suitable system either for special continuous measurements or for the special case study measurements. The uncertainty and resolution requirements must be at least of the same class as for the best sensor connected to the system.

2.2.2.6 **Maintenance and calibration**

The meteorological instruments and the logging equipment must be maintained to provide at least an annual 90% data cover. The maintenance and calibration programme for all the individual parts, as well as the measuring systems as a whole, must be developed and used in accordance with the best available practices and regulatory requirements.

2.2.2.7 **Quality control procedures**

Automated quality control procedures (data validity checking) should be applied at all automatic weather stations to monitor the quality of sensor data before their use in statistical and meteorological analyses (WMO, 2010, Appendix VI.2).

2.2.2.8 **Satellite observations**

In some instances, additional contribution to the meteorological investigations based on the surface-based meteorological measurements can be obtained by satellite observations (CIMO Guide, Part III).

2.2.2.9 **Summary of profiling systems**

Table 3 provides a summary of the performance and limitations of various available profiling systems.
### Table 3. Summary of performance and limitations of profiling systems

<table>
<thead>
<tr>
<th>System</th>
<th>Typical temporal resolution</th>
<th>Minimum to maximum altitude range</th>
<th>Measured parameters and their achievable measurement uncertainty</th>
<th>Benefits</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meteorological tower</td>
<td>144 profiles d⁻¹</td>
<td>2 m to ~200 m</td>
<td>Wind: 0.5 m s⁻¹ below 5 m s⁻¹, 10% above 5 m s⁻¹ Temperature: 0.2 K Relative humidity: 3% (WMO, 2018a)</td>
<td>Automatic 24 h–7 d In situ profile measurements</td>
<td>Limited vertical extension (below the planetary boundary-layer top) Maintenance cost</td>
</tr>
<tr>
<td>Radiosounding</td>
<td>2 profiles d⁻¹</td>
<td>2 m to 30 km</td>
<td>Wind: 0.2 m s⁻¹ Temperature: 0.2 K to 0.5 K Relative humidity: 5% to 10% (Nash et al., 2011)</td>
<td>In situ profile measurements High vertical resolution</td>
<td>Low temporal resolution Cost</td>
</tr>
<tr>
<td>SODAR (with Radio Acoustic Sounding System for temperature profiling)</td>
<td>48 profiles d⁻¹</td>
<td>40 m to ~2 km</td>
<td>Wind: 1.5 m s⁻¹ Temperature: 0.5 K (de Noord, 2005)</td>
<td>Automatic 24 h–7 d High vertical resolution</td>
<td>Noise Limited vertical extension (below the planetary boundary-layer top) Signal contaminated by precipitation</td>
</tr>
<tr>
<td>Low tropospheric radar wind profiler</td>
<td>48 profiles d⁻¹</td>
<td>100 m to 8 km</td>
<td>Wind: 1.5 m s⁻¹ (Haefele and Ruffieux, 2015)</td>
<td>Automatic 24 h–7 d High vertical resolution all-weather system</td>
<td>Possible contamination (by birds)</td>
</tr>
<tr>
<td>Wind lidar (continuous and pulsed)</td>
<td>48 profiles d⁻¹</td>
<td>10 m (continuous) to 8 km (pulsed)</td>
<td>Wind: 0.5 m s⁻¹ (Päschkle et al., 2015)</td>
<td>Automatic 24 h–7 d High vertical resolution</td>
<td>Signal completely attenuated in liquid clouds and precipitation</td>
</tr>
<tr>
<td>Microwave radiometer</td>
<td>144 profiles d⁻¹</td>
<td>100 m to 5 km 100 m to 5 km</td>
<td>Temperature: 0.5 K to 1.5 K Absolute humidity: ±0.4 g m⁻³ (Löhner and Maier, 2012)</td>
<td>Automatic 24 h–7 d High vertical resolution</td>
<td>Possible contamination by precipitation Low vertical resolution</td>
</tr>
<tr>
<td>Automatic lidar ceilometer</td>
<td>288 profiles d⁻¹</td>
<td>60 m to 15 km</td>
<td>Backscatter profile: 0.5 mm⁻¹ sr⁻¹ Planetary boundary height: 100 m (Haefelin et al., 2012)</td>
<td>Automatic 24 h–7 d High vertical resolution</td>
<td>Signal completely attenuated in liquid clouds and precipitation</td>
</tr>
</tbody>
</table>

#### 2.2.3 Hydrological observations

In addition to meteorological observations and data, observations relating specifically to the water cycle are needed for: rainfall, river level and river discharge; groundwater level;
evaporation (evapotranspiration); flood measurement; specific forecast and warning data for heavy rainfall and floods; and supporting contaminant fate and transport modelling. The observation network will need to be considered separately from the meteorological network. The Guide to Hydrological Practices (WMO, 2008a) provides full details of instruments used in hydrological measurements, and the selection of network structure and site requirements.

Station metadata for the existing networks with the NMHS must be collated as far as possible, to include: location information (geographic coordinates), site conditions (including accessibility arrangements), record length, holder of data, type of record (electronic or paper), type of instrument, instrument physical condition and so forth.

Most existing hydrological networks have evolved in a piecemeal manner in terms of instrumentation and for the types of applications required. Thus, a network designed for water resource evaluation will concentrate on the lower part of the flow range spectrum, as interest is focused on reliability of low flows. The distribution of stations in this sort of network and the design of measuring structures may not therefore be suitable for flood-flow measurement and estimation. Similarly, joint water quantity and quality applications are frequently not combined, as these activities may have historically developed under separate operational departments within the large framework of the water resources undertaking. Environment, conservation and fisheries are frequently operated as separate component organizations within an environmentally focused government department, and may also be subdivided into units to cover biological conditions as distinct from chemical/physical water quality measurement and pollution monitoring.

A primary purpose for obtaining and maintaining hydrological observations is to provide comprehensive characterization for the catchment and local area or larger river basin in which the NPP is located. This characterization will need historical data and a suitable network for ongoing monitoring. The methods for observation of rainfall were dealt with under section 2.2.2 above, but some specific aspects are particularly relevant to hydrology. These include:

- Establishment of a rainfall climatology, on a monthly, seasonal and annual basis.
- Estimation of extreme statistics, for rainfall excess or deficit.
- Provision of short-period rainfall characteristics, from subdaily to 5 d, to estimate probability and duration design data, and also depth and areal extent (storm volume). These may be referred to as depth–duration–frequency and depth–area–duration statistics.
- Establishment of precipitation phase data (rainfall versus snowfall), and spatiotemporal data on snow-covered area and snow-water equivalent.
- Provision of the required inputs for flood forecasting and warning, as well as drought monitoring and forecasting.
- Detailed analysis of particular historical extreme events, to cover floods and droughts.

The historical records, particularly for extreme events, must be compiled for as long as possible rather than for a climatological standard period of 30 years, as long there is confidence in data quality (see Box 1 in section 2.3.2 for data suitability evaluation). Results from their analyses may differ from general spatial data, which may be based on interpolated standard period data, derived from spatial analysis, for example specific discharges (in m$^3$ s$^{-1}$ km$^{-2}$) or more recently, from gridded datasets.

High-quality hydrometric instruments are widely available from commercial suppliers, and these are now invariably of an automatic, digital type. However, it is essential that instruments used by NPP operators or their contractors are compliant with WMO Technical Regulations. Instruments also need to be sited, as far as possible, in accordance with international and national standards. The great advantage of digital instruments is that as long as power supplies are adequate, they can operate with minimum attention for extended periods. However, it is highly recommended that a regular programme of checking and inspection is carried out, to ensure that the conditions
of housing and surrounding areas in the instrument compound are not interfering with the performance of measurement devices. This should include cutting of vegetation, for example, to prevent overshadowing of raingauges and climate station compounds by trees and long grass, or blockage of a river gauge inflow pipe by silt or aquatic weeds. The effective performance of batteries must be ensured, which can be achieved by following a strict routine for regular changing of batteries or providing suitable sources for recharging, for example, solar panels or small wind generators.

If conditions at the site permit, the overall performance of tipping-bucket raingauges should be checked against standard storage gauges, to ensure that the tip mechanism is functioning and volumetric measurements are congruent within acceptable error bands. Similarly, to monitor the performance of water-level recorders, they should have a staff gauge in the river adjacent to the recorder that can be measured manually when inspection visits are made.

Table 4 shows the relevant main topics relating to observations and guidance from the Guide to Hydrological Practices (WMO, 2008a).

### Table 4. Topics relating to observations in the Guide to Hydrological Practices (WMO, 2008a)

<table>
<thead>
<tr>
<th>Chapter topic</th>
<th>Section topic</th>
<th>Subtopics</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Methods of Observation</td>
<td>2.4 Design and evaluation of hydrological networks</td>
<td>Concepts of network design; appropriate station network density; operational data acquisition</td>
</tr>
<tr>
<td></td>
<td>2.5 Data collection</td>
<td>Site selection; regularity of station visits; maintenance; transmission systems</td>
</tr>
<tr>
<td>3. Precipitation Measurement</td>
<td>3.2 Raingauge location</td>
<td>Positioning and site exposure (standards)</td>
</tr>
<tr>
<td></td>
<td>3.3 and 3.4. Types of raingauge</td>
<td>Standard (storage) raingauges; recording raingauges (subdaily for example, tipping bucket); methods of recording subdaily rainfall</td>
</tr>
<tr>
<td></td>
<td>3.7 and 3.8. Precipitation observation by weather radar</td>
<td>Uses of radar observation; types of radar; radar networks</td>
</tr>
<tr>
<td></td>
<td>3.11 Observations of rainfall by satellite</td>
<td>Visible and infrared images; microwave radar; accuracy considerations</td>
</tr>
<tr>
<td>4. Evaporation, Evapotranspiration and Soil Moisture</td>
<td>4.1 Evaporation and evapotranspiration</td>
<td>Measurement of evaporation and evapotranspiration – instruments and remote-sensing</td>
</tr>
<tr>
<td></td>
<td>4.2 and 4.3. Estimating evaporation from free surfaces and drainage basins</td>
<td>Combination of aerodynamic and energy balance methods; empirical formulae; Penman–Monteith method; crop coefficient and reference evapotranspiration</td>
</tr>
<tr>
<td></td>
<td>4.5 Soil moisture measurement</td>
<td>Quantitative measurements; remote-sensing</td>
</tr>
<tr>
<td>5. Surface Water Quantity and Sediment</td>
<td>5.1 Water levels of rivers and other water bodies</td>
<td>Types of water level gauge; procedures and frequency of measurement</td>
</tr>
<tr>
<td></td>
<td>5.3 Discharge measurement and computation</td>
<td>Measurement by current meter or floats; indirect measurementsb</td>
</tr>
<tr>
<td></td>
<td>5.4 Stream (river) gauging stations</td>
<td>Site selection; measurement structures; stage-discharge relationships</td>
</tr>
<tr>
<td></td>
<td>5.5 Sediment discharge and yield</td>
<td>Measurement of suspended sediment and bed-load discharge</td>
</tr>
<tr>
<td>6. Groundwater</td>
<td>6.2 Occurrence of groundwater</td>
<td>Water-bearing geological units</td>
</tr>
<tr>
<td></td>
<td>6.3 and 6.4 Observation wells and groundwater-level measurements</td>
<td>Installation of observation wells; instruments and methods of observation</td>
</tr>
<tr>
<td></td>
<td>6.5 and 6.6 Aquifer and hydraulic properties; recharge and discharge of a groundwater system</td>
<td>Hydraulic parameter estimation; recharge from precipitation; groundwater–surface water relationships</td>
</tr>
</tbody>
</table>
### 7. Water Quality and Aquatic Ecosystems

#### 7.2 Requirements for water quality monitoring
- Surface and groundwater quality parameters; sediment quality

#### 7.3 Sampling methods
- Types of water samplers; collection of representative samples; field techniques

#### 7.6 Monitoring and sampling for biological analysis
- Micro and macro biological analysis; biochemical oxygen demand

### 9. Data Processing and Quality Control

#### 9.3 Coding
- Location codes; variable codes; missing data codes; transmission codes; geographic information systems (GIS)

#### 9.5 Primary processing activities
- Preliminary checking; data registers; data adjustments for errors; computation of derived variables

#### 9.6 Specific primary processing procedures
- Climatological data (including rainfall), streamflow data, water quality data: tabulation of daily, monthly and annual statistics

#### 9.8 and 9.9 General and specific validation procedures
- Routine checking of data; station inspection; water level and flow data; rainfall and climatological data; water quality and sediment data

### 10. Data Storage, Access and Dissemination

#### 10.2 Data storage and retrieval
- Storage methods; types of data and information to be stored

#### 10.3 Data retrieval
- Data analysis; extraction of single data items (interrogation); data retrieval system

#### 10.4 Data dissemination
- Catalogues of data availability; summary reports; yearbooks; data exports and exchange formats

### Notes:

* The chapter and sector topics are referenced by the numbering used in the Guide to Hydrological Practices (WMO, 2008a).

* Since the publication of the Guide to Hydrological Practices (WMO, 2008a), the use of ultrasonic flow measurement by fixed installations and by acoustic Doppler current profilers has become more widespread.

**Source:** WMO (2008a)

Further to the topics listed in Table 4, the following are stressed:

- Use of instruments compatible with those used by NMHSs and capable of recording and delivering data in as close a way as possible as those available from the NMHSs, for example, at the same quantitative definition and time intervals.

- Use of high-quality and proven instruments from established suppliers capable of providing long-term support, which includes service, repair and replacement.

- Maintenance of data-logging and processing systems and routines compatible with those used by NMHSs, for example, timing of observations and summary statistics, so that NPP operator records can be directly compared with those held by NMHSs.
2.3 DATA ANALYSIS

2.3.1 Meteorological and climatological data analysis

2.3.1.1 General procedure for assessing meteorological hazards

NPPs are designed to withstand some degree of magnitude of extreme meteorological events and to retain an acceptable level of operational integrity. This is why the design and operation of an NPP considers, with high priority, the inclusion of the effects of rare and extreme meteorological parameters and hazardous phenomena (with a view towards preventing damage to the installation and ensuring public health and safety) resulting from planned and inadvertent releases of radioactive material.

The general procedure for assessing the hazards associated with extreme values of meteorological parameters includes the following steps:

- Classification of parameters and events in terms of their effect on safety. The classification conducted in Meteorological and Hydrological Hazards in Site Evaluation of Nuclear Installations (IAEA, 2011), Chapter 4, should be retained here.

- Identification of available data sources. Ideally, long time series of meteorological variables measured at the site would be requested for developing a suitable climatology, and for evaluating the extremes of meteorological variables and phenomena. However, for most proposed sites, such information is not available. As an initial assessment, continuous data from existing off-site stations have to be looked at, and a first a priori selection of locations that are representative of the site and its surroundings can be done. Once the on-site measurement programme has been implemented for some time (a minimum of 2 years but preferably longer), the measurements can be used to identify off-site stations for which long-term records exist that are best correlated to the site. Measurements should be for standard meteorological quantities using a professional quality automatic weather station with additional equipment to monitor the vertical structure of the atmospheric boundary layer, such as instrumented masts and different types of profilers for wind, temperature and moisture. In the case where no representative long-term station can be identified, the previous edition of the present Guidelines (WMO, 1981, 1985) recommended that the off-site data be adjusted conservatively and used to approximate conditions for the site, provided that the adjustment is based on a statistical comparison of short-term near-site and off-site data. Nowadays, the use of meteorological NWP analyses and reanalyses at the mesoscale, available from many NMHSs, is recommended (see section 2.4).

- Statistical analysis of the probability distribution function meteorological variables being considered. This aims to provide the probability of occurrence of the variables exceeding different thresholds, with some confidence limits (see recommended methods in use in section 2.3.2.2). A similar analysis is also used for identification of the design phenomenon events. The data sample to be used is usually the time series of the annual extremes over a 30 year period or even more.

- Definition of the design-basis value for the variable or phenomenon. Design-basis values are derived from extreme value analysis of considered meteorological variables. The result is the value of the variable corresponding to a selected low probability of exceedance in a reference time slot (usually the expected lifetime of the facility), with an associated confidence interval. Chapter 3 deals with the specific issue of assessing hazards for NPPs.

2.3.1.2 Rarely occurring hazardous meteorological phenomena

Historical accounts, publications and records are a significant source of information on the occurrence of extreme weather events; however, this type of information is generally mostly qualitative.
Such extreme phenomena are unlikely to have their maximum intensity at a given place, and may not be observed by a fixed instrument network. They are, by nature, destructive, and it is possible that in some cases, standard instruments will be damaged or produce unreliable records of such an event at site level.

Two methods are generally used for evaluating the design basis for extreme meteorological phenomena:

- The deterministic method, based on knowledge of the physics of the phenomena. This can be used to develop a model. For a given input or a set of initial and boundary conditions, the model will predict a set of output values to describe the state of the system. To obtain extreme or conservative estimates, extreme or conservative values of the input parameters have to be used. Examples illustrating this approach are the Design-Basis Tornado and Tornado Missiles for Nuclear Power Plants of the United States of America’s Nuclear Regulatory Commission (USNRC, 2007), the probable maximum precipitation (PMP) and the probable maximum flood (PMF) (see section 2.3.2.2).

- The probabilistic method, based on statistical analysis of historical events to evaluate an extreme event with a given probability of non-exceedance. Sardeshmukh et al. (2015) discuss the need for caution in interpreting extreme weather statistics.

Cross-checking using the two approaches is recommended when feasible.

2.3.1.3 Statistical methods for analysing climatological datasets

The datasets of interest are essentially time series. Time-series analysis is addressed by many publications (for example, Klein Tank et al., 2009; WMO, 1990a, 1990b, 2007, 2018b) and statistical packages. First, an assessment of the consistency, quality, representativeness, completeness, stationarity of the time series and metadata, which are requested for further statistical analysis, has to be conducted. The Guide to Climatological Practices (WMO, 2018b) provides appropriate guidance and links to associated publications about best practices. All aspects of time-series analysis are covered including:

- Dataset evaluation: quality assurance/quality control (QA/QC), measurement of variability and confidence of measures (Klein Tank et al., 2009; WMO, 2018b).

- Data transformation: the normal or Gaussian frequency distribution is widely used, as it has been studied extensively in statistics. If the data do not fit the normal distribution well, applying a transform (for example, a logarithmic or power function) to the data may result in a frequency distribution that is nearly normal, allowing the theory underlying the normal distribution to be used.

- Frequency distributions: how the observed frequency distributions should be modelled by given statistical distributions so that statistical methods can be exploited.

- Standard climatological normals: these are averages of climatological data computed for consecutive periods of 30 years: 1 January 1901 to 31 December 1930, 1 January 1931 to 31 December 1960 and so forth. Climate normals are used for two principal purposes. They serve as a benchmark against which any observation can be compared. They are also widely used as a prediction of the conditions most likely to be experienced at a given location (Klein Tank et al., 2009; WMO, 2007).

- Extreme value analysis: classical approaches to extreme value analysis represent the behaviour of the sample of extremes by a probability distribution that fits the observed distribution sufficiently well (see section 2.3.2.1.3; Klein Tank et al., 2009; Von Storch and Zwiers, 1999).

- Goodness of statistical tests.
– Missing data, and time and space interpolation.

– Homogenization and metadata analysis: a homogeneous climate time series is defined as one where variations are caused only by variations in weather and climate. Unfortunately, most long-term climatological time series have been affected by non-climatic factors that make these data unrepresentative of the actual climate variation occurring over time, for example, changes in instruments, observing and processing practices, station locations and station environment. Therefore, it is important to remove the inhomogeneities or at least determine the possible error they may cause. Peterson et al. (1998) reviewed the different available techniques. Several freely available software packages have been developed for that purpose (see RClimDex in section 2.3.2.1.3).

2.3.2 Hydrological–hydrometeorological analysis

2.3.2.1 Methods of analysis

2.3.2.1.1 Hydrological data

The statistical analysis of hydrological data is almost the same as that used for meteorological variables: for establishing means and variations, probability and confidence limits. The magnitudes of extreme events and rare events are important for drainage and flood control design, and conversely in drought risk assessment. Therefore, rare events have to be considered for contingency and risk planning. The distinction between extreme and rare events cannot be rigidly defined, but it is imperative that all NPPs should demonstrate high degrees of resilience. Statistical analyses for coastal hazards used in the design and siting phase of NPPs can be different, and are addressed in Chapter 4.

The Guide to Hydrological Practices (WMO, 2009a), Chapter 4, presents the topic of analysis methods for water resources applications to water management. These are distinct from purely statistical analyses; there are some analytical methods specific to hydrological characterization. Figures 1 and 2 are means whereby the river flow at a given river measurement station can be visually summarized. The information plotted in both figures is the mean daily flow for the complete length of the station record, rather than a standard period.

The black line in Figure 1 shows the daily mean flow for a particular year; the upper (blue shaded area) delineates the value of the maximum flow on that particular day from all the years of the record; similarly, the red area delineates the lowest flows of a given day of the year. Thus, a plot of any year may be compared with the long-term flow characteristics. Figure 2 provides an example of a flow-duration curve, which is akin to a cumulative distribution function. In this figure, the red line is for the low-flow season, the blue line is for wet season conditions and the black line is for annual conditions.

2.3.2.1.2 Coastal storm surges

Coastal storm surge measurements are extremely lacking around the world. For this reason, most studies of surge extremes relevant to NPPs must create datasets synthetically, using hindcasting and forecasting techniques. Three main approaches to the statistical problem of surge extremes have now been developed and applied in studies around the world:

1. The historical storm method using parametric fits to surge data (usually obtained from numerical models forced by reconstructions of historical wind fields) (Cardone and Cox, 2009; Powell et al., 2010);

2. The joint probability method (JPM) in which a set of parameters used to characterize hurricane wind fields are combined within a multivariate distribution to represent a set of all storms that can occur in an area, with a subset of the combinations within the continuous distribution used to define the surge response at a given site;
3. The stochastic–deterministic method (SDM) in which a combination of physically based models and stochastic storm track behaviour is used to create a large set of synthetic storms (Emanuel et al., 2006).

In each of these approaches, the means of estimating extreme values are somewhat different. In the historical storm method, the analyses typically utilize the generalized extreme value (GEV) distribution or the generalized Pareto distribution (GPD) (Picklands, 1975; Leadbetter, 1991; Coles, 2001), but as tropical storms are relatively infrequent, they incorporate the Poisson frequency of such storms into the estimation of return periods:

\[ T = \frac{1}{\lambda(1 - F(\chi))} = \frac{1}{\text{AEP}(\chi)} \]

where \( \lambda \) is the mean frequency of tropical cyclones, \( T \) represents the mean return period for a surge level of \( \chi \), \( F(\chi) \) is the cumulative frequency distribution of \( \chi \) and \( \text{AEP}(\chi) \) is the annual exceedance probability of a surge equal to \( \chi \). The sequence of values of \( \chi \) in the equation represents the sequence of maximum surge in each individual event (storm) (that is, it is a distribution of largest values, either from a block of time or an exceedance of a threshold value).

In JPM, the storm wind fields are parameterized by a set of variables used to create detailed wind field needs for surge modelling. The multivariate probability structure is usually derived from an area that is considerably larger than that of the surge produced by a single storm; consequently, there is a gain in information content compared to that of the historical storm method (Irish and Resio, 2013). SDM uses an idealized model with a relatively unquantified epistemic uncertainty and requires many more storm simulations than JPM; however, it has a distinct advantage over JPM in that it can accommodate climate change within its basic framework.

2.3.2.1.3 Extreme value analysis

Many practical problems in hydrology and climatology require knowledge of the behaviour of extreme values of meteorological or hydrological parameters, in terms of frequency and intensity. A return period (or recurrence interval) \( T \) is defined as the mean interval of time, usually in years, between two occurrences of values equal to or greater than a given value (that is, the quantile of return value \( T \), or with a probability \( 1/T \)). This is an interesting concept, particularly

![Figure 1. Annual hydrograph of daily flows (red and blue envelopes respectively represent lowest and highest flow on each day over the period of record)](https://nrfa.ceh.ac.uk/data/station/info/36005)
at the design level, to avoid adopting too high safety margins that are overly costly, and also to prevent major damage to equipment and structures in case of extreme events that are likely to occur during their lifetime.

This is particularly true for the design of structures sensitive to large precipitation events and resulting streamflows (for example, sewer systems, dams, reservoirs, bridges, and residential and industrial properties), low streamflows, high wind speed (resistance of buildings, bridges, cranes, trees and electrical lines, causing excessive wind load) or heavy snowpacks (on roofs, electrical distribution systems and so forth).

Extreme events may broadly be considered as the events falling close to the high and low extremes of the data population that could be reasonably anticipated within the design life of the NPP. The *Guide to Hydrological Practices* (WMO, 2009a), Chapter 5, comprehensively covers this topic. Given that the general level of construction safety at an NPP will be conservatively derived, it is suggested that the design of internal drainage networks (rainfall runoff) should be adequate for the 100 year or 200 year level (1% and 0.5% probability). Annual totals, such as flow volumes, or rainfall depths, tend to be normally distributed due to forces described by the central limit theorem in statistics. Variability and probability assessments of these data can therefore be made on the assumption that the data range in terms of the mean and standard deviation of a data series can be assumed as fitting a normal distribution, as shown in Table 5. Monthly and weekly totals have less symmetric distribution, displaying a definite skewness that is mostly positive and cannot usually be modelled by the normal distribution. Distributions of annual extremes (high or low) are positively skewed and cannot be properly described by a normal distribution (WMO, 2009a).

**Table 5. Probability ranges of the normal distribution**

<table>
<thead>
<tr>
<th>Variability/confidence range</th>
<th>Probability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean ± one standard deviation</td>
<td>66</td>
</tr>
<tr>
<td>Mean ± two standard deviations</td>
<td>95</td>
</tr>
<tr>
<td>Mean ± three standard deviations</td>
<td>99</td>
</tr>
</tbody>
</table>
In many cases, the random variable corresponding to the logarithm of the considered meteorological or hydrological variable will be adequately described by a normal distribution, and is referred to as a two-parameter log-normal distribution. However, it has been found that the logarithms of a random variable $X$ are not distributed normally. The linear transform of these series requires the introduction of a third, or boundary, parameter taking logarithms, and is known as a three-parameter log-normal distribution.

The probability (frequency) assessments of discrete event items, for example, peak flows, low flows or storm event rainfalls, are better suited to fitting to some form of extreme probability distribution, which should describe the distribution of the largest or smallest value in a large sample. Two extreme value distributions are commonly used, although several other methods are available (for example, log-Pearson type 3 distribution, which has been one of the most frequently used distributions for hydrologic frequency analysis). Several approaches are briefly mentioned below, and the Guide to Hydrological Practices (WMO, 2009a) provides more information:

- **GEV (including Gumbel) distribution.** It has been shown that this is suited for representing many extreme value distributions of either hydrological or meteorological parameters. It has the advantage of combining, under a single formulation, the three types of distributions for extreme values originally derived by Fisher and Tippett (Coles, 2001; see Figure 3).

- **The peak over threshold (POT) method.** Adjustments by the GEV distribution or similar laws that use a single value every year may have a severe limitation when the data sample covers a limited number of years. An alternative is to select values above a chosen high threshold instead of a single annual maximum to enlarge the data size available for the analysis. The threshold has to be such that selected values are not correlated. In that case, the appropriate distribution function is GPD.

- **In the case of storm surges from specific sources (as required by the need for a statistically homogeneous sample), the GEV distribution is sometimes combined with a Poisson distribution to form a sample that is used to develop an annual exceedance probability of the type noted in section 2.3.2.1.2.**

- **Regional flood frequency analysis (RFFA).** Estimation of rare flood events in ungaged sites is often performed through RFFA. Methods of analysis are based on a prior aggregation of the hydrological data from different stations in a hydrologically homogeneous region to obtain regional flood information. One of the most widely used methods of RFFA is the Hosking and Wallis (1993) method when the so-called index flood method is combined with regional growth curves based on the method of L-moments.

The plotting position of ranked data is defined in terms of the rank and the total number of items in the data series. The Gringorten formula, as given below, is frequently used in conjunction with any of the above distributions to define the plotting position of each data item. The distribution function and plotting formulae are mathematical means of providing the best fit of data so as to achieve the optimum confidence level for assigning design event probability:

$$P(X) = \frac{r - 0.44}{N + 0.12},$$

where $P(X)$ is the probability of exceedance of an item of a ranked series of annual extremes, $r$ is the rank of an item and $N$ is the number of items in the series (Shaw et al., 2010).

The first step in extreme value analysis is to collect available data from a candidate station series for extreme analysis on the basis of series length, data completeness and homogeneity. Such data preparation is extensively described in the literature, for example, for the climate community in the Guide to Climatological Practices (WMO, 2018b), and for the hydrological community in the Guide to Hydrological Practices (WMO, 2009a). Several software packages are freely available for this purpose, like the RClimDex software developed by the Commission for Climatology/World Climate Research Programme (WCRP)/Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) Expert Team on Climate Change Detection and Indices (ETCCDI), which can be downloaded at https://www.wcrp-climate.org/etccdi, as well as various
guides for users. More generally, RClimDex is an easy-to-use software package for the calculation of climate indices, which includes preliminary calculations (QC of the data and tests of the time series for homogeneity) necessary to reach this objective.

The second step involves fitting a statistical model to the probability distribution of the considered extremes. Many publications cover statistical modelling of extremes. In addition to the two guides mentioned above (WMO, 2009a), the previous edition of the present Guidelines (WMO, 1981, 1985) includes a detailed analysis of meteorological and hydrological considerations for extreme variables and phenomena. Statistical Distributions for Flood Frequency Analysis (WMO, 1989) provides an extensive review of probability distributions and methods for estimating their parameters in hydrology. Finally, ETCCDI has published an excellent review on climate change and extremes (Klein Tank et al., 2009).

The data series must meet certain statistical criteria such as randomness, independence, homogeneity and stationarity (briefly defined in Box 1) so that the results of a frequency analysis

![Gumbel probability paper](image)

**Figure 3.** Examples of Gumbel and GEV distributions plotted on a Gumbel paper ($Q$ is the discharge in cubic metres per second)

*Source: J. Dent, United Kingdom of Great Britain and Northern Ireland*
are theoretically valid. Statistical tests can indicate only the significance of the observed test statistics and do not provide unequivocal findings. It is therefore important to understand the interpretation of the results and to corroborate findings with physical evidence of the causes, such as land-use changes. Caution is advised in interpolation and extrapolation when data do not meet the assumptions.

**Box 1. Statistical criteria for data suitability**

In a hydrological context, randomness means that the fluctuations exhibited by a variable arise from natural causes. For instance, flood flows appreciably altered by reservoir operation or abstraction are unnatural and therefore cannot be considered as random, unless the effect of the regulation is removed first (naturalized).

Independence implies that no observation in the data series has any influence on any following observations. Even if events in a series are random, they may not be independent. Large natural storage, in a river basin for example, may cause high flows to follow high flows, and low flows to follow low flows. The dependence varies with the interval between successive elements of the series: dependence among successive daily flow values tends to be strong, while dependence among annual maximum values is generally weak. Likewise, the elements of annual series of short-duration rainfall may, in practice, be assumed to be independent, but care should be taken in ascertaining the true duration of an event. Rainfall from a raingauge read at a set time each day can artificially split the measurement between two rainfall days.

Homogeneity means that all the elements of the data series originate from a single population, although the cause of the events may differ. For instance, a flood series that contains snowmelt and rainfall floods may not be homogeneous in cause, but reflects the unifying influence of the catchment, so, depending on the application of the results, it may be acceptable to treat it as such. When the variability of the hydrological phenomenon is too high, as in the case of extreme precipitation, non-homogeneity tends to be difficult to decipher, but non-homogeneity in yearly precipitation sums is easier to detect.

Stationarity means that, excluding random fluctuations, the data series is invariant with respect to time. Types of non-stationarity include trends, jumps and cycles. In flood analysis, jumps are generally due to an abrupt change in a basin or river system, such as the construction of a dam. Trends may be caused by gradual changes in climatic conditions and long- or short-term climatic oscillations, or in land use such as urbanization.

2.3.2.2 *Probable maximum precipitation and probable maximum flood*

The Manual on Estimation of Probable Maximum Precipitation (WMO, 2009b) gives a detailed review of all aspects of PMP and PMF.

PMP and PMF are considered to be outside the limits of high extremes that were discussed in the previous section. PMP and PMF events are considered to be at least two degrees of magnitude greater ($10^4$–$10^6$) than those events that may be considered as extreme events, as estimated by statistical methods. These methods of statistical extreme analysis are considered inappropriate above the $10^3$ or $10^4$ level (Stewart et al., 2010). As the probability function extends to low levels of probability, magnitude becomes asymptotic to the probability axis. In this way, PMP cannot be considered as having a specific return period, which can be related to results from an extreme probability analysis of an annual maximum dataset.

PMP is the theoretical maximum precipitation for a given duration under present-day meteorological conditions. There is a finite possibility that such a precipitation event could occur over the watershed relevant to the NPP during the design life of the plant. Such events may be associated with certain times of the year when the combination of conditions could maximize rainfall. Typically, these might be major cyclones, mesoscale convective storms or supercell thunderstorms. At these different scales, the optimum for producing PMP would be: high temperatures and humidity, persistence for several hours of inflowing low-level saturated air, enhanced convergence at low levels, rapid and deep upward convection and sustained divergence at high levels in the atmosphere, with the whole system remaining mainly stationary in its geographical position.
Under a combination of disadvantageous conditions in a catchment (a worst-case scenario), PMP could be converted into PMF – the theoretical maximum flood. Box 2 describes typical hydrological conditions to be considered in the case of determining PMF.

**Box 2. Features that contribute to the development of PMF**

Saturation of soils over large parts of the catchment, primarily due to a long period of persistent antecedent rainfall.

The presence of large depths of snow in upper reaches of rivers that rise in mountainous areas subject to large winter snowfalls.

Frozen ground, which renders surfaces impermeable to rain and meltwater.

Rapid rise in temperature over snow, ice and frozen ground producing a rapid thaw and release of stored water.

Ice in rivers that can cause temporary dams, as frequently occurs in large continental rivers.

River diversions resulting from bank and bed erosion.

Even though a combination of the causes of an extreme event may have a low probability of occurrence in some countries, the PMP/PMF approach is a statutory requirement for the design of major infrastructure, including dams, reservoirs and nuclear installations.

PMP/PMF may be considered as arising from a worst-case combination of physical circumstances. Wiesner (1970) gives a comprehensive review of PMP estimation. PMP/PMF estimation requires an approach that combines hydrology and meteorology and therefore requires close cooperation between hydrologists and meteorologists. The concepts and theories of maximization of physical processes in hydrology and meteorology should be considered. In this way, the PMP/PMF estimates may be optimized to reflect a balance between safety and cost-efficiency in project design. PMP storms, and their associated PMF floods, have physical upper limits. Due to the physical complexity of the phenomena and limitations in data in meteorological and hydrological sciences, approximations only are currently available.

There are six methods of PMP estimation used:

(a) Local storm maximization (local model);

(b) Storm transposition (transposition model);

(c) Temporal and spatial maximization of storm or storm combination (combination model);

(d) Inferential method;

(e) Generalized estimation;

(f) Statistical estimation.

In addition, two other methods can be used for deriving PMP/PMF in extremely large watersheds:

(a) Major temporal and spatial combination method;

(b) Storm simulation method based on historical floods.

A typical PMP analysis, using the combination method (c) above, will require a comprehensive set of temporal and spatial rainfall data. In addition to the historical rainfall data required for extreme event statistical analysis, the spatial and temporal distribution of rainfall data for specific large rainfall events is required. The plotting of isohyetal maps is a key requirement for PMP studies, as these provide the basis for depth–area–duration analyses over the catchment.
Maximization of the storm conditions relies on data of vertical atmospheric water content (dependent on temperature and humidity observations), and information of wind fields, distance from the sea and prevailing weather types. These data will need to be of sufficient duration to be used in probability estimates, for example, maximum persisting dewpoints (6 or 12 h duration at the 100 year level (1%)). Once the PMP structure has been defined as a storm profile, this will have to be convoluted with a design flood hydrograph, or used as input to a rainfall–runoff model to provide an estimate of PMF. The parameters of the design flood hydrograph also need to be maximized, usually by assuming worst-case conditions, for example for response time, catchment wetness and other antecedent conditions, position and movement of the PMP storm and river base flow.

2.3.2.3 Hydrological studies to support model development

The Guide to Hydrological Practices (WMO, 2009a), Chapter 6, contains a full discussion of the modelling of hydrological systems.

Observations and statistical estimation methods are rarely adequate to provide a basis for the complex hydrological information needed for the design and operation of an NPP. The complex interactions among individual meteorological and hydrological elements occurring in a geographical context are most often analysed through model studies, which are capable of producing meaningful outcomes and scenarios. The background information, data and observations noted above will form the basis of model studies and development.

There are two main types of hydrologic models (WMO, 2011a): catchment (or watershed) models, which simulate watershed response to meteorological (mainly precipitation) inputs, and routing models, which analyse transformation of the flood wave through a river channel system.

Catchment models simulate watershed runoff that generates on the catchment from meteorological forcing and catchment conditions. There are different catchment models used in modern hydrology – from empirical “black box” models to conceptual models, which tend to take into account physical processes on a watershed in simplified form, and so-called physically based models, which apply a detailed mathematical description of runoff generation processes on a watershed. The Guide to Hydrological Practices (WMO, 2009a) and the Manual on Flood Forecasting and Warning (WMO, 2011a) give detailed descriptions of model types.

Many aspects have to be considered when selecting and applying a catchment model, including the following: physical conditions of a watershed (to make sure a model covers all necessary processes, for example, snow dynamics in regions with moderate climate), data availability (the more complex the model is, the more data in temporal and spatial scales it demands) and institutional capacities to be able to support sustainable the model’s utilization in operational mode (periodic recalibration if needed, model updating and so forth).

The conceptual modelling approach has been developed over many years, and involves simulating the systems, concepts and physical processes of flow on the land surface, in channels and in groundwater. One of the most important and difficult aspects of applying conceptual models is to give the model comprehensive representativeness and successful calibration of a chosen model to a particular catchment. Most of the parameters included in models are determined by iterative processes for optimization – either by automatic or manual means, but both approaches use historical data as a basis.

The selection and development of hydrological models to define the related design parameters and safety assessment of an NPP installation basically has two choices: to devise a hydrological (catchment model) or to use an established model (or suite of models) that is structured, modified and calibrated to meet the specific requirement. It must not be assumed that a model developed successfully on one catchment can be directly transposed onto another without a detailed process of data selection and parameter estimation. Unless there are exceptional circumstances, it is recommended that an established model be used, and that this should be obtained from a proven commercial source. This has the advantage that the basic model
structures, algorithms, display features, database and information systems have been rigorously
tested and proven. A commercially acquired model will have comprehensive support for
development, maintenance and software upgrades.

The hydrological data used for model development are essentially the same as for wider
hydrological analysis. However, special attention and effort need to be given to ensure that
the specific purpose and focus of the model are addressed. For example, in providing a flood
prediction model for a given location or river reach, the correct time frame of incremental rainfall
measurement and flow prediction must be adopted.

A detailed hydrological model that needs to predict flood levels and timing of flows will require
subdaily data or continuous measurement, which is not necessarily the level of detail needed for
a water resources model. Depending on the nature and size of the catchment, special attention
may be required to model the rainfall–runoff response of subcatchment units. This is especially
important where a subcatchment exhibits particular characteristics, such as orographically
enhanced rainfall behaviour or marked influence of hydrogeological processes. Thus, if a
catchment is dominated by major aquifers, flow response may be suppressed through infiltration
and recharge, which may also result in prolonged base-flow release and groundwater flooding
long after the causative rainfall event has taken place. Such models, known as distributed
models, have become increasingly powerful since the inception of the Stanford Watershed Model
in the early 1960s. Modern freely available models, such as TOPMODEL (TOPography-based
MODEL), or TOPKAPI X, the extended version of TOPKAPI (TOPografic Kinematic Approximation
and Integration) (Ciarapica and Todini, 2002; Liu and Todini, 2002), or the commercial version of
SHE (système hydrologique européen), MIKE-SHE, are physically based distributed models that
account directly for the spatial and temporal variations in hydrological inputs and catchment
responses. While in TOPMODEL the spatial information is lumped into an overall mass balance
equation in time, in the TOPKAPI X and SHE models, discretization of the catchment is made
on a square grid, and thus the spatial data have, in some way, to be interpolated from point
measurement, for example, rainfall from point measurements and topography from contours
into a representative elevation for the unit in question.

In a major catchment with significant subcatchments and tributary streams, a complex model
may be required that simulates the routing of flows through the river system. Flood routing
models are used to simulate the timing of each catchment’s contribution into the trunk river. In
addition to the rainfall–runoff (or snowmelt–rainfall–runoff) behaviour of each subcatchment, a
routing component must be introduced to mimic the behaviour of the passage downstream of a
flood wave. This has to take into account the effects of combining flows, attenuation and losses.

Routing techniques are broadly classified as either hydraulic or hydrologic routing, based on the
complexity of the flood propagation process schematization. Hydraulic routing provides more
physically based description of the flow’s dynamics. However, it requires more sophisticated
data (details of channel sections) and much greater computational power. In contrast to this,
hydrologic routing techniques tend to model flood wave transformation using different forms of
approximations of the process. The Manual on Flood Forecasting and Warning (WMO, 2011a) gives
an overview of routing techniques.

The vast computing power of present-day computers allows the flow simulation to be carried
out by hydrologic routing through a system of interconnected river nodes, where nodes
represent individual river reaches that are treated as single inflow–storage–outflow segments.
This is mathematically defined as a lumped system, which can be solved through linear transfer
functions or lumped linear models such as the Muskingum model. Alternatively, non-linear
lumped models can be used such as the Muskingum–Cunge model. These fully conserve mass
and offer an effective technique for flood routing where detailed information on channel cross-
sections is not available. This is still the basis of a number of commercially supported software,
for example, the Infoworks package from Wallingford Software. This type of model needs to be
calibrated and verified using the relationships among gauged river sections, and decisions made
on dividing reaches in segments where the basic parameters of the channel and flood-plain can
be assumed to be the same.
However, the Muskingum–Cunge-type approach is somewhat simplistic, as the river is basically represented as a storage responding to upstream inputs. These models do not represent the hydraulic characteristics of river and flood-plain reaches. Hydraulic routing models using the concepts of dynamic hydraulics or hydrodynamics are widely available, using the solution of the Saint-Venant equations that govern gradually varying, non-steady flow in open channels. Initially applied through many software packages as one-dimensional channel flow models, the approach can be expanded to include variation in flow in the river and adjacent flood-plain, and these are termed 2D models.

Hydraulic models are now widely applied in flood mapping and modelling projects. Examples of widely used hydraulic models include the freely available HEC-RAS (Hydrologic Engineering Center River Analysis System) model and commercial MIKE 11 model. Another example is the use of LISFLOOD-LP, for flood simulation, and JFlow, to produce a national map of areas at risk of flooding in the United Kingdom. Many other software tools are available for usage. Hydraulic models require high-accuracy, high-resolution topographic survey information of flood-plains that can only be effectively achieved by lidar survey.

Once the channel and flood-plain structures have been carefully identified, including the characteristics of major structures like bridges, flood defences and so forth, the appropriate roughness factors have to be selected for the channel, its banks and the flood-plain surfaces. Roughness factors are the classical means of representing the energy loss due to friction, and hence replicating the water surface slope of the river. Values for a range of roughness factors are widely available in hydraulic engineering reference textbooks and via the Internet. There is a tendency to apply roughness values in a general way to channel and flood-plain sections. To obtain good results from a sophisticated hydraulic model, it is necessary to estimate local roughness and effective roughness, which represent all energy losses for each element. These must include:

- Form roughness as the channel geometry changes
- Interactions with obstructions, for example, trees and walls on the flood-plain
- Eddy and boundary shear changes where a channel flow moves out of the bank
- Depth-dependent shear and roughness, and the effects of bypassing meanders at high flow

In hydraulic models, the Saint-Venant equation, also known as the shallow-water equation, is inherently unstable, and most model numerical codes have automatic time-step controls to manage calculation instability. However, these can add time to model runs. Choice and adjustment of time steps are an important part of setting up and calibrating models. A further source of uncertainty in models is the specification of upstream and downstream boundary conditions. In the equations, depth and mean velocity are unknown, and have to be optimized. A simple example is whether the flow being modelled is on the rising or falling limb of the flood hydrograph (the hysteresis effect). Although the latest generation of hydraulic models are powerful and highly effective, their predictions, where possible, should be checked against field information, for example, flow measurements, flood and wrack marks on the flood-plain or structures.

As the power of computing increased over the past two decades, consideration has been given to the development and use of continuous flow simulation modelling, sometimes referred to as “whole catchment modelling”. This would, in theory, provide a platform for near-real-time modelling and offline models for a wide range of applications. Thus, a basic model could be used as a framework for water resources planning, design flood estimation and flood warning. However, it has proved impossible to achieve, largely through problems of conceptualizing the different types of hydrological behaviour and observations operating on different time and areal scales. Because of the different foci of studies relating to NPP safety, planners and operators will need to adopt separate approaches for whatever range of tasks are required and the necessary specialist expertise involved.
2.3.2.4  *Studies to support surge model development*

Given the lack of data, it is critical that all available historical data on water levels (from measurements, high-water marks and historical accounts) be used to help assess the storm surge threat and to provide data for model calibrations. Two factors work together to complicate the estimation of extremes for local site analysis. First, reliable meteorological data in most coastal locations around the world are typically limited to only a few decades at most. For risks in the range associated with most NPP designs, this requires extensive extrapolation to obtain usable statistical quantities from local records alone. Chapter 4 provides additional information on this.

Good-quality hydrographic mapping is also required for the littoral area and deeper sea locations. This is necessary for the development of tidal and surge models in the same way that topographical mapping is an essential part of hydrological and hydraulic models. Although international hydrographic mapping operations exist at national and international levels to aid shipping, some detailed scale mapping may be lacking. In areas where the coastline or estuary are geomorphologically active (for example, migrating sand bars and tidal channels), the local mapping needs frequent updating.

In addition to information needed for 1–3 d forecasting, there is a general lack of detailed information on tropical cyclones in many areas of the world. Much of the data used in long-term studies are taken from inferences of cloud patterns and post-storm forensics. Data that are critical for the quantification of storm surges along the coast, such as the radius to maximum wind speed, are usually not available. Information on tracks can be obtained from the International Best Track Archive for Climate Stewardship (IBTrACS; National Centers for Environmental Information (NCEI), 2016).

2.4  **METEOROLOGICAL (NUMERICAL WEATHER PREDICTION) ANALYSES**

This section summarizes techniques to create meteorological analyses useful to site evaluation for nuclear installation (IAEA, 2016a). The objective is to help assess the impact of the atmospheric environment on the NPP and of the NPP on the environment in case of a release of radioactive material.

2.4.1  *Available meteorological analyses*

The atmospheric planetary boundary-layer (PBL) height and meteorological parameters such as winds and temperatures in the boundary layer are key elements that influence conditions at the NPP and drive atmospheric transport and dispersion of pollutants in the atmosphere (see Figure 4).

PBL experiences a marked diurnal cycle (see Figure 5) and is influenced by synoptic and local weather conditions. Mountain–valley winds in complex topography, sea and lake breezes, and urban heat islands are all examples of commonly occurring local wind circulation that influences weather conditions at NPPs and atmospheric transport and dispersion. Features that drive these flows should be resolved in the meteorological analysis if the NPP site is located in complex terrain, near coastlines or in urban areas. The COMET MetEd training web page provides detailed training modules on these atmospheric boundary-layer processes:

- PBL processes in complex terrain:
  - [https://www.meted.ucar.edu/training_module.php?id=258](https://www.meted.ucar.edu/training_module.php?id=258)
  - [https://www.meted.ucar.edu/training_module.php?id=259](https://www.meted.ucar.edu/training_module.php?id=259)

- Sea breezes:
  - [https://www.meted.ucar.edu/training_module.php?id=8](https://www.meted.ucar.edu/training_module.php?id=8)
GUIDELINES ON METEOROLOGICAL AND HYDROLOGICAL ASPECTS OF SITING AND OPERATION OF NUCLEAR POWER PLANTS

- Mountain–valley breezes:
  
  [https://www.meted.ucar.edu/training_module.php?id=55](https://www.meted.ucar.edu/training_module.php?id=55)

- Tropical mesoscale and local circulation:
  
  [https://www.meted.ucar.edu/training_module.php?id=994](https://www.meted.ucar.edu/training_module.php?id=994)

High-resolution meteorological analyses or prediction (NWP) models are needed to simulate PBL correctly, as well as flows and meteorological parameters at local and regional scales near the NPP. These are available to NMHSs within the framework of the WMO Global Data-processing and Forecasting System (GDPFS) programme, including the Severe Weather Forecasting Demonstration Project. A list of meteorological model outputs through GDPFS is available at [https://community.wmo.int/activity-areas/gdpfs](https://community.wmo.int/activity-areas/gdpfs).

Several NMHSs have long-term meteorological analyses that can be used to assist with the evaluation of weather conditions at an NPP site location. These analyses assimilate standard and remotely sensed measurements. Parameters needed to evaluate NPP site location such as typical wind, mixing conditions (for example, mixing height and stability), temperature and rainfall can be retrieved from these analyses. The climatology can then be created by averaging over a number of years as a function of months, seasons or other specific periods.

Figure 4. Example of the influence of PBL and low-level winds on the height and movement of smoke near the surface

An alternative approach is to use a coarser-resolution NWP model analysis combined with downscaling techniques based, for example, on diagnostic statistical methods or the use of mesoscale NWP models. Draxler et al. (2015) provide a summary of some of the global meteorological analyses that are available for this.

Many NMHSs have implemented these techniques operationally, and others can request assistance from designated WMO centres as part of GDPFS services.

2.4.2 Methods for creating a representative analysis

Downscaling is a method to derive microscale to regional-scale information from larger-scale models or data analyses.

There are many statistical, physical and dynamic techniques to downscale coarser-scale meteorological analyses to the mesoscale (tens to a few hundred kilometres) or microscale (hundreds of metres). An excellent training module on downscaling NWP data is available at https://www.meted.ucar.edu/training_module.php?id=794.

Recognizing the amount of effort needed to develop a thoroughly tested and validated analysis and forecasting system, a range of options are described in the following. As mentioned previously, global meteorological analyses from NMHSs can be used. Regional and specialized analyses at higher resolution and targeted for near-surface weather are also available from some NMHSs.

In all cases, NPP analyses should be used as adjuncts, not substitutes, to instrumented observations.

Figure 5. Diurnal cycle of PBL height over land for a clear convective day (BL = boundary layer; L = layer; SBI = surface-based temperature inversion)

Source: Collaud Coen et al. (2014)
2.4.3 Diagnostic mass-consistent wind field analyses

Diagnostic mass-consistent wind field analysis techniques are often used by air quality regulatory agencies to capture complex wind flows affecting transport and dispersion of pollutants (Stohl et al., 1997).

Surface winds are interpolated to a regular grid, and some type of interpolation is performed that accounts for the effect of orography. Some mass-consistent downscaling techniques include:

- Inverse distance-squared weighting (Goodin et al., 1979)
- Inverse elevation difference weighting (Palomino and Martin, 1995)
- Upper-level wind data interpolated to the 3D grid
- Topographic effects, slope winds and blocking are parameterized (for example, CALMET (California Meteorological Model); Scire et al., 2000)
- 3D wind field adjustments to ensure conservation of mass (Moussiopoulos and Flassak, 1986; Brocchini et al., 1995)

2.4.4 Combined physical and statistical downscaling

A combined approach utilizes the physical adjustment with statistical corrections based on climatology. Wistral et al. (2017) describe a combined technique based on a statistical model that includes topographical influences on winds. The MeteoSwiss COSMO-7 model wind predictions at around 6.6 km horizontal resolution were downscaled by first correlating model error to topographical elevation and exposure (upwind or downwind of obstacles) at surface weather stations over Switzerland. Then, a corresponding topographical structure at a station was determined from 25 m resolution DEM data with similar corrections to the COSMO forecast made based on topographical structure. These resulting high-resolution terrain-dependent winds reduced the wind biases across various topographical elevations and exposures. Figure 6 shows an example of downscaled adjusted wind fields over Switzerland.

![Figure 6](image.png)

**Figure 6.** (a) COSMO-7 raw forecasted wind field and (b) downscaled to a 25 m resolution grid using high-resolution topographical fields. Note increases in wind speeds along ridge lines with enhanced differentiation between windward and leeward locations. Winds were primarily out of the west-southwest at this time.

2.4.5 **Examples**

2.4.5.1 **WindNinja diagnostic wind field model**

WindNinja is a mass-conserving diagnostic wind model developed and maintained by the United States Forest Service Missoula Fire Sciences Laboratory (Forthofer et al., 2014). It uses a variational calculus technique to minimize the change in the initial wind field from terrain differences while conserving mass locally and globally over the computational domain. WindNinja includes a diurnal slope flow parameterization that employs a one-dimensional model of buoyancy-driven flow along a slope. Buoyancy is determined from a micrometeorological model similar to the one used in CALMET (Scire et al., 2000), and is used to compute surface heat flux, Monin–Obukhov length and boundary layer height. The slope flow is then calculated as a function of sensible heat flux, distance to ridgetop or valley bottom, slope steepness, and surface and entrainment drag parameters.

An example of downscaling winds from the United State National Weather Service North American Model (NAM) at 12 km using WindNinja is shown in Figure 7 over the Big Southern Butte mountain range in south-east Idaho. A 30 m resolution terrain database is used in WindNinja to downscale NAM winds to 138 m. Flow around the Butte is completely missed by NAM but better captured after diagnostic downscaling.

2.4.5.2 **Uncoupled high-resolution land surface model**

Bernier et al. (2011) applied an uncoupled high-resolution land surface model over Vancouver for the 2010 Winter Olympic Games. This external high-resolution prognostic surface model is driven by a regional atmospheric model. The interactions between surface, biosphere and atmosphere surface scheme are integrated using downscaled atmospheric fields on a 100 m grid (140 km × 180 km). Local land characteristics are defined with the following datasets:

- Microscale topographic information from the Shuttle Radar Topography Mission DEM
- GlobCover, a global database, at 300 m and several Canadian databases

![Figure 7. Predicted (NAM and WindNinja) and observed winds for a downsloping event at Big Southern Butte, Idaho](source: Wagenbrenner et al. (2016))
Height differences between the high-resolution (100 m) grid and the low-resolution atmospheric forcing grid are computed and a constant atmospheric lapse rate of 0.0060 K m$^{-1}$ is used to adjust key meteorological fields to the high-resolution elevation grid. The downscaled fields include surface pressure, temperature, humidity and rate of precipitation. At low levels, the difference in elevation between the driving and high-resolution grids, together with the lapse rate, may lead to a phase change in the precipitation. In this case, the phase is adjusted while assuming conservation of relative humidity. Initial conditions of surface variables (for example, snow surface temperature and snow depth) are taken from the 24 h external microscale forecast of the previous day (Figure 8). This system is run operationally at a coarser resolution for all of Canada by the Canadian Meteorological Centre.

### 2.4.5.3 Real-time mesoscale analysis system

The National Oceanic and Atmospheric Administration (NOAA)/National Weather Service (NWS) variational Real-Time Mesoscale Analysis (RTMA) is executed at high resolution (2.5 km) to produce time-continuous 3D distributions of boundary-layer products, calibrated by measurements. The COMET MetEd web page gives more detailed information on using RTMA at [https://www.meted.ucCOMETar.edu/training_module.php?id=272](https://www.meted.ucCOMETar.edu/training_module.php?id=272).

RTMA, which is run by NOAA/NWS production over the United States of America, is an example of a high-resolution meteorological analysis. The RTMA suite of analyses comes from three sources with two running at the National Centers for Environmental Prediction (NCEP). An effective cloud amount is produced from GOES (Geostationary Operational Environmental Satellite) data by NOAA and the National Environmental Satellite, Data, and Information Service. An hourly analysis of raingauge observations and radar estimates of precipitation accumulation over the contiguous United States is produced at NCEP and is called the Stage II National Precipitation Analysis. For RTMA, this analysis is converted and interpolated to the 2.5 km NWS National Digital Forecast Database used by all NWS forecast offices to produce gridded forecast products.
The primary RTMA system component is based on a 2D application of the NOAA Environmental Modelling Center unified 3D variational analysis system called Grid-point Statistical Interpolation (GSI, Figure 9). GSI runs in the North American Mesoscale and the Global Forecast System. A 3D version of an assimilation system like GSI could be used in conjunction with a high-resolution 3D NWP model. This is the most expensive technique; therefore, the 2D RTMA approach can be used to create a longer-term and higher-resolution analysis of near-surface atmospheric conditions.

Using a first guess obtained by downscaling a 1 h rapid update cycle forecast from 13 to 2.5 km, RTMA performs an analysis of all surface observations (surface-synoptic, METAR, mesonet, ship, buoy and so forth) of temperature and dewpoint at 2 m and wind at 10 m above ground level. In addition, estimates of analysis uncertainty for each variable are also produced. Reducing the assimilation process to two dimensions enables the development of high-resolution analysis in real time for various applications. A high horizontal resolution analysis is essential for dispersion and air quality applications that are sensitive to fine-scale boundary-layer processes such as land–sea breezes, flows in complex terrain and urban heat island effects.

2.4.5.4 **Meteorological nowcasting systems**

Nowcasting is considered as forecasting with local detail, by any method, over a period from the present to 6 h ahead, including a detailed description of the present weather (WMO,
2017b). Such systems can catch weather phenomena with high spatial and temporal resolutions. Meteorological nowcasting systems can merge, in real time, observations from automatic weather stations, radars and satellites, forecasts of high-resolution NWP models, and high-resolution geographical and topographic data to obtain high-quality analyses that can be used in emergencies.

As an example, the Austrian Central Institute for Meteorology and Geodynamics has developed the INCA (Integrated Nowcasting through Comprehensive Analysis) system and applied for civil protection purposes in the Central European domain (WMO, 2016). INCA has also been used for the Olympic Games in Beijing (2008), Vancouver (2010), Sochi (2014) and PyeongChang (2018).

2.4.6 Integrated approach useful for atmospheric dispersion

High-resolution meteorological analyses can be used to help assess the atmospheric dispersion of radioactive material and help quantify concentrations and doses (section 3.5). These analyses better capture important atmospheric boundary-layer processes that influence the dispersion. The following integrated approach can be used:

(a) Collect basic meteorological and atmospheric turbulence parameters in time and space (section 2.2).

(b) Integrate these observations into a retrospective analysis or RTMA around the site through downscaling techniques. A PBL analysis can be created by ingesting on-site or nearby surface mesonets and the upper-level Aircraft Communication Addressing and Reporting System, profiler or lidar measurements through dynamic or statistical downscaling. Adequate meteorological analyses may also be obtained through the regional NMHS, which may have already run higher horizontal resolution (~ 4 km) weather analysis and forecast models. Typically, high vertical resolution (50–100 m) meteorological fields are also desired to accurately resolve boundary-layer information.

(c) Output from these analysis parameters that are important for dispersion modelling, such as:

(i) Surface and boundary-layer winds, temperature, moisture and pressure;
(ii) Mixed-layer depth;
(iii) Precipitation;
(iv) Cloud fraction, base and heights;
(v) Surface momentum, heat and moisture fluxes;
(vi) Estimates of mixed-layer turbulence (for example, turbulent kinetic energy, energy dissipation rate) and stability.

2.5 CLIMATE PREDICTIONS AND PROJECTIONS

2.5.1 Climate predictions

A climate prediction is a probabilistic statement about the future climate conditions on timescales ranging from seasons to decades. It is based on conditions that are known at present and assumptions about the physical processes that will determine future changes. Climate predictions are generally the products most eagerly sought for longer-term decisions and early warning of potential hazards. Predictions can be produced on the global, regional or local scales.
2.5.1.1  *Products from WMO Global Producing Centres for Long-Range Forecasts*

The process of computing long-range forecasts (climate predictions from 30 d up to 2 years) on the global scale requires huge amounts of computer power along with a specialized knowledge. For this reason, there are only a few centres around the world that are producing long-range forecasts. These centres are known as WMO Global Producing Centres of Long-Range Forecasts (GPCLRFs). The service provided by these centres sets the frame or context essential for predicting climate and weather on regional and local scales and is used by regional and local forecasting centres.

The websites of the Global Producing Centres give WMO global forecast products. WMO GDPFS also provides data forecasting products and information to NMHSs and WMO Regional Climate Centres (RCCs) around the world.

2.5.1.2  *El Niño–Southern Oscillation updates*

WMO produces an El Niño/La Niña update on a quasi-regular basis (approximately once in 3 months) through a collaborative effort between WMO and the International Research Institute for Climate and Society. The ability to predict the status of the El Niño/La Niña phenomenon is particularly important given its impact on global climate conditions.

2.5.1.3  *Predictions from WMO Regional Climate Centres*

Regional predictions are generally conducted by WMO RCCs. These are centres of excellence that assist WMO Members in a given region to deliver better climate services and products, including regional long-range forecasts, and to strengthen their capacity to meet national climate information needs.

2.5.1.4  *Products from Climate Outlook Forums*

In the mid-1990s, WMO, NMHSs, regional institutions and other international organizations initiated an innovative process known as the Regional Climate Outlook Forum (RCOF). The forums bring together experts from regions that are climatologically similar and provide consensus-based climate predictions and information. The information is usually based on the season that has the highest socioeconomic significance. This information has been applied to reducing climate-related risks and supporting sustainable development. Such forums now exist in many regions across the world.

2.5.1.5  *National climate prediction products*

National climate predictions are usually the responsibility of NMHSs. Many produce predictions on a seasonal scale as well as projections for climate change impacts. WMO keeps a list of all the websites of Member NMHSs, at the Members page of the WMO website (https://public.wmo.int/en/about-us/us/members).

2.5.2  *Climate projections*

A climate projection is usually a statement about the likelihood that something will happen several decades to centuries in the future if certain influential conditions develop. In contrast to a prediction, a projection specifically allows for significant changes in the set of boundary conditions, such as an increase in greenhouse gases (GHGs), that might influence the future climate. As a result, conditional expectations emerge (if this happens, then that is what may be expected). For projections extending well out into the future, scenarios are developed of what could happen given various assumptions and judgements. Section 7.1 details climate projections.
2.6 UNCERTAINTIES IN DATA AND MODEL ESTIMATES

2.6.1 Introduction

Uncertainty is an inherent part of the hydrometeorological observing and forecasting system. Estimating it is important and enables users to make better decisions. This section discusses how to estimate it. Section 2.9 presents how to communicate information about forecast uncertainty.

The following definitions are taken from the Guide to Hydrological Practices (WMO, 2008a) and the Manual on Flood Forecasting and Warning (WMO, 2011a).

Uncertainty: the interval about the measurement within which the true value of a quantity can be expected to lie with a stated probability. The numerical value of uncertainty \( e \) is a product of the true required standard deviation of the errors and a numerical parameter \( \alpha \) depending on the confidence level:

\[
e = \pm \alpha \sigma_y = \alpha s_y,
\]

where the standard deviation, \( s_y \), computed from \( n \) observations, approaches the true standard deviation, \( \sigma_y \), as \( n \) approaches infinity. The factor \( \alpha \) is a measure of the range of confidence probability (or uncertainty), as a multiplier to the estimate of \( s_y \). In the case of a normal distribution of error, values of \( \alpha \) are as given in Table 6.

<table>
<thead>
<tr>
<th>Confidence level</th>
<th>Multiplier ( \alpha ) for ( \pm ) range of ( s_y )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>0.674</td>
</tr>
<tr>
<td>0.60</td>
<td>0.843</td>
</tr>
<tr>
<td>0.66</td>
<td>0.954</td>
</tr>
<tr>
<td>0.80</td>
<td>1.282</td>
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<tr>
<td>0.90</td>
<td>1.645</td>
</tr>
<tr>
<td>0.95</td>
<td>1.960</td>
</tr>
<tr>
<td>0.98</td>
<td>2.326</td>
</tr>
<tr>
<td>0.99</td>
<td>2.576</td>
</tr>
<tr>
<td>0.999</td>
<td>3.291</td>
</tr>
</tbody>
</table>

Source: WMO (2008a)

The variations of estimates of mean and standard deviation over a range of record lengths can be illustrated by the following example for the annual maximum daily river flow series for the River Thames at Kingston upon Thames in the United Kingdom, which commenced in 1882. In addition to the statistics for the whole data series (130 years), the resulting average and standard deviation values have been calculated for successive 30 year periods, two consecutive 50 year periods and two 100 year periods. Table 7 summarizes the results.

Table 7. Estimates of mean and standard deviation of annual maximum flood at Kingston upon Thames (United Kingdom), for various record lengths

<table>
<thead>
<tr>
<th>Periods of estimate</th>
<th>Average maximum (m³ s⁻¹)</th>
<th>Standard deviation (m³ s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete record</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1882/1883 to 2011/2012</td>
<td>325</td>
<td>117</td>
</tr>
<tr>
<td>30 year periods</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1882/1883 to 1911/2012</td>
<td>301</td>
<td>143</td>
</tr>
</tbody>
</table>
### Periods of estimate

<table>
<thead>
<tr>
<th>Periods of estimate</th>
<th>Average maximum (m³ s⁻¹)</th>
<th>Standard deviation (m³ s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1912/1913 to 1941/1942</td>
<td>340</td>
<td>119</td>
</tr>
<tr>
<td>1942/1943 to 1971/1972</td>
<td>336</td>
<td>120</td>
</tr>
<tr>
<td><strong>50 year periods</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1882/1883 to 1931/1932</td>
<td>316</td>
<td>134</td>
</tr>
<tr>
<td>1932/1933 to 1981/1982</td>
<td>337</td>
<td>116</td>
</tr>
<tr>
<td><strong>100 year periods</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1882/1883 to 1981/1982</td>
<td>327</td>
<td>125</td>
</tr>
<tr>
<td>1912/1913 to 2011/2012</td>
<td>333</td>
<td>107</td>
</tr>
</tbody>
</table>

Source: Data from the Environment Agency, United Kingdom, processed by James Dent

Although estimates of the average are reasonably consistent over the different period lengths, the standard deviation estimates are more variable, thus demonstrating that caution should be used in applying multipliers for confidence or estimates of extremes (Table 6).

#### 2.6.2 Predictive uncertainty

Hydrological and meteorological forecasts have inherent errors and uncertainties. These forecasts are now predominantly model based, and all models are affected by different types of error such as:

- Model structural errors
- Model parameter errors
- Boundary condition errors
- Initial condition errors
- Observation errors
- Input forecast errors

All of these cause errors that amplify with increasing lead time of the forecast.

In theory, the degree and influence of all these errors should be accounted for to obtain an unbiased minimum variance forecast. From statistical theory, it is known how best to account for, and possibly eliminate, errors in forecasts. Following the statistical approach, each error source should be described through its probability density function and marginalized from the predictive probability. Unfortunately, most of the relevant probability densities are unknown and also extremely difficult to infer. Even the choice of model has a degree of error involved.

In flood management operations, there may be significant consequences due to timing or magnitude errors. Although a flood forecast has benefits, there is a problem in communicating uncertainty to the end users and decision-makers, such as water managers and emergency managers. Traditionally, predictive uncertainty stated for example, as: “the probability of flooding in the next 12 h is 66.5%” (that is, there is a 2/3 likelihood of the event happening but a 1/3 likelihood that it will not) is meaningless to a non-specialist end user. Flood forecasters must be able to explain the uncertainty as a form of utility function, allowing users to tailor their decisions to their specific needs (for example, using cost–loss estimation).
This is why, also considering the difficulty of accounting for all the above-mentioned errors in flood management operations, the new approaches tend to develop “uncertainty post-processors”, namely processors that convert the deterministic or probabilistic model forecasts into the “predictive uncertainty” now defined as the probability of a future outcome conditional to the model forecast (Krzysztofowicz, 1999). The resulting predictive uncertainty measure, a proper predictive probability density, which represents the best available knowledge on the future event, can be operationally used to trigger probabilistic thresholds for warning purposes (Coccia and Todini, 2011) or to operationally manage reservoirs by minimizing damages or risks (Todini, 2014).

2.6.3 Ensemble prediction system

Many NMHSs delivering meteorological analyses and forecasting products have developed an ensemble prediction system (EPS) allowing the assessment of predictability at all forecast ranges (short to medium range, monthly and seasonal timescales) and the investigation of methods to appropriately represent forecast uncertainty.

An ensemble forecast comprises multiple realizations for a single forecast time and location, which are intended to generate a representative sample of the future states of the weather. The user guide to the European Centre for Medium-range Weather Forecasts (ECMWF) forecast products provides comprehensive guidance on the use of ECMWF systems including detailed advice on the use of EPS (ECMWF, 2015).

The different realizations are generated through applying different perturbations to a single control forecast. For instance, the ECMWF weather prediction model is run 51 times from slightly different initial conditions. One forecast, called the control forecast, is run from the high-resolution (HRES) ECMWF analysis. An additional 50 integrations, the perturbed members, are made from slightly different initial conditions that represent equally probable analyses and are designed to reflect the uncertainties inherent in the HRES analysis. ECMWF (Richardson, 2015) and WMO (WMO, 2008a) provide different approaches to represent, quantify and communicate forecast uncertainty (see section 2.9).

It has been shown that the method of forecasting using different forecast models called “multi-model ensemble forecasting” significantly improves forecasts compared to a single-model approach, especially when each model is adjusted for its biases. The approach is named “super ensemble forecasting”.

These techniques have been deeply explored within the Observing System Research and Predictability Experiment (THORPEX), which is an international research and development programme to accelerate improvements in the accuracy of 1 d to 2 week high-impact weather forecasts. THORPEX establishes an organizational framework that addresses weather research and forecast problems whose solutions will be accelerated through international collaboration among academic institutions, operational forecast centres and users of forecast products.

WCRP TIGGE (THORPEX Interactive Grand Global Ensemble) is a key component of THORPEX, focusing on the above objective, extensive data sharing and research. The data are available to the public and for non-commercial research from ECMWF at https://confluence.ecmwf.int/display/TIGGE.

Nowadays, ensemble predictions are produced operationally at most of the major weather prediction facilities worldwide. Ensemble forecasting is used to account for uncertainty. There are various ways of viewing the data, where different results from the models run can be compared.

The Guidelines on Ensemble Prediction Systems and Forecasting (WMO, 2012) are intended to provide some general advice to forecasters and forecast providers on the effective use of EPS, and on what EPS can be expected to provide.

The basic model output product generation includes the following (WMO, 2012):
(a) Ensemble mean and spread (Figure 10);

(b) Probability, that is, the proportion of the ensemble members that predict an event to occur at a particular location (Figure 11);

(c) A set of quantiles of the ensemble distribution, which can provide a short summary of the uncertainty – commonly used quantiles are:

(i) Terciles (especially for seasonal forecasting, see Figure 12);

(ii) The maximum and minimum of the ensemble distribution, and the 25th, 50th (median) and 75th percentiles;

Others often used include the 5th, 10th, 90th and 95th percentiles;

(d) Spaghetti maps, where a meteorological variable is drawn on a chart for all the model runs from the ensemble, over the lead time of the forecast (Figure 13);

(e) A set of postage stamp maps showing contoured plots of each ensemble individual member, allowing the forecaster to view the scenarios in each member forecast and assess the possible risks of extreme events (Figure 14);

(f) Site-specific meteograms, which show the dispersion in the forecast for a single given meteorological variable (Figure 15).

Figure 10. ECMWF ensemble mean and spread for mean sea-level pressure. On the left panel, the contours represent the average (mean) of the ensemble – known as the ensemble mean. On the right panel, the contours show, for comparison, the single higher-resolution forecast. The spread within the ensemble is also represented on each panel, using coloured shading. On the right panel, spread is simply represented as the standard deviation. The left panel shows the normalized standard deviation, that is, the standard deviation from the right panel divided by a mean standard deviation.

Source: ECMWF, https://www.ecmwf.int/en/forecasts/charts/catalogue/plot_ensm_essential?facets=Range,Medium%20(15%20days)%3BParameters,Mean%20sea%20level%20pressure&time=2019112712,0,2019112712&parameter=MSLP&area=Europe
Figure 11. Possible temperatures with associated levels of confidence

Figure 12. Calibrated 3 month forecast probability of above-normal, near-normal and below-normal temperatures

Figure 13. ECMWF ensemble forecasts of monthly mean NINO3.4 sea-surface temperature (SST) anomalies with respect to the 1981 to 2010 climate issued on 1 December 2015; the dotted line shows the observed evolution of SST anomalies


2.6.3.1 Verification

The overall purpose of verification is to ensure that products such as forecasts and warnings are accurate, skilful and reliable.
Figure 14. Ensemble “postage stamps” of Hurricane Joaquin; different members of this 3 d high-resolution and ensemble forecast for Joaquin from 00 Universal Time Coordinated (UTC) on 29 September 2015 indicated different scenarios for the strength of the hurricane vortex and outflow configurations.


Figure 15. Example of predicted maximum and minimum temperatures at 6 hour intervals for each day at the given location. Forecast distributions are displayed using a box and whisker plot, which shows the median (short horizontal line), the 25th and 75th percentiles (wide vertical box), 10th and 90th percentiles (narrower boxes) and the minimum and maximum values (vertical lines).

Source: ECMWF, [https://www.ecmwf.int/en/forecasts/charts/web/classical_meteogram?facets=undefined&time=2019112900,0,2019112900&epsgram=classical_10d&lat=51.57&lon=-0.83&station_name=Reading,%20United%20Kingdom](https://www.ecmwf.int/en/forecasts/charts/web/classical_meteogram?facets=undefined&time=2019112900,0,2019112900&epsgram=classical_10d&lat=51.57&lon=-0.83&station_name=Reading,%20United%20Kingdom)
The Guidelines on Performance Assessment of Public Weather Services (WMO, 2000) provide general guidance, especially from the point of view of verification of products delivered to users.

The WCRP/WMO Working Group on Numerical Experimentation Joint Working Group on Forecast Verification (https://www.wmo.int/pages/prog/arep/wwrp/new/jwgfvr.html) describes methods of forecast verification, including their characteristics as well as their advantages and disadvantages.

Among them, the Brier skill score (BSS) and the relative operating characteristic (ROC) are frequently used by producers of weather and climate forecasts. BSS establishes the relative skill of the probabilistic forecast over that of climatology, in terms of predicting whether or not an event occurred, while ROC quantifies the ability of the forecast to discriminate between events and non-events.

WMO has a dedicated Lead Centre for Long-Range Forecast Multi-Model Ensemble (https://www.wmolc.org) with links to verification results for each of the Global Producing Centres (https://www.wmolc.org/seasonVrfyFcstUI/plot_VrfyFCST).

2.6.3.2 Probabilistic nowcasting

Ensemble nowcasting systems are increasingly being developed, in addition to EPSs. The uncertainty information is usually provided by a high-resolution NWP EPS and by the error estimates of the observations processed (surface observations, radar, satellite data and so forth). Highly resolved probabilistic nowcasts can facilitate decision-making in an emergency situation, as deviations between model forecasts and measurement data are better represented (WMO, 2017b).

2.6.4 Further thoughts on uncertainty

It may be noted that the statistical methods used in meteorology and hydrology are essentially similar, dealing with observational datasets intended to estimate means, variations and extremes. These data are primarily time series sets (annual or monthly totals), which will exhibit the characteristics of the normal distribution. Some datasets such as 1 d rainfall or river discharge will conform to a skewed distribution, with a few large values and mostly low-magnitude or zero values. Annual maximum or minimum series are normally analysed by fitting an exponential function, which is commonly used in meteorology and hydrology to estimate probability (frequency or return period) of a given magnitude of event (Shaw et al., 2010).

There are always inherent uncertainties in data relating to water and flow pathways that exist outside of data and observation errors and uncertainties noted in section 2.6.2 above. The nature of meteorological and hydrological data observations is that they are based on spatial sampling, requiring point data to be interpolated or extrapolated over a catchment area. Some specific hydrological measurements are indirect, for example, the estimation of river flow by means of rating curves or the estimation of evapotranspiration through mathematical relationships.

Some fluxes, especially those relating to deep groundwater storage and discharge, are ignored as they are difficult to measure. These relationships are accommodated by “sinks”, to adjust and optimize the calibration of groundwater and water resources models. A similar situation exists with the identification of incremental flow between nodes, and ungauged points in river reaches.

The uncertainties of data measurement will be compounded by the need to create a “best fit” for models, although this approach can include the quantification of uncertainty, for example, a flow estimate can be assigned a ± range. However, it is recognized that processes may be too complex to model efficiently, so the model may be simplified or truncated. Hence, in some water engineering applications (for example, dam safety), there is a move to risk-based assessments rather than rigid use of probability (for example, that a dam or river protection work is designed to specified probability criteria). The risk-based approach takes into account the potential
impacts and consequences of a certain situation. The appreciation and understanding of uncertainty and its implications is an active field of study, and inherently related to the evolution of data sources, measurement techniques and so forth.

2.7 CLIMATOLOGICAL PRODUCTS

There is a large variety of climate products tailored and suitable for use in nuclear power activities. Tailored may have two meanings here:

(a) A systematic operational production made available freely to all users, considered by them as suitable for their objectives. The different types of climatological data and products of this kind are described in several publications, for example:

(i) Guide to Climatological Practices (WMO, 2018b);

(ii) Manual on the Global Data-processing and Forecasting System (WMO, 2017a);

(iii) International websites about climatological data and related products (for example, http://www.wmo.int/pages/prog/wcp/index_en.html#WCSP);

(iv) World Data Centres, such as NOAA NCEI (https://www.ncei.noaa.gov/);

(v) The series of IPCC Assessment Reports (IPCC, 2013, 2014b);

(vi) The ETCCDI website on climate indices (http://etccdi.pacificclimate.org/list_27_indices.shtml);


(viii) NMHS websites.

(b) Specific climate data and products made available to a single user, on request. In this case, data supply between NMHSs and operators of NPPs generally requires that formal arrangements be established, covering the types of activities to be covered, data and products required, their frequency of delivery, the reliability of the service and quality indicators.

Resolution 40, adopted at the twelfth World Meteorological Congress (WMO, 1995), and Resolution 25, adopted at the thirteenth World Meteorological Congress (WMO, 1999), give the WMO policies and practices for the exchange of meteorological (and hydrological) and related data and products, including guidelines on relationships in commercial meteorological activities. They make a distinction between:

– Essential data: data and products to be exchanged without charge and with no conditions on use

– Additional data: it is understood that WMO Members may be justified in placing conditions on additional data re-export for commercial purposes for reasons such as national laws or costs of production

Resolution 60, adopted at the seventeenth World Meteorological Congress (WMO, 2015b), is the WMO Policy for the International Exchange of Climate Data and Products to Support the Implementation of the Global Framework for Climate Services. It adopts the policies, practices and guidelines of Resolution 40 and Resolution 25 for the exchange of GFCS-relevant data and products.
At the national scale, the essential climate-related activities are conducted by NMHSs, and cover the following:

(a) Observations:
   (i) Management of observational networks;
   (ii) Data management including archiving, QA/QC and data rescue;
   (iii) Analysis of historical and real-time observations of the Global Climate Observing System essential climate variables (see https://gcos.wmo.int/en/essential-climate-variables and section 7.1 about climate indices);
   (iv) Contribution to the WMO Global Observation System;

(b) Operations:
   (i) Generation of climate information (normals, other statistics and extremes) and weather and climate prediction products (including the linkage with GPCLRFs, RCCs and RCOFs);
   (ii) Tailoring and downscaling;

(c) User interface:
   (i) Climate analysis, diagnostics and assessments: many NMHSs are now offering regional climate change reference scenarios based on representative concentration pathways (RCPs), from which socioeconomic sectors can derive specific impacts;
   (ii) Provision of climate services based on historical climate data, and of operational climate predictions (for example, seasonal);

(d) Capacity-building.

IPCC and IAEA have expressed their views on nuclear power and climate change, essentially with regard to nuclear power being an effective GHG mitigation option (IPCC, 2013, 2014b; IAEA, 2014, 2015). To better tackle issues raised by the impact of climate change on nuclear facility design and operation, an international framework is probably necessary, in close cooperation with IAEA, WMO and other relevant partners.

Based on information gathered through extensive consultations with governments, users, scientists, and operational observing and information systems, the World Climate Conference-3 (2009) proposed to establish GFCS (see http://gfcs.wmo.int). The main goal was to “enable better management of the risks of climate variability and change and adaptation to climate change, through the development and incorporation of science-based climate information and prediction into planning, policy and practice on the global, regional and national scale”.

GFCS is a global partnership of governments and organizations that produce and use climate information and services, managed by the Intergovernmental Board on Climate Services. It seeks to enable researchers, producers and users of information to join forces to improve the quality and quantity of climate services worldwide, particularly in developing countries.

The components of GFCS (https://www.wmo.int/gfcs/components-of-gfcs) are:

1. A User Interface Platform, to provide ways for climate service users and providers to interact and improve the effectiveness of the framework and its climate services;
2. A Climate Services Information System, to produce and distribute climate data and information based on the needs of users and agreed standards;
3. An Observations and Monitoring programme, to develop agreements and standards for generating necessary climate data;

4. A Research, Modelling and Prediction programme, to harness science capabilities and results to meet the needs of climate services;

5. A capacity-development programme, to support the systematic development of the institutions, infrastructure and human resources needed for effective climate services.

All climate-sensitive sectors can and will benefit from climate services. As a first step, a High-Level Taskforce has identified (WMO, 2011b) the following as urgent priorities and where the most short-term benefits could be obtained:

- Agriculture and food security
- Water
- Health
- Disaster risk reduction
- Energy

Most of these are relevant to the nuclear power sector.

2.8 SOURCES OF AND ACCESS TO METEOROLOGICAL AND HYDROLOGICAL INFORMATION AND PRODUCTS

The main sources of and access to meteorological and hydrological information are:

- National or regional meteorological and hydrological management services
- Global databases of meteorological data
- Site-specific operation, either by NPP operators or their contractors
- Specialist reference libraries (for example, the Met Office Library, the Institution of Civil Engineers and national archives)

The arrangements made will also depend on whether the NPP is at the planning, development, construction or operation phase. Before operation, the studies required will most probably be carried out by consultants and contractors or NMHSs, building on the existing networks and databases available. Specialist consultants will have the expertise and knowledge to address the various aspects of meteorological and hydrological topics required, and this knowledge should extend to the availability of data and information sources.

NMHSs will have the authority to maintain national network data and have a service obligation to provide such information to users. Depending on the way NMHSs operate, these data may be available free of charge, or under some charging arrangement. It should be noted that NMHSs may have data in standard formats (for example, daily values and averages), and it is likely that the requirement for the NPP will need more specialist data (for example, instantaneous or short-term data, occasional or irregular measurements) such as might be obtained from drought or flood event surveys. Obtaining such data may require the development of a direct arrangement between NMHSs and NPP staff.
2.8.1 **History of catchment flooding**

Data on catchment flooding should not be limited to recent electronic data, and may be obtained from:

- Archive sources, for example, newspapers, photographs and municipal records
- Historical sources such as chronicles and ancient publications
- Flood marks on bridges and riverside buildings
- Past editions of topographic maps

Information should be sought from general archive sources, especially newspapers and photographs. Older historical records are available from municipal authorities, estate archives and even chronicles from religious establishments. Flood marks on bridges and buildings can be highly specific in helping to identify potential present-day flood impacts, for example, the Elbe floods at Dresden (Germany) in 2002 could be compared against a record of permanent flood markers on a bridge, extending back almost 200 years. Such non-technical historical records are useful where data-based information is limited, but they are also helpful as a check on recorded data. There is an unfortunate propensity in flood analysis to use only the easily available, electronic format records, and ignore a wealth of information that can be gleaned through intelligent investigation.

Older editions of topographic maps can also be useful as they show settlement and communications prior to modern developments. These maps may show flood-plains and river crossings before the expansion of towns and most major engineering and road developments, which have often ignored the presence of flood risk areas. Old maps can also show the different courses that rivers occupied in the past. This demonstrates the dynamic instability of rivers, highlighting the potential for a change of river course or structural failure during an extreme event.

All sources need to be identified, not just the easily obtained electronic data, which may have limited extent in time. Now that many data are available electronically, printed sources must not be ignored. For example, in the investigation for the building of a new NPP for Hinkley Point in the United Kingdom, data were obtained from the relevant British rainfall annual publication for an extreme event locally in 1924.

Some sources may be anecdotal, for example, from the press and old maps. Table 8 shows examples from the British Hydrological Society’s Chronology of British Hydrological Events (see [http://cbhe.hydrology.org.uk/](http://cbhe.hydrology.org.uk/)), which is specifically for the River Ouse catchment in the United Kingdom.
Table 8. Extracts from the British Hydrological Society’s Chronology of British Hydrological Events

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>1866</td>
<td>11</td>
<td>15–17 November 1866, “The Ouse at York rose 15 ft. above its ordinary level.”</td>
</tr>
<tr>
<td>1866</td>
<td>11</td>
<td>15–17 November 1866, “The Aire at Leeds rose higher than had ever been known before.”</td>
</tr>
<tr>
<td>1866</td>
<td>11</td>
<td>15–17 November 1866, Rainfall observer at Halifax (Well Head) noted, “On 15th and 16th 3.25 inches of rain, and between 13th and 17th 4.25 inches, the result being destructive floods in all the West Riding and Lancashire valleys. In the valley of the Calder the flood far exceeded anything within memory, and no old flood marks are so high as the present ones.” [R. Calder]</td>
</tr>
<tr>
<td>1872</td>
<td>6</td>
<td>18 June 1872, Rainfall observer for Otterburn-in-Craven noted, “The destruction of floodgates, culverts, and small bridges on the streams flowing down the sides of these ranges into the Ribble and Wharfe valley was enormous on this day.” [R. Wharfe; Upper R. Ribble]</td>
</tr>
<tr>
<td>1872</td>
<td>6</td>
<td>24 June 1872, Rainfall observer for Thorganby (Thicket Priory) remarked, “...these continuous thunderstorms have caused greater floods than have been known for 42 summers.” [R. (Yorkshire) Derwent]</td>
</tr>
<tr>
<td>1872</td>
<td>9</td>
<td>26–28 September 1872, Thunderstorm and floods in N. Yorkshire.</td>
</tr>
<tr>
<td>1900</td>
<td>7</td>
<td>12 July 1900, “Bradford Beck drains an area of 10 915 acres. At Bradford Exchange, rain between 3.10 p.m. and 6 p.m. was 1.31 inches. In the higher reaches of the Beck a violent storm was raging before the storm commenced in the lower part of the city ... the storm travelled down the valley and reached Bradford Exchange 1 hour and 25 minutes after it had reached Brayshaw-about 3 miles away. On the high steep hills 3.30 inches fell in 3 hours. At Bradford Exchange 0.86 inches fell in 20 minutes. This enormous excess of water flooded Amblers Works and all the other works on the Beck, flooded all the shops and warehouses in the lower part of the City—turned Market Street, Forster Square, etc. into rivers, causing great loss ... over a large area. In general—wrought havoc and devastation the like of which was never before known. At Shepley, Bingley, Morton, Ilkley, low lands flooded for many miles along the course, uprooting trees, removing immense boulders. At Ilkley, bridges and houses were swept away. At Bingley, the Midlands Railway stood in a sea of water. At Sunnydale or Morton Beck-drainage area of 1 000 acres on which 4 inches fell in 2 hours—old disused reservoir constructed over 60 years ago—waste weir 30 feet wide by 3 feet deep - never before known to be full—only not full, but 9 inches in depth of water passed over the whole length of the embankment—equal to 61 000 cubic feet per minute.”</td>
</tr>
<tr>
<td>1901</td>
<td>11</td>
<td>11–12 November 1901, Rainfall observer for Todmorden (Fielden Hospital) noted, “Heavy rain resulting in one of the worst floods known; many parts of the town were covered to a depth of several feet.” [Calder]</td>
</tr>
</tbody>
</table>

Source: British Hydrological Society, University of Dundee, http://cbhe.hydrology.org.uk/

2.8.2 History of dangerous weather events

In a similar way to flooding, information on some dangerous weather events should also be obtained from archive sources. Thus, maximum possible wind speed in some areas of the European part of the then Union of Soviet Socialist Republics (USSR) was estimated indirectly taking into account descriptions of storms and intensive whirlwinds damage (trees torn up by the roots, broken wooden houses and so forth) according to Borisenkov and Pasetsky (1988). Information on unusual weather activity on the USSR territory since the eighth century on the basis of about 30 chronicles and 400 other literary sources was available. The study also used, for data correction on extreme rainless period duration, maximal snow depth, temperature extremes (since the eighteenth century) and other meteorological parameters included in publications
on atomic engineering. These data were considered when calculating wind, ice, snow and temperature loads and effects of rare occurrence (once in 10,000 years). Sufficient water quantity and quality are of great importance for secure performance of NPP cooling systems. Therefore, maximal rainless period duration must also be taken into account.

2.9 QUALITY MANAGEMENT, COMMUNICATION OF INFORMATION AND UNDERSTANDING OF TECHNICAL OUTPUTS

2.9.1 Quality management

Quality management and the WMO Quality Management Framework initiative are important and overarching principles for all components of these Guidelines. They are an integral part of operational activities at NMHSs.

Quality management is a process for ensuring that all the activities necessary to design, develop and deliver goods and services are conducted effectively and efficiently. It includes the coordinated activities that organizations use to direct, control and coordinate quality. These activities embody formulating a quality policy and setting quality objectives. They also include quality planning, QC and QA to achieve continual improvement. Thus, quality management focuses on the quality of products and services, and also on the means to achieve it.


ISO 9001:2015 (ISO, 2015d) sets out the criteria for a quality management system and is the only standard in the family that can be certified. This standard is based on some quality management principles including a strong customer focus, the motivation and implication of top management, the process approach and continual improvement. Quality Management Principles (ISO, 2015e) explains these principles in more detail. Principle 1 is customer focus and states that "the primary focus of quality management is to meet customer requirements and to strive to exceed customer expectations".

The WMO Quality Management Framework initiative has been implemented to encourage NMHSs to develop quality management systems and to provide appropriate guidance. Part of this initiative has seen the development of a WMO–ISO working arrangement to strengthen the development of international standards and to avoid duplication of work on standards related to meteorological, climatological, hydrological, marine and related environmental data, goods and services.

The Guide to the Implementation of a Quality Management System for National Meteorological and Hydrological Services and Other Relevant Service Providers (WMO, 2017c) provides the following definitions that are relevant here:

**Quality** refers to the perception of the extent to which a product or service meets customer expectations. It should be noted that quality has no explicit meaning unless it is related to a specific set of requirements. To highlight this, ISO defines quality “as the degree to which a set of inherent characteristics fulfils requirements”.

**QA** aims to instil confidence that quality requirements have been met. It involves the systematic monitoring and evaluation of the processes associated with the generation of a product or service.

**QC** aims to ensure that quality requirements have been fulfilled before dissemination of a product or delivery of a service.
**Quality management** is a process that focuses not only on the quality of the product or service but also on the means to achieve it. It is centred on four activities: quality planning, QC, QA and quality improvement.

The **quality management system** is the organizational structure, procedures, processes and resources needed to ensure the delivery of an organization’s quality products and/or services to its customers. WMO Member NMHSs are strongly encouraged to undergo third-party (external) audit to achieve certification of compliance with ISO 9001:2015, *Quality Management Systems – Requirements* (ISO, 2015d).

The **Quality Management Framework** is a framework specific to WMO, which addresses a wide range of quality management issues of interest to WMO Members, including ISO 9001:2015 (ISO, 2015d) and the provision of appropriate guidance.

These are important elements that encompass all aspects of these Guidelines, and the reader is invited to consult the WMO quality management website hosted by the Australian Government’s Bureau of Meteorology for details (see [http://www.bom.gov.au/wmo/quality_management.shtml](http://www.bom.gov.au/wmo/quality_management.shtml)).

Some of the publications of interest in this regard are:


  
  Chapter 2 covers climate observations, stations and networks
  
  QC of climate data is part of Chapter 3 on climate data management

  
  Chapter 9 covers hydrological data processing and QC
  
  Chapter 10 covers data storage, access and dissemination


For nuclear installation applications, the quality management system should comply with the general safety requirements defined in *Leadership and Management for Safety* (IAEA, 2016b).

### 2.9.2 Communication of information and understanding of technical outputs

In addition to being raw data providers, NMHSs play an important role in the provision of guidance on how predictions, design probabilities and forecasts can be better used and interpreted by users. This also implies that NMHSs have to identify user needs, to adjust their products and services accordingly. Simply providing information to decision-makers does not automatically result in adequate decisions in emergency management (Hoss and Fischbeck, 2016).
One specific aspect of the relationships between NPP operators and NMHSs is the need to have an efficient interfacing between the weather and hydrology modellers, as most of the hydrometeorological products are now based on numerical models.

Nowadays, EPSs are routinely used operationally. For meteorology, they are part of NWP systems that include estimation of the uncertainty in a weather forecast as well as the most likely outcome, and the degree of confidence in a deterministic forecast (see section 2.6).

The *Guidelines on Ensemble Prediction Systems and Forecasting* (WMO, 2012) describe how to optimize the necessary interaction between the organization issuing the forecast and the users, to allow them to tune their decision-making to take account of their particular applications, and to facilitate the understanding of the probabilistic forecast and its estimated uncertainty, especially using appropriate graphical representations and statistical tools.

The *Guidelines on Communicating Forecast Uncertainty* (WMO, 2008b) cover, in detail, how communicating the uncertainty of the forecast is vital to users. This allows users to make better decisions that are attuned to the reliability of the forecast. It also helps to manage user expectations by understanding the limits of the forecast. For example, when a forecast is presented as a probability, it is important to express clearly what the probability is for, so that it is clear and understandable to the forecaster and the user.

Similarly, severe or high-impact weather event warning systems should have appropriate thresholds, lead times and levels of service agreed with users. Many countries and users now use a four-colour system (green, yellow, amber and red) indicating different levels of risk and corresponding levels of action that users should take; see for example, the European meteoalarm system (https://www.meteoalarm.eu/).

In addition, specific thresholds, products, lead times and levels of service have to be defined in more detail when necessary, as well as operational procedures and requirements for the various stages of siting and operating an NPP.

### 2.10 PERIODIC SAFETY REVIEW AND UPDATE

From *Safety of Nuclear Power Plants: Commissioning and Operation* (IAEA, 2016c):

Systematic safety assessments of the plant, in accordance with the regulatory requirements, shall be performed by the operating organization throughout the plant’s operational lifetime, with due account taken of operating experience and significant new safety related information from all relevant sources.

And from *Site Evaluation for Nuclear Installations* (IAEA, 2016a):

Site specific hazards shall be periodically reviewed using updated knowledge, typically every ten years, and shall be re-evaluated when necessary. A review after a shorter interval shall be considered in the event of evidence of potentially significant changes in hazards (for example, in the light of the feedback of operating experience, a major accident or the occurrence of extreme events). The implications of such a review of site specific hazards for the safe operation of the nuclear installation shall be evaluated.

In many States, periodic safety review (PSR) forms part of the regulatory system, though the scope and content of PSR, the manner of its implementation and the regulatory activities relevant to PSR vary depending on national regulations. *Periodic Safety Review for Nuclear Power Plants* (IAEA, 2013) provides detailed guidance for conducting PSR.
3. ASSESSMENT OF METEOROLOGICAL HAZARDS

3.1 GENERAL CONSIDERATIONS

According to IAEA, most meteorological hazards affect specific NPP systems and safety-related systems (IAEA, 2003, 2011). For example:

- Extreme winds can affect the power supply and availability of the electricity grid. Accidents typically evolve into turbine trips and loss of off-site power. In a few cases, the atmospheric pressure differential can create some false signals to instrumentation. At sites close to the marine environment, heavy salt sprays from the sea in the form of precipitation during the most violent phases can create shocks in exposed electrical equipment, and later, deep corrosion and malfunctions. High winds have been known to cause collapse of cooling towers.

- The availability of the ultimate heat sink (a complex cooling water system that serves the plant during a variety of normal and emergency) can be affected by ice and drought.

- The availability of off-site power can be affected by wind, snow, frost and lightning.

- The functionality of safety-related equipment, particularly the instrumentation and control (I&C) equipment, can be affected by temperature, moisture and lightning.

- Extreme low temperatures have been the root cause of many malfunctions in NPPs, particularly affecting I&C systems, which on many occasions have generated spurious signals.

- Low temperatures have at times created moisture condensation in closed rooms, with consequent dripping of water onto electrical equipment causing short circuits and malfunctions.

- Low temperatures have prevented air ventilation systems of some NPPs from working properly, hindered proper operation of diesel generators where the fuel showed separation of paraffin, damaged the external power supply system and limited the availability of service water.

- A flood resulting from heavy precipitation or from any other cause may affect the road network around a nuclear installation and hinder emergency response by making escape routes impassable and isolating the site in an emergency, with consequent difficulties in communication and supply.

- Snow-induced damage is usually represented by the unavailability of the power supply or the electrical grid, but snow could also affect ventilation intakes and discharges, structural loading, access by the operator to external safety-related facilities and mobility of emergency vehicles.

- The damage caused by lightning has been shown to be extensive: it can affect electrical equipment, but has often developed into explosions of transformers, serious fire accidents and spurious signals to valves with consequent flooding and loss of off-site power.

3.2 EXTREME METEOROLOGICAL PHENOMENA

The meteorological parameters to consider for extreme meteorological phenomena, following IAEA guidance, are air temperature, wind speed, precipitation and snowpack (IAEA, 2011). The design-basis parameters for the meteorological hazards are summarized below.
3.2.1 Minimum and maximum daily air temperatures

The result of hazard assessment is the appropriate extreme temperatures characterized by their annual frequency of exceedance of given thresholds, with an associated confidence interval. The persistence of high or low temperatures may also be a factor to consider.

The dataset of daily minimum and maximum temperatures collected in the off-site monitoring programme should be used in a first step. The on-site measurements are then progressively accounted for, to improve and update the estimates.

3.2.2 Dry and wet bulb temperatures (humidity)

The result of hazard assessment is the appropriate extreme temperatures characterized by their annual frequency of exceedance of given thresholds with an associated confidence interval. The persistence of high or low dry bulb and wet bulb temperatures, and hence dewpoint temperatures, above or below given thresholds may also be a factor to consider.

The dataset of hourly dry bulb and wet bulb temperatures collected in the off-site monitoring programme should be used in a first step. The on-site measurements are progressively accounted for, to improve and update the estimates.

3.2.3 Maximum wind speed

The result of hazard assessment is the appropriate extreme wind speed at a reference height (usually 10 m) corresponding to a defined frequency of exceedance of given thresholds, with an associated confidence interval.

The dataset of hourly maximum wind speed and direction collected in the off-site monitoring programme should be used in a first step. The on-site measurements are progressively accounted for, to improve and update the estimates. The wind directions for the extremes should be recorded as well.

3.2.4 Extreme maximum and minimum precipitation

The dataset of continuously recording raingauge (for example, tipping bucket) data collected in the off-site monitoring programme should be used in a first step and may be complemented by radar data. The on-site measurements, using a similar type of equipment to that used in off-site stations, are progressively accounted for, to improve and update the estimates.

The results of the hazard assessment for extreme maximum precipitation include identifying the maximum amount of precipitation accumulated over various periods of time, typically ranging from 5 min to 24 h or more. This in turn allows the drainage and hazard-safety designer to derive local rainfall intensity–duration–frequency relationships.

For plant design, the appropriate extreme precipitation totals for each time period should be characterized by the annual frequency of exceeding given thresholds with an associated confidence interval sometimes referred to as a depth–duration–frequency analysis.

The results of the hazard assessment for extreme minimum precipitation should include an identification of the worst drought considered reasonably possible in the region. This is generally quantified as the number of days with zero (or trace) rainfall.

3.2.5 Extreme snowpack

The results of the hazard assessment for extreme snowpack should include determination of the water equivalent and the annual frequency of exceedance.
For plant design, the appropriate extreme snowpack for each time period should be characterized by the annual frequency of exceedance of given thresholds with an associated confidence interval.

All data should be complemented by explanatory information on the data, and measuring systems (metadata).

3.3 RARE METEOROLOGICAL PHENOMENA

The parameters to consider are given below (IAEA, 2011).

3.3.1 Lightning

The hazard assessment for lightning is an estimated annual frequency of exceedance for lightning strike at the NPP site. The dataset of lightning flash density from lightning detection networks is preferred. An alternative method is to use isokeraunic maps on the occurrence of lightning.

3.3.2 Tropical cyclones, typhoons and hurricanes

The hazard assessment for tropical cyclones, hurricanes or typhoons should determine a maximum wind speed corresponding to an annual frequency of exceedance and atmospheric pressure, as an extreme single value and persistence below a given threshold. It should also include an estimate of coastal surge hazards where appropriate. The information is available from IBTrACS (NCEI, 2016), except for storm size, which is a critical parameter for surge prediction.

Other features of interest for design, such as the vertical profile of the wind velocity, the duration of the wind intensity above specified levels and windborne projectiles, should also be described.

The datasets of tropical cyclones that crossed the region of the NPP site are of particular importance. The information should refer to minimum central pressure of the cyclonic system and its location position (track) with respect to the NPP site.

In recent years, high-resolution images from orbiting and geostationary meteorological satellites have become readily available to many NMHSs. They provide valuable information for the detection and tracking of tropical disturbances, the estimation of their intensity and wind speeds based on cloud motions.

3.3.3 Tornadoes

The hazard assessment for tornadoes should be the annual frequency of exceedance at which a particular site will experience tornado wind speeds in excess of a specified value.

Several countries prone to important tornadic activity use the concept of Design-Basis Tornado to derive the maximum expected pressure drop and the maximum rate of pressure drop. Tornado-generated projectiles should also be specified in terms of their mass and velocity (for example, USNRC, 2007).

A homogeneous region centred at the site should be considered for developing the tornado inventory. Generally, an area of about 100 000 km² is considered as appropriate.
3.4 OTHER METEOROLOGICAL PHENOMENA

The design-basis parameters for other meteorological hazards are given below (IAEA, 2011).

3.4.1 Duststorms and sandstorms

The results of the hazard assessment for duststorms and sandstorms should be the total dust or sand loading (kg m\(^{-2}\)), duration (h) and average dust or sand loading (kg m\(^{-2}\)) for the historical duststorm or sandstorm that had the largest calculated time-integrated dust or sand loading. Appropriate values of dust or sand concentration should be computed on the basis of empirical relationships using visibility observations (Song et al., 2007).

3.4.2 Hail

If relevant to the site, the results of the hazard assessment for hail should include an estimate of the maximum hail size, on the basis of historical records for the site vicinity and an estimate of the concurrent terminal velocity.

3.4.3 Freezing precipitation and frost-related phenomena

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

Examples of application of IAEA guidance by national authorities are given by the Canadian Nuclear Safety Commission (CNSC, 2008) and USNRC (2014).

3.5 TRANSPORT, DISPERSION AND DEPOSITION OF AIRBORNE RADIOACTIVITY

3.5.1 Introduction

Design and licensing of NPPs require an evaluation of the dispersion of radioactive material discharged to the atmosphere under normal operational or accidental conditions. The following key points are taken from *Dispersion of Radioactive Material in Air and Water and Consideration of Population Distribution in Site Evaluation for Nuclear Power Plants* (IAEA, 2002) and *Generic Models for Use in Assessing the Impact of Discharges of Radioactive Substances to the Environment* (IAEA, 2001).

3.5.1.1 General considerations

The effects and consequences for the public and the environment of short- or long-term radioactive discharges should be assessed on the basis of meteorological information and site-specific conditions relating to land and water uses, population distribution, infrastructure in the vicinity of the site and relevant radiological parameters.

The calculations of the dispersion and concentrations of radioactive material should show whether the radiological consequences of routine discharge and potential accidental release of radioactive material into the atmosphere are acceptable. The results of these calculations may be used to establish authorized limits for radioactive discharges from the plant into the atmosphere.

3.5.1.2 Modelling of atmospheric dispersion

Atmospheric dispersion models should typically be applied in site evaluation and design for NPPs to meet the following objectives:
- To derive short-term (a few hours) normalized concentrations and deposition values, to assess the probability of occurrence of high normalized concentrations and contamination levels due to postulated accidents (normalized refers to the ratio of the actual concentration to the release rate)

- To derive longer-term (up to 1 month) time-integrated normalized concentrations and deposition values for postulated accidents

- To derive long-term (around 1 year) time-integrated normalized concentrations and deposition values for routine operations

**Role of National Meteorological and Hydrological Services**

Some NMHSs have an atmospheric dispersion modelling capability and can assist NPP operators and state regulatory authorities in this regard. The role of a specific NMHS in dispersion modelling will vary from State to State, in accordance with the structure of authority and responsibilities of the various agencies. Therefore, not all NMHSs with modelling capability will necessarily participate in atmospheric dispersion evaluations for NPP siting.

### 3.5.2 Basics of atmospheric transport and dispersion

Three distinct components have to be quantified to calculate atmospheric concentrations from a release of radioactive material and the corresponding radiation exposure: (a) the source or emission term, (b) the meteorology and (c) the transport and dispersion. It is beyond the scope of this publication to cover in detail atmospheric transport and dispersion but in light of its importance, Annex 1 presents a summary. See also the COMET MetEd module on dispersion basics at [https://www.meted.ucar.edu/training_module.php?id=33](https://www.meted.ucar.edu/training_module.php?id=33).

### 3.5.3 Atmospheric transport and dispersion models

Atmospheric transport and dispersion models use mathematical formulations to characterize the atmospheric processes that transport and disperse an airborne substance emitted from a source.

The models can be classified as a function of three general characteristics: (a) their coordinate systems (Eulerian or Lagrangian), (b) their wind fields and (c) the type of averaging used to solve the mass-conservation equation (see Annex 1).

Many models and software exist to predict concentrations and perform radiation exposure and dose calculations during normal operational conditions at an NPP (for example, the United States Environmental Protection Agency Compliance Software for Radioactive Air Emission, [https://www2.epa.gov/radiation/compliance-software-radioactive-air-emissions](https://www2.epa.gov/radiation/compliance-software-radioactive-air-emissions)) and for emergency situations with potential or actual release of radioactivity to the atmosphere (for example, NOAA HYSPLIT, Stein et al., 2015; FLEXPART, Stohl et al., 2005). They cover a wide range of spatial and temporal scales with varying levels of sophistication. The choice of a specific model can also be guided by regulations within a given state.

As discussed in section 2.4, high-resolution meteorological analyses, nowcasts and forecasts can be used to drive dispersion models and help assess concentrations and doses from radioactive material released to the atmosphere.

The source term, defined in section 3.5.4, is rarely known. In this case, a dispersion analysis based on a unit release can be created by computing a transfer coefficient matrix that accounts for the atmospheric transport of a general tracer for consecutive time intervals (Draxler and Rolph, 2012). A gridded concentration analysis based on various emission scenarios can then be quickly calculated without rerunning the dispersion model (for example, Draxler et al., 2015).
For emergency situations, the WMO Environmental Emergency Response programme offers global modelling systems of atmospheric transport, dispersion and deposition from designated RSMCs (see WMO, 1997; IAEA, 2017). This is discussed in section 8.5.

3.5.4 **Source-term estimation**

The magnitude, time profile of the release and nature of the radionuclides discharged to the atmosphere are commonly referred to as the source term or emission term.

With a few exceptions, the source term is unknown in real time. However, an accurate estimation of the source term is required to quantify the actual release of radioactivity to the atmosphere and corresponding radiological doses for impact assessments.

Fortunately, some techniques exist to estimate the emissions. They are based on measurements of radionuclides combined with simulations of their atmospheric transport and dispersion using reverse and inverse estimation methods (UNSCEAR, 2013).

A reverse estimation method determines the release rates of radionuclides by comparing measurements of air concentration of a radionuclide or dose rates in the environment with values calculated by ATDM for unit release of a radionuclide. The estimate of the release rate is simply the ratio of the measurement to the corresponding calculation result. This method allows rapid order-of-magnitude estimates of the source term based on a few measurements. However, this simple comparison without consideration of the uncertainty of ATDM results may contain large errors; consequently, expert judgement is essential to correct the discrepancy between the measurement and the calculation.

An inversion estimation method evaluates the release rates in an objective way using an algorithm to minimize the differences between calculated and measured air concentrations or dose rates. This method is mathematically sophisticated, and technical errors are explicitly considered. However, to return the highest-quality estimates, the method requires a large number of measured values of air concentrations or dose rates in time and space along with high-accuracy meteorological fields for ATDM simulations. Given that the mathematical problem is usually underdetermined due to insufficient measurement coverage, inversion methods usually rely on regularization assumptions to obtain good results. Such assumptions frequently include estimates of a priori release rates derived from independent considerations or studies (for example, Stohl et al., 2012; Katata et al., 2015). To obtain correct estimates, the accuracy of the meteorological field is essential, particularly if this method is applied to local-scale dispersion simulations with a point source.
4. ASSESSMENT OF HYDROLOGICAL HAZARDS

4.1 EXTREME FLOOD EVENTS

This section principally concerns the hydrological causes of flood hazards, that is, those events that arise from occasional behaviour of parts of the hydrological cycle (rain, snow and river flow). There are, of course, other meteorologically generated types of flooding, such as coastal or littoral flooding from sea and lakes, storm surges, wind-generated waves and seiches, flash flooding and floods that compound the effects from more than one origin.

There is no precise definition of what constitutes an extreme flood, either in terms of quantity (discharge in cubic metres per second) or probability of occurrence (return period in years). There is a considerable subjectivity introduced by impact, or effects, and therefore, by definition, risk and impact. Table 9 is an illustration of subjective interpretation of the benefit of flood forecasting and warning on the interaction between magnitude of event and risk/impact.

Table 9. Risk and impact matrix

<table>
<thead>
<tr>
<th>Flood risk</th>
<th>High</th>
<th>High/low</th>
<th>Medium/medium</th>
<th>Medium/high</th>
<th>High/very high</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>High/low</td>
<td>Medium/medium</td>
<td>Medium/high</td>
<td>Medium/very high</td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>Medium/low</td>
<td>Medium/medium</td>
<td>Medium/high</td>
<td>Medium/very high</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>Low/low</td>
<td>Low/medium</td>
<td>Low/high</td>
<td>Low/very high</td>
<td></td>
</tr>
<tr>
<td>Undeveloped area</td>
<td>Low/low</td>
<td>Low/medium</td>
<td>Low/high</td>
<td>Low/very high</td>
<td></td>
</tr>
<tr>
<td>Agricultural land</td>
<td>Low/low</td>
<td>Low/medium</td>
<td>Low/high</td>
<td>Low/very high</td>
<td></td>
</tr>
<tr>
<td>(medium)</td>
<td>Low/low</td>
<td>Low/medium</td>
<td>Low/high</td>
<td>Low/very high</td>
<td></td>
</tr>
<tr>
<td>Low density urban</td>
<td>Low/low</td>
<td>Low/medium</td>
<td>Low/high</td>
<td>Low/very high</td>
<td></td>
</tr>
<tr>
<td>(high)</td>
<td>Low/low</td>
<td>Low/medium</td>
<td>Low/high</td>
<td>Low/very high</td>
<td></td>
</tr>
<tr>
<td>Urban centres and key infrastructure</td>
<td>Low/low</td>
<td>Low/medium</td>
<td>Low/high</td>
<td>Low/very high</td>
<td></td>
</tr>
</tbody>
</table>

Note: The colour codes (green, turquoise, orange, red and red bold) are indicative of the importance and benefit of flood forecasting and warning.

The nature of the precipitation that causes flooding at a particular location needs to be fully understood, in the context of individual events and seasonal climatology. Significant types of flood-causing precipitation are:

- Short-duration high-intensity rainfall (often local)
- Long-duration widespread rainfall
- Snowfall and snowmelt
- Extended seasonal rainfall (monsoon conditions)

An extreme event may be considered as a particularly large magnitude event that may be expected to occur within the lifetime of the NPP. Thus, for a design life of 100 years, flood and drainage design is required to meet the 1% magnitude of the variable concerned. In practice, design criteria are often based on the possibility of a more extreme event, say 0.2% (1 in 500 years) occurring in the lifetime of a structure.

The issue of flood risk has been extensively researched, and is progressively evolving to meet demands created by society, the insurance industry and national safety, in response to increased physical and financial impact of flood events. There is now wide recognition that many of the elements contributing to flood risk are dynamic, in the natural environment and in the social and built environment. Thus, there has been a move away from a deterministic approach to flood risk design and management, where a particular structure had a recommended standard of protection, for example, 50 years for a major flood levee, to a risk-based approach. For NPPs, two concepts may be considered alongside the basic statistical analyses of hydrological data. They are:
- The source–pathway–receptor (SPR) approach
- Overall risk classification

In the SPR approach to flood risk, the contributing factors are identified as to how they might affect the situation sequentially and by interactions. For an NPP as the main receptor for flood risk, Box 3 summarizes the typical sources, pathways and receptors.

**Box 3. Source, pathway and receptors for an NPP as the main receptor for flood risk**

**Source:** the physical and environmental conditions of events that create the hazard. Major meteorological phenomena causing excess rainfall and/or storm conditions.

**Pathway:** dynamics of the river system and catchment, the condition of the area local to the site, sea or estuary.

**Receptors:** flood embankments, physical structures (buildings, as reactors will have differing levels of resilience), access routes and personnel.

The overall risk classification is a means of prioritizing flood risk from different risk factors and the weighting given in a particular situation. Flood risk comprises three components:

- The likelihood of flooding: the greater the chance of flooding, the greater the risk
- The nature of the assets(s) at risk: the more important the asset in terms of people, value, importance to society, sensitivity of the environment and so forth, the greater the risk
- The degree to which the potential consequences are likely to be realized: the better the protection of assets, the lower the risk of critical impacts

Scoring or weighting systems are widely used as an analytical tool. The development of a scoring and weighting system involves the following steps:

- Definition of a framework
- Identification of relevant factors and subfactors
- Definition of scores, usually on a three- or five-tier gradation from low to high
- Definition of weighting, usually on severity of potential impact

This approach can be expressed in tabular form, as in Table 10, and used as a basis for a decision support framework. A further consideration must be the risk of unforeseen, but theoretically possible, failure. For example, the Environment Agency in the United Kingdom now requires that flood risk assessment includes the results of embankment overtopping or breach failure to major flood defence structures, especially when they protect an area of high-value infrastructure to a high degree of safety – also see section 4.2.2 below.

### Table 10. Scoring/weighting system for flood risk prioritization

<table>
<thead>
<tr>
<th>Factor</th>
<th>Subfactor</th>
<th>Lowest likelihood (score = 0)</th>
<th>Highest likelihood (score = 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Likelihood of flooding – contributory factors</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Defences</td>
<td>State of defences</td>
<td>Robust, continuous, hard/soft</td>
<td>No defences</td>
</tr>
<tr>
<td></td>
<td>Design standard</td>
<td>Return period greater than 1 000 years</td>
<td>None/unknown</td>
</tr>
<tr>
<td></td>
<td>Flood history</td>
<td>No floods in last 100 years</td>
<td>More than one flood in last 10 years</td>
</tr>
</tbody>
</table>
## Problems in arid and semi-arid areas

Desert or semi-desert areas can often be attractive to the siting of NPPs due to their remoteness and sparse population, and could be viewed as having lower levels of hydrological risk. Rainfall in these climatological and hydrological regimes is infrequent, and highly variable in quantity, temporal occurrence and spatial distribution. However, the rainfall can be intense, leading to flash floods that may produce damaging conditions. The problem of variability applies to individual events and the evaluation of historical datasets. For example, storms may be highly localized and short lived, and significant events may be so infrequent that it is difficult to develop conclusions on depth–duration–frequency characteristics.

In such areas, the use of a conventional hydrological network that would be properly representative of areal rainfall or runoff is limited. Arid and semi-arid areas are also typically areas of low population density, there is a scarcity of population centres, and major infrastructure that requires good levels of meteorological and hydrological information and services is also lacking. It is also more difficult to apply conceptual modelling approaches as used in the commonly available hydrological and hydraulic models, because these depend heavily on good connectivity over an area in observations and processes. Typical problems encountered in arid or semi-arid areas are:

- Raingauges may be too sparsely distributed to record storm events
Highly variable rivers are difficult to measure either with structures or at rated sections by current meters.

Channel conditions and dimensions change during and after each flood event: channels are often referred to as “mobile-bed” rivers.

Ephemeral rivers have considerable losses through the channel bed.

Floods can cause changes in river courses and destruction of measuring devices.

Performance of monitoring equipment is threatened by harsh conditions.

Modern techniques of remote-sensing can prove more useful over desert and semi-arid regions than conventional instrumentation. It may be possible to use satellite or radar-based monitoring for the observation of rainfall, though the wider economic justification of the latter is likely to be low. River conditions will need to be observed at suitable places for at-risk locations, but it is imperative that these be selected to provide adequate lead time, as the high-speed downstream propagation of flooding is also a common feature of semi-arid and arid regions.

4.2 RARE FLOOD EVENTS

Due to their inherent status as highly critical infrastructure, the design and operation of NPPs require the consideration of rare flood and rainfall events. Extrapolation by statistical means to low return periods becomes increasingly approximate, and the effects of other catastrophic events such as dam break and tsunami, with few historic exceptions, also lie outside observational experience, and require special processes of estimation.

4.2.1 Probable maximum flood

PMF is the ultimate design theoretical maximum flood that poses a critical threat to the integrity of flood protection and resilience of infrastructure. It is particularly relevant to NPP sites, where high-impact consequences may result. Section 2.3.2.2 discussed the analytical methods involved in the estimation of PMP and PMF – this section will focus on the causes of PMF events, which should provide insights on how such events may be taken into consideration in an operational context.

The primary driver for a PMF event is PMP, which is driven by an adverse combination of meteorological conditions. The critical combination of meteorological phenomena, along with a worst-case set of catchment conditions will lead to the possibility of PMF. A flood monitoring and estimation system, such as a flood forecasting and warning facility will contain some triggers used to highlight the existence or development of critical conditions. There do not appear to be any accounts of the progress of a PMF event as it occurred, but there are many reports of extreme events involving the contributing factors listed in Box 2. Some of these reports were compiled soon after the flood event in question, but many have been inferred from historical records and evidence. Box 4 gives some examples.
Box 4. Extreme floods as a guide to PMP/PMF behaviour

**Cannington, Somerset, United Kingdom, August 1924.** Detailed studies of this storm have revealed high efficiency in convection, coupled with a high persistent dewpoint temperature (Natural Environment Research Council, 1975). It is estimated that the storm depth of 238.8 mm in 5 h over a small area of 34 km² approaches the theoretical limit for conditions in the United Kingdom – that is, close to PMP (Department for Environment, Food & Rural Affairs, 2002, 2008, 2009). The storm was located within 10 km of the site now occupied by a major United Kingdom nuclear power station, Hinkley Point. This storm was restudied as part of defining a design approach for management of excessive rainfall at the next generation of nuclear plant (Francis et al., 2010).

**River Elbe, Central Europe, 2002.** The flood in the Elbe river basin in August 2002 was a natural disaster with severe flood peaks in the River Elbe and many tributaries reaching far above the previously known maxima, resulting in unprecedented material loss in the Czech Republic and Germany. During the first 13 d of August 2002, Central Europe experienced three heavy precipitation events, driven by a low-pressure system moving slowly from northern Italy to Central Europe. The third period of rainfall triggered the flood in the Elbe basin. Severe flooding was already taking place in parts of the Czech Republic across the watershed with the Elbe, especially on the River Moldau (Vltava), as well as the River Eger (Ohre). The material losses caused by the Elbe flood was estimated at around € 2 500 million in the Czech Republic and € 9 000 million in Germany (Ulbrich et al., 2003). Many chemical plants were affected, causing additional problems of polluted waste being mobilized.

**Brisbane, Queensland, 2011.** The Brisbane River has a history of damaging floods, as it is subject to tropical storms during the wet season. The flooding in south-east Queensland during the second week of January in 2011 was caused by the interaction of a low-pressure system situated off the mid and south Queensland coasts, and upper-level and monsoonal troughs. The greatest historic flood was experienced in 1893, and after another major event in 1974, the Wivenhoe Dam was constructed in part to provide enhanced flood management. The 2011 flood followed two large rainfall events within a few days. The flood storage compartments of the Wivenhoe and upstream dams were filled to a high level by the first event, and there was not sufficient time to release this water before the second event. Accordingly, the water from the second event could not be completely contained without risking the safety of the dams. The release of large quantities of water, coupled with flows in other parts of the river system resulted in significant urban damage. However, the extent of this damage was greatly reduced by the operation of the dams.

### 4.2.2 Dam break and glacial lake outburst floods

Dam break and the failure of flood embankments are primarily issues relating to civil engineering design, and therefore beyond the remit of this publication. Structural failure may be as much the result of underdesign or poor maintenance, as a consequence of extreme flood. It is therefore important with regard to NPP safety that the location and condition of dams and embankments in the upstream catchment are considered in the assessment of possible flood risk. Dam break and embankment failure can result from excessive quantities of water in the reservoir behind the dam and in the river, and also by overtopping, which leads to erosion and failure of the landward side of the structure. Erosion and weakening of the landward slopes of dams and embankments can also result from excessive soil wetness leading to the loss of cohesiveness.

Dam and embankment failure have been comprehensively studied, and sophisticated models are available to assess potential behaviour. These models are a specialist development of hydraulic models, and simulate the 2D or 3D behaviour of the speed, height and spatial extent of floodwaters downstream of a hypothetical break. Figures 16 and 17 are diagrammatic representations of the impact of flows from a breach in a defensive embankment. These diagrams are primarily for the breaching of longitudinal flood embankments (or levees).

The situation arising from dam break is more complex, given the greater head and volume of water retained behind the impoundment. Modelling of the downstream flood extent needs to take into account the shape of the valley and flood-plain. Figure 18 shows the result of 2D flood modelling in the valley of the River Nene, upstream of the town of Northampton, United Kingdom. Some reservoirs are located in the headwaters of the River Nene for water supply, flood control and canal navigation. The Environment Agency in the United Kingdom has produced mapping from models using the same hydrodynamic models that are used for river flood design. The flood outline produced is similar to a flood with 0.5% (1 in 200 years) probability.
Dam break events are rare. In view of their suddenness and often unforeseen lead-up conditions, documented evidence is largely obtained from post-event survey and analysis. Due to the importance of such events through their impact, often the large financial and insurance costs involved and sometimes legal proceedings, post-event studies are usually detailed and include:

- Meteorological conditions, particularly with respect to synoptic evolution, rainfall quantity and distribution in time and area
- River flow behaviour from water-level recorders

**Figure 16. Plan view of danger to people for a breach scenario**


**Figure 17. Diagrammatic representation of flow depth and extent from an embankment breach**

Flood extent and levels, either from direct observations, or post-event from rubbish marks and structural damage

Two typical post-event analyses were carried out in the Dublin area of Ireland, following floods caused by extreme rainfall from the remnants of Hurricane *Charlie*, 25–26 August 1986. One study was on flooding of the River Dodder within Dublin city, where many houses and streets were involved, and on a dam break event in the foothills of the Wicklow Mountains affecting the River Dargle at the coastal town of Little Bray.

Glacial lake outburst floods (GLOFs) may be sources of significant threats to NPP sites in mountainous areas. Rapid melting of glaciers can lead to flooding of rivers and to the formation of glacial meltwater lakes, which may pose the serious threat of dynamic outburst floods, caused by continued melting or calving of ice chunks into lakes.

In Peru, the Cordillera Blanca, with more than 1 000 lakes formed by recent glacial retreat, is an area at risk of an outburst of moraine-dammed lakes (Coudrain et al., 2005).

In Asia, the Hindu Kush Himalayas (HKH) are called the water towers of Asia as they are the source of 10 major rivers and have the largest snow and ice deposits outside the two poles (Mukherji et al., 2015). Given the mountainous terrain, the region is also prone to natural hazards, of which floods, including GLOFs, flash floods and riverine floods are common. GLOFs are also related to climate change in that rapidly melting glaciers leave behind glacial lakes, which are then at risk of bursting due to destabilization of moraine dams. Historical records confirm incidences of GLOF events causing catastrophic flash floods from the mountains in the HKH region.

4.2.3 Tsunamis

Tsunamis are not strictly hydrological or meteorological phenomena, but their manifestation as extreme flood occurrences have many aspects similar to hydrological and coastal flooding.
events. Tsunamis arise from tectonic sources, either as sub-marine centred earthquakes and major tectonic shifts, or from deep sub-marine sediment slips. They can also be produced by underwater landslides and, less commonly, by volcanic eruptions. The shock waves caused by these events are translated into deep-sea waves, which propagate over long oceanic tracks into large tidal waves. Given the coastal or estuarine location of many NPPs, tsunamis provide a serious source of risk, as evidenced by the Fukushima Daiichi disaster in Japan in March 2011.

Although the highest level of risk from tsunamis will be for sites in active tectonic zones, such as the Pacific Rim or South-East Asia, tsunami-type events have been identified in areas not generally considered to be of high seismic activity. Thus, in the United Kingdom, major tsunami-type floods have been attributed as the cause of major historic coastal and estuarine floods that occurred in the Severn estuary in the south-west in 1607, 1755 and 1858. The major floods on the east coast of the United Kingdom and in the Netherlands, though largely the result of a storm surge, are considered by some sources as having had a contribution from tectonic activity. The 1607 event in the Severn estuary is of uncertain origin, due either to sub-marine landslips in the Canary Isles, or tectonic movements in the Azores or off south-west Ireland. The resultant flood inundation spread over 20 km inland, and flood marks on a church 2 km from the sea recorded a flood depth of almost 4.9 m. These effects are far in excess of historical sea and river flood levels in the area.

In some areas of the world, the development of predictive models for estimating expected tsunami inundation levels from a range of possible earthquakes are being used to improve quantitative knowledge of potential tsunami hazards in areas of high seismic activity. These models can be used in conjunction with the existing DART (Deep-ocean Assessment and Reporting of Tsunamis; see http://nctr.pmel.noaa.gov/Dart/) to provide data-assimilated predictions of tsunami inundation for most areas within the Pacific Ocean “Ring of Fire” seismic region.

4.2.4 Storm surges

The estimation of storm surges, from tropical and extratropical cyclones, is critical to quantifying long-term hazards in coastal areas. Until recently, most decisions related to design and siting of NPPs utilized concepts of the probable maximum hurricane/tropical cyclone as their primary basis. However, recently in some countries, significant efforts have been devoted to probabilistic flood hazard assessment, including floods generated by tropical cyclones. In the aftermath of Hurricane Katrina, extensive efforts were funded and significant advances made in this area (Resio et al., 2009; Irish et al., 2009; Irish and Resio, 2010; Niedoroda et al., 2010; Toro et al., 2010a, 2010b).

Figure 19 shows an example of surge hindcasts of historical storms from 1940 through to 2005. This set of storms was used in a hazard assessment for flood mitigation in the 50–100 year range of return intervals. The hindcast (a posterior) point location is in Lake Pontchartrain along the north side of New Orleans in the United States. The surges show three different, roughly linear, trend lines within the overall hindcast results, even though the sample of events has been stratified to contain only hurricanes: (i) distant landfall or non-events; (ii) direct hit event and (iii) potential extremes that occur when the large-scale circulation is aligned to produce especially intense storms. Therefore, it is typically not a good practice to depend only on historical storms for extreme surge estimates. As shown in the figure, a review of these results shows that hurricanes which passed close to the site produced significantly different surge characteristics than storms making landfall more than 100 km away from the site. Furthermore, Hurricane Katrina definitely shows up as an outlier in this dataset. The figure shows that several populations of surge response exist at this site in Lake Pontchartrain, making it questionable to use a single best-fit line to represent the natural structure inherent in the surge dynamics at this location.

It is clear that a resampling of this plot and an extrapolation to longer return periods would neglect the possibility that Hurricane Katrina is a storm that occurs on average at a longer period than the timespan of the record, commonly termed as an “outlier”. This is a good example of why it is essential to come as close to meeting the assumptions under which each distribution is
derived as possible in its application. In the case of the non-parametric distributions combined with resampling, outliers are plotted in incorrect plotting locations, unless some effort is made to formulate a different plotting position for such storms. In the case of GEV, each sample should be drawn from blocks of time, with each block of time taken from a larger (single) identically distributed homogeneous population. In the case of GPD, each sample should contain only data points above a threshold value and generated by a common class of storm, to represent a (single) homogeneous identically distributed population. Thus, it is advisable to stratify samples into physically based subsets before performing an analysis of extremes. Each subset should be analysed independently and then be combined into a total hazard estimate.

As shown by Resio et al. (2012, 2013), the estimation of low probabilities can be strongly affected by uncertainty in estimated values, since the aleatory (sampling-related) variability increases non-linearly with the ratio of the return period estimated to the record length upon which the extrapolation is based. For this reason, when dealing with estimates more than about an order of magnitude greater than the record length, it is often important to establish upper limits for some of the meteorological parameters used to categorize tropical cyclone wind fields: central pressure, storm size, storm forward speed, storm landfall location relative to a point of interest (or nearest point to landfall), the Holland B parameter (Holland, 1980) and angle of the head of the storm at landfall. Sensitivity studies have shown that the largest uncertainty in the probabilistic estimates is usually related to the central pressure.

Figure 19. Plot of surge height versus the logarithm of the return period, using the Gringorten plotting position for the Gumbel distribution

Source: D. Resio, University of North Florida
Most parameters (storm size, storm track angle at the coast, Holland B parameter and storm forward speed) tend towards asymptotic maxima (Irish and Resio, 2010); however, central pressure does not have a clearly defined value in many areas. Hurricane surges are expected to scale approximately linearly with pressure differential (the difference between the peripheral pressure surrounding a tropical cyclone and its central pressure. Thus, the combination of small datasets and long extrapolation distances makes it difficult to use only historical data to establish a maximum potential storm surge. One tool that has shown excellent promise for creating a lower limit for central pressure comes in the form of idealized theoretical models for the probable maximum intensity (lowest central pressure) developed by Emanuel (1988) and Holland (1997). A comparison of these models to the lowest observed central pressures in tropical cyclones around the world by Tonkin et al. (2000) shows that these models appear to provide a reasonable bound to the lowest pressures in areas with SSTs greater than about 26 °C (see Figure 20). Departures at lower SST values are likely due to the omission of baroclinic energy sources, which contribute significantly to the overall energy balance in many areas of the world with lower SSTs. In such cases, it is important to consider a tropical cyclone as a hybrid storm such as Hurricane Sandy in 2012. Although many public information sources described this as unusual, an excellent study by Jones et al. (2003) shows that a relatively high percentage of tropical cyclones have begun transition poleward of 35° latitude.

For comparison to the risk-impact matrix for flooding shown in Table 9, Table 11 shows a similar matrix. The variation between the two tables is due to the historical evidence that many underdeveloped and agricultural areas of the world have experienced repeated large death tolls in coastal areas, when forecasts were unavailable, due to the interaction and combination between river, tidal and cyclone activity. For example, in Bangladesh in 1970 and 1988 (500 000 and 100 000 lives lost), Myanmar in 2008 (over 150 000 lives lost) and several countries around the world where the death toll has exceeded 10 000 lives since 1970.

Figure 20. Comparison of Emanuel (1988) (solid line with circles) and Holland (1997) (dashed line) models to the lowest observed central pressures in all ocean basins combined (solid line with triangles)

Table 11. Flood risk and impact matrix

<table>
<thead>
<tr>
<th>Inundation risk</th>
<th>High</th>
<th>High/very high</th>
<th>High/high</th>
<th>Medium/high</th>
<th>Medium/very high</th>
<th>Medium/very high</th>
<th>Medium/very high</th>
<th>Low/very high</th>
<th>Low/very high</th>
<th>Low/very high</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undeveloped area</td>
<td>Low/low</td>
<td>Medium/low</td>
<td>Low/medium</td>
<td>Medium/medium</td>
<td>Medium/very high</td>
<td>Medium/very high</td>
<td>Medium/very high</td>
<td>Low/low</td>
<td>Medium/low</td>
<td>Low/medium</td>
</tr>
<tr>
<td>Agricultural land</td>
<td>Low/medium</td>
<td>Low/medium</td>
<td>Low/medium</td>
<td>Medium/medium</td>
<td>Medium/very high</td>
<td>Medium/very high</td>
<td>Medium/very high</td>
<td>Low/medium</td>
<td>Medium/low</td>
<td>Low/medium</td>
</tr>
<tr>
<td>Low density urban</td>
<td>Low/medium</td>
<td>Low/medium</td>
<td>Low/medium</td>
<td>Medium/medium</td>
<td>Medium/very high</td>
<td>Medium/very high</td>
<td>Medium/very high</td>
<td>Low/medium</td>
<td>Medium/low</td>
<td>Low/medium</td>
</tr>
<tr>
<td>Urban centres and key infrastructure</td>
<td>Low/medium</td>
<td>Low/medium</td>
<td>Low/medium</td>
<td>Medium/medium</td>
<td>Medium/very high</td>
<td>Medium/very high</td>
<td>Medium/very high</td>
<td>Low/medium</td>
<td>Medium/low</td>
<td>Low/medium</td>
</tr>
</tbody>
</table>

Note: The colour codes (green, turquoise, orange, red and red bold) are indicative of the importance/benefit of flood forecasting and warning for inundation by tropical cyclone storm surges in areas affected by this hazard.

Several recent studies (Irish et al., 2009; Resio et al., 2009; Irish and Resio, 2010) have shown that the maximum surge can be estimated as a function of several storm parameters as shown here:

\[
\eta_{\text{max}} (x, y) = \eta_{\text{max}} (x, y, \Delta p, R_{\text{max}}, v_f, \theta_f, B, x_0) + \varepsilon
\]

where
- \(x\) = along-coast spatial coordinate
- \(y\) = cross-coast spatial coordinate
- \(\Delta p\) = peripheral pressure minus central pressure
- \(R_{\text{max}}\) = distance from eye of storm to maximum winds
- \(v_f\) = forward velocity of the storm
- \(\theta_f\) = angle of storm heading
- \(B\) = Holland B parameter
- \(x_0\) = along-coast location of landfall
- \(\varepsilon\) = deviation from storm due to potential errors in estimate.

The last term in this equation represents the sum of a wide range of omissions and errors in the predictive state of the art for surges. Some examples of this are: (a) the difference between actual (very complex) space–time-varying winds in a real hurricane and the parametric representation of these winds in a model driven by a small set of parameters, (b) numerical surge models are still imperfect and produce errors related to these imperfections (in the physics and numerical approximations utilized within the models) and (c) the coast is always in a state of change, so the use of present-day topographic/bathymetric representations in simulations of a future storm may not be precise.

Before proceeding, it is important to note that the verified accuracy of a numerical model for its application to a particular situation/area is absolutely essential to ensure that any of the results are usable for critical applications such as those being discussed here. As discussed by Resio and Westerink (2008), this absolutely requires: (a) the application of a model with sufficient resolution to represent important bathymetric/topographic features accurately and (b) that all terms contributing to the surge are represented in the proper physical context. For modern applications, this latter stipulation has shown that a coupled surge–wave model must be applied,
and the computational domain must be sufficiently large to negate the need for empirical factors along an offshore grid boundary. In turn, this means that run-time requirements for such models tend to be considerably higher than for simpler models.

4.3 LOW-FLOW RISK

Low flows may not be a source of significant physical and structural damage to NPPs, with the main source of adverse effects being the impact on the operation and safety of the plant. All NPPs require large volumes of cooling and effluent-receiving water from a reliable source; hence the preferred location for sites is adjacent to major rivers or the coast. In the case of rivers, the risk of extreme low flow needs to be assessed.

The Manual on Low-flow Estimation and Prediction (WMO, 2008c) provides a thorough reference to the subject as it affects surface and groundwater. A useful summary of data requirements, given as Table 1.1 in the Manual, is reproduced here as Table 12.

Table 12. Summary of low-flow regime measures

<table>
<thead>
<tr>
<th>Regime measured</th>
<th>Property described</th>
<th>Data employed</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean flow</td>
<td>Arithmetic mean of the flow series</td>
<td>Daily or monthly flows</td>
<td>Resource estimation</td>
</tr>
<tr>
<td>Coefficient of variation in annual mean flow</td>
<td>Standard deviation of annual mean flow divided by mean flow</td>
<td>Annual mean flow</td>
<td>Understanding of regime interannual variability; definition of carry-over storage requirements</td>
</tr>
<tr>
<td>Flow-duration curve</td>
<td>Proportion of time a given flow is exceeded</td>
<td>Daily flows or flows averaged over several days, weeks or months</td>
<td>General regime definition; licensing abstractions (water rights) or effluents (discharge consents); hydropower design</td>
</tr>
<tr>
<td>Annual minimum series</td>
<td>Annual lowest flows (of a given duration)</td>
<td>Annual minimum flows – daily or averaged over several days</td>
<td>Drought return period; preliminary design of major schemes; first step in some storage/yield analyses</td>
</tr>
<tr>
<td>Streamflow deficit durations</td>
<td>Frequency with which the flow remains below a threshold for a given duration</td>
<td>Periods of low flows extracted from the hydrograph followed by a statistical analysis of durations</td>
<td>More complex water quality problems, such as fisheries and amenity, navigation; general indication of drought frequency</td>
</tr>
<tr>
<td>Streamflow deficit volumes</td>
<td>Frequency of requirements for a given volume of “make-up” water to maintain a threshold flow</td>
<td>Same as above, except the analysis focuses on the volume below the threshold</td>
<td>Preliminary design of regulating reservoirs; general indication of drought frequency</td>
</tr>
<tr>
<td>Recession indices</td>
<td>Rate of decay of hydrograph</td>
<td>Daily flows during dry periods</td>
<td>Short-term forecasting; hydrogeological studies; modelling</td>
</tr>
<tr>
<td>Base-flow index (BFI)</td>
<td>Proportion of total flow which comes from stored catchment sources</td>
<td>Daily flows</td>
<td>Hydrogeological studies; preliminary recharge estimation</td>
</tr>
</tbody>
</table>

Source: WMO (2008c)

In the case of NPPs, principal interest will lie in the gathering and assessment of information on the frequency of the low river flows, to assess the probability of the abstraction source not
meeting the anticipated demand or dilution/cooling capacity. The volume of receiving waters is also importantly linked to the maintenance of adequate water quality. Section 4.5 further deals with this topic.

Low flows occur after periods of low rainfall or when precipitation falls as snow and when soil water in frozen ground is unavailable, which result in a reduction in water stored in soils, aquifers and lakes and in a decrease in the outflow to the river. The timing of depletion depends primarily on antecedent weather and climate conditions. The understanding of the climate regime of the region where the NPP installation will be located is therefore fundamental to the assessment of low-flow characteristics.

The rate of depletion within a catchment depends on hydrological processes, its size and the storage properties of the geology within the catchment. Thus, a catchment founded on impermeable strata will be prone to low flows after a relatively short period of little or no rainfall. On the other hand, a similar-sized catchment with significant storage in groundwater or wetlands will maintain consistent flows over a much longer period.

The Manual on Low-flow Estimation and Prediction (WMO, 2008c) explains five main methods of assessment and analysis, as briefly summarized below. No one of these methods is recommended over another, but if data availability permits, the methods should comprehensively characterize the low-flow behaviour of the rivers and catchments involved with a particular NPP site.

4.3.1 Low-flow indices

Low-flow statistics provide a valuable estimate of the conditions experienced during the dry season. For rapid assessment of the availability of water for abstraction in temperate regimes, simple flow statistics such as $Q_{95}$ (the flow equalled or exceeded for an average of 95% of the time) are often used to assess the amount of water available at low flows. For a process water supply, a constant abstraction is often required, perhaps with seasonal variability. In conjunction with $Q_{95}$, the mean of the 7 or 10 d annual minima may be useful. For preliminary design, $Q_{95}$ is also used to assess the availability of water for the dilution of industrial or domestic effluents.

The base-flow separation index is produced by hydrograph separation over an extended period, separating the total streamflow into an immediate (surface water) runoff component and a delayed flow component – see Figure 21. The delayed flow component (base flow, $Q_b$), represents the proportion of flow that originates from stored sources. A high index of base flow implies that the catchment is able to sustain river flow during extended dry periods. BFIs are generally highly correlated with the hydrological properties of soil, geology and other storage-related features, such as lakes. In Figure 21, the impermeable catchment has a BFI of 0.47 and the permeable catchment a BFI of 0.91 over an annual flow period.

4.3.2 Recession analysis

The gradual depletion of the water stored in a catchment during periods with little or no precipitation is reflected in the shape of the recession curve, that is, the falling limb of the hydrograph. The recession curve describes in an integrated manner how different catchment storage and processes control the river outflow. Rivers with a slow recession rate are typically groundwater or lake dominated, whereas a fast rate is characteristic of flashy rivers draining impermeable catchments with limited storage. The quantification of the recession curve is useful for water resources management, including low-flow forecasting and the estimation of low-flow variables at ungauged sites from regional values. The recession curve is fitted as an outflow function $Q_t$, where $Q$ is the rate of flow and $t$ is the time. The time interval $\Delta t$ is normally of the order of days. If $Q_t$ is modelled as the outflow from a first-order linear storage with no inflow, the recession rate will follow the simple exponential equation:

$$Q_t = Q_0 \exp(-t / \Delta t) \quad \text{or} \quad \ln Q_t = \ln Q_0 - t / \Delta t,$$

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where $Q_t$ is the flow at time $t$, $Q_0$ the flow at the start of the modelled recession period ($t = 0$) and $C$ the recession constant (dimensions of time). The curve is a straight line, with a slope $-1/C$, on a semi-logarithmic plot of $t$ against $\ln Q_t$.

### 4.3.3 Flow-duration curves

A flow-duration curve is a graph of river discharge plotted against exceedance frequency and is normally derived from the complete time series of recorded river flows. It is simple to construct and used in many different water resources applications over the entire range of river flows. The construction is based on ranking the data (normally daily mean discharge) and calculating the frequency of exceedance for each value. It effectively reorders the observed hydrograph from

![Figure 21. Base-flow separation for an impermeable catchment (top) and a permeable catchment (bottom)](image)

*Source: WMO (2008c)*
one ordered by time to one ordered by magnitude. The percentage of time that any particular discharge is exceeded can be estimated from the plot. Specific percentiles from the curve, for example, the flow exceeded for 95% of the time ($Q_{95}$), are often used as an intercomparison between catchments, when expressed by flow per unit area, or specific discharge. Figures 22 and 23 give examples of low and high BFIs, respectively, and it is worth noting the differences in steepness and range of flows shown by the lines. In both examples, the black line is the annual series, the blue line, December to March (winter), and the red line, June to September (summer). Table 13 gives comparative statistics for the stations.

### Table 13. Comparative flow statistics for two rivers in the United Kingdom

<table>
<thead>
<tr>
<th>Statistic</th>
<th>River Uck at Isfield</th>
<th>River Lambourn at Welford</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Catchment area = 87.8 km$^2$</td>
<td>Catchment area = 176 km$^2$</td>
</tr>
<tr>
<td>BFI</td>
<td>0.41</td>
<td>0.98</td>
</tr>
<tr>
<td>Mean flow (m$^3$ s$^{-1}$)</td>
<td>1.132</td>
<td>1.023</td>
</tr>
<tr>
<td>$Q_{95}$ (m$^3$ s$^{-1}$)</td>
<td>0.166</td>
<td>0.369</td>
</tr>
<tr>
<td>$Q_{10}$ (m$^3$ s$^{-1}$)</td>
<td>2.29</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Source: National River Flow Archive, [https://nrfa.ceh.ac.uk/data/station/meanflow/41006](https://nrfa.ceh.ac.uk/data/station/meanflow/41006) (River Uck at Isfield), [https://nrfa.ceh.ac.uk/data/station/meanflow/39031](https://nrfa.ceh.ac.uk/data/station/meanflow/39031) (River Lambourn at Welford)

### 4.3.4 Extreme value analysis

The extreme value analysis of low flows and low levels is approached in much the same way as for high flows, though the choice of the distribution functions and plotting position may be different to those used in high-flow analysis. This is primarily because the “tail” of the distribution or the values of low extremes are different in character to the extreme items of a high-flow or high-rainfall dataset.
Generally, plotting positions that attempt to achieve unbiased quantile estimates for different distributions can be written as follows:

\[ p_i = \left(1 - a\right) \frac{1}{n} \]

where \( p_i \) is a plotting position that gives an estimate of the non-exceedance probability of the \( i \)th smallest event, \( n \) is the total number of events and \( a \) is a parameter \( (0 \leq a \leq 1) \) whose value depends on a particular distribution.

Because low-flow events are persistent over periods of days or weeks, a difficulty arises over the independence of items in the data series, that is, low flow on Day0 is closely correlated with the low flow on the previous day, Day−1, and the next day, Day+1. It may be possible to select a single item as the minimum daily flow for a given year, but it is likely that this flow value is equalled on a number of days. Thus, extreme probabilities of low flows are often applied to minimum values that are averaged over different durations to produce annual minimum (\( n \)-day) series. The derived time series are the result of passing an \( n \)-day moving average through the daily data, and it is common practice to consider \( n \) as 7, 10 or 15 d. It is also important that the hydrological year used for selecting the low-flow data is arranged so that the low-flow season is not split between years. In the northern hemisphere, the calendar year is often used to select the annual minimum flows as the low-flow period commonly occurs in late summer, namely July and August. For a location in the southern hemisphere, the hydrological year is defined to start on 1 August, as the summer covers the December–February period.

### 4.3.5 Streamflow deficit

Streamflow deficits are periods when the river is below a specific threshold that defines a drought or critical deficit. The most widely used with regard to assessing the importance of low-flow periods is the threshold level method, which defines reliability (or rather variation from reliable flow requirements). Figure 24 shows the definition of the timing, durations and volumes of deficits below a threshold discharge in a river.

The threshold level \( Q_0 \) is also referred to as the truncation level and is used to define whether the flow in a river is in deficit (Figure 24). The deficit starts when the flow goes below the threshold and ends as soon as the flow returns above the threshold. Thus, the beginning and the end of a deficit period can be defined. In addition, the following deficit characteristics can be defined:
(a) The duration, which is the period of time when the flow is below the threshold level and is also referred to as drought duration, low-flow spell or run length ($d_1$, $d_2$, and so forth in Figure 24);

(b) The volume or severity, which is also referred to as drought volume or run sum (the shaded areas in Figure 24);

(c) The intensity, which is also referred to as deficit or drought magnitude, $m_i$, is the ratio between deficit volume ($v_1$, $v_2$, and so forth in Figure 24) and deficit duration;

(d) The minimum flow of each deficit event ($Q_{\text{min}}$ in Figure 24);

(e) The time of occurrence, for example, the starting date, the mean of the onset and termination, or the date of the minimum flow.

Based on the time series of the deficit characteristics, it is possible to derive indices such as the average deficit duration or average deficit volume.

4.4 HIGH GROUNDWATER LEVELS

The presence of an aquifer at the NPP site, although providing a potential reliable water source, must also be assessed for the risks it may impose during periods of high groundwater levels. The response of groundwater to excess rainfall is often complex. It is dependent on the nature of the aquifer, its size and configuration, even in localized sites, with regard to recharge areas, outflow controls and particularly if it displays artesian characteristics.

Typically, where a catchment has a significant proportion of groundwater influence from a predominant aquifer, it can be expected that the immediate response to heavy rainfall will be reduced by the proportion that goes directly to aquifer recharge. However, the longer-term build-up of groundwater, for example during a prolonged wet season, can result in high groundwater levels and even flooding of low-lying areas, at some significant time lag after the time when rainfall occurred. The structure of the aquifer may also be such that the location of groundwater flooding may be separate from the area in which the main rainfall occurred. As the decline in high groundwater levels usually takes place slowly, it may take some time for groundwater flooding to recede.

Major wetlands such as the Okavango Swamp in Botswana are maintained by wet season rainfall over a vast area remote from the swamp, which lies in an essentially arid or semi-arid

Figure 24. A drought sequence illustrating variable streamflow deficit

Source: Hisdal et al. (2004). © Elsevier BV.
area adjacent to the Kalahari Desert. Similarly, the river flows and aquifers of the Murray–Darling Basin in central Australia are dependent on rainfall falling over the mountains that run parallel to the east coast of the continent. The controlling aquifer is known as the Great Artesian Basin. Much smaller areas can be affected by artesian behaviour, for example, areas of north-eastern France and south-eastern United Kingdom after excessive rainfall over two winters, 2000–2002. Both areas have a geological basin structure, with extensive limestone (chalk) aquifers. The social impact of this response was exacerbated in that there had been two significant droughts in the previous decade (1990–1999). There were several examples in south-east United Kingdom of new building construction during the drought period that became flooded from rising groundwater in 2001 and 2002, which had not been anticipated during design.

A commonly observed feature in many climatic areas is that a period of heavy rainfall occurs after a prolonged or intense drought. In these situations where groundwater levels have become severely depressed (lowered), it has also been observed that after a time lag, in which initial soil and substrata recharge takes place, recharge to the aquifer is accelerated, leading to a rapid recovery in groundwater levels and even flooding. The important point to note from these examples is the long time frame over which the drought–flood sequence took place. Figure 25 illustrates the behaviour of rising groundwater beneath a river valley in a typical aquifer-controlled area.

As well as deep, extensive strata on a basin scale, groundwater flooding can also occur in areas of shallow, unconsolidated sedimentary aquifers that overlie an impermeable base. These aquifers are susceptible to flooding as the storage capacity is often limited, direct rainfall recharge can be relatively high and the sediments may be permeable, creating a good hydraulic connection with adjacent river networks. Groundwater levels in this situation are often close to the ground surface during much of the year. Intense rainfall can cause a rapid response in groundwater levels; rising river levels, as the upstream catchment responds to the rainfall, can create increased heads that drive water into the aquifer. Figure 26 illustrates the process of groundwater flooding in these areas. The groundwater surface is in hydraulic continuity with the river, and as the river rises, outflow through the riverbed sediments flows into the shallow aquifer and floods low-lying, protected areas behind levees.

Natural levees and human-made structures can allow river levels to rise without overflowing their banks. However, in this situation, groundwater flooding will occur in low-lying areas beyond the banks, preceding any fluvial flooding and lengthening the overall period of flooding. Flooding in these systems can be relatively short-lived compared with major basin aquifer flooding such as rivers, thus returning to pre-flooding levels and quickly draining the highly permeable aquifer. These hydrogeological settings often coincide with urban areas or protected major flood-plains. The contribution of groundwater to flooding needs to be addressed separately, as the traditional

![Figure 25. Groundwater (GW) flooding due to a rising water table in an unconfined major aquifer setting](https://www.bgs.ac.uk/research/groundwater/flooding/major.html)
engineered methods of flood protection may be circumvented by flow through the subsurface. There is a difficulty in that it can be hard to distinguish this type of groundwater flooding from fluvial or pluvial floods.

Where there are rapid fluctuations in groundwater (water table) levels of significant magnitude, risks may exist to the foundations of a major building. It may be anticipated that for a major structure like an NPP, deep and extensive foundations will be required. The fluctuations of groundwater levels can result in changing pore pressure within the soil or rock in which the foundations have been constructed. The changes in pore pressure could introduce stresses within the structure, unless allowed for in the design, perhaps by providing an impermeable vertical curtain outside the foundation. Repeated fluctuations of water level and pressure can cause weakness to develop progressively over a long period (several years). A special case of this situation can arise when the groundwater characteristics of a site or locality are drastically altered by major changes in water uses. For example, it became apparent that groundwater levels below central London rose steadily during the latter part of the twentieth century as major industrial users of groundwater decreased. This phenomenon has been of such an extent that foundations built in the dry 100 or more years ago are now in saturated conditions, and basements and underground railways have to be pumped for long intervals to remove water. Similar behaviour has been observed in former mining areas or major industrial sites where regular dewatering activities have ceased.

The assessment of this aspect of hydroclimatological risk can be made only through careful hydrogeological characterization of the catchment, along with long-period analysis of rainfall and groundwater records. Remedial measures against the risk of groundwater flooding usually involve dewatering by significant underground drainage systems connected to a network of wells (well field) that can be pumped at required intervals.

4.5 WATER CONTAMINATION

Section 2.1 outlined water quality management requirements. Operators of NPPs will have to obtain licences and permits with water management agencies to detail the control requirements for potential contaminants. It is usual for plant operators to carry out routine monitoring – of operating performance and of receiving waters. However, the water management agency should also carry out check monitoring, particularly for physical and chemical indicators remote from the site, and also biological and biodiversity checks at more infrequent intervals.

The routine monitoring programme has to be linked to emergency response actions, in reporting and in instigating remedial measures. Monitoring can also provide inputs to water quality

Figure 26. Groundwater flooding due to a rising water table in a shallow unconsolidated sedimentary aquifer setting

Source: Based on https://www.bgs.ac.uk/research/groundwater/flooding/unconsolidated.html, with permission of the British Geological Survey
modelling, aimed at performance checking and prediction. Water quality models based on the rate and quality of the effluent and the flow and quality of the receiving stream are used to determine the frequency distribution of downstream water quality.
5. DESIGN-BASED PARAMETERS

Site Evaluation for Nuclear Installations (IAEA, 2016a) gives requirements for site-specific hazard assessment and derivation of the related design basis. Examples of such requirements relevant for meteorological and hydrological hazards are:

- The extreme values of meteorological variables and rare meteorological phenomena listed below shall be investigated for the site of any installation. The meteorological and climatological characteristics for the region around the site shall be investigated.

- To evaluate their possible extreme values, the following meteorological phenomena shall be documented for an appropriate period of time: wind, precipitation, snow, temperature and storm surges.

- The output of the site evaluation shall be described in a way that is suitable for design purposes for the plant, such as the probability of exceedance values relevant to design parameters. Uncertainties in the data shall be taken into account in this evaluation.

- The potential for the occurrence and the frequency and severity of lightning shall be evaluated for the site.

- The region shall be assessed to determine the potential for flooding due to one or more natural causes, such as runoff resulting from precipitation or snowmelt, high tides, storm surges, seiches and wind waves, that could affect the safety of the nuclear installation. If there is a potential for flooding, then all pertinent data, including historical data, meteorological and hydrological, shall be collected and critically examined.

- A suitable meteorological and hydrological model shall be developed with account taken of the limits on the accuracy and quantity of the data, the length of the historical period over which the data were accumulated, and all known past changes in relevant characteristics of the region.

- The possible combinations of the effects of several causes shall be examined. For example, for coastal sites and sites on estuaries, the potential for flooding by a combination of high tides, wind effects on bodies of water and wave actions, such as those due to cyclones, shall be assessed and taken into account in the hazard model.

- The parameters used to characterize the hazards due to flooding shall include the height of the water, the height and period of the waves (if relevant), the warning time for the flood, the duration of the flood and the flow conditions.

- The potential for instability of the coastal area or river channel due to erosion or sedimentation shall be investigated.


5.1 METEOROLOGICAL PARAMETERS

Definition of the environmental parameters follows evaluation of the extreme values for the quantities of interest including the duration of such conditions, their periodicity and their reasonable combination with other load cases, such as wind or precipitation. For the different meteorological hazards, extreme values are specified, and Meteorological and Hydrological Hazards in Site Evaluation of Nuclear Installations (IAEA, 2011) describes the hazard assessment methods. Table 14 shows examples of design-basis parameters for meteorological hazards.
Table 14. Examples of criteria for defining the design-basis parameters for a given meteorological variable as taken from the practice in a particular State

<table>
<thead>
<tr>
<th>Design parameter</th>
<th>Frequency of occurrence/return period</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Air temperature</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum dry bulb temperatures and coincident wet bulb temperatures</td>
<td>100 year return period; 1% (2%) annual frequency of exceedance</td>
<td>The dry bulb temperature that will be exceeded for 1% (2%) of the time annually and the mean coincident wet bulb temperature; these parameters are used for cooling applications such as air conditioning</td>
</tr>
<tr>
<td>Maximum non-coincident wet bulb temperatures</td>
<td>100 year return period; 1% (2%) annual frequency of exceedance</td>
<td>This parameter is useful for cooling towers, evaporative coolers and fresh air ventilation systems</td>
</tr>
<tr>
<td>Minimum dry bulb temperature</td>
<td>100 year return period; 98% (99%) annual frequency of exceedance</td>
<td>This parameter is used in the sizing of heating equipment</td>
</tr>
<tr>
<td><strong>Wind</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 s gust wind speed</td>
<td>100 year return period; at 10 m above the ground that has a 1% annual frequency of exceedance</td>
<td>This parameter is used to specify wind loads</td>
</tr>
<tr>
<td><strong>Precipitation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Local intense precipitation</td>
<td>100 year return period; PMP depth of rainfall for a specified duration and surface area</td>
<td>This parameter is used for water drainage systems and flooding evaluations</td>
</tr>
<tr>
<td>Ground snowpack weight</td>
<td>100 year return period</td>
<td>This parameter is used for determining the design snow loads for roofs</td>
</tr>
<tr>
<td>Ice thickness and concurrent wind speed</td>
<td>100 year return period</td>
<td>These parameters are used in the design of ice-sensitive structures such as lattice structures, towers and overhead lines</td>
</tr>
<tr>
<td><strong>Lightning</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lightning strike frequency</td>
<td>Lightning strikes per year</td>
<td>This parameter is used in the design of lightning protection systems</td>
</tr>
<tr>
<td><strong>Tornadoes</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum wind speed</td>
<td>10 000 year return period; tornado having a 0.01% annual frequency of exceedance (10 000 year mean recurrence interval)</td>
<td>Maximum wind speed resulting; this parameter is used to specify wind loads due to the passage of a tornado</td>
</tr>
<tr>
<td>Pressure drop</td>
<td>10 000 year return period; tornado having a 0.01% annual frequency of exceedance (10 000 year mean recurrence interval)</td>
<td>This parameter is used to evaluate the capacity of airtight structures to withstand a drop in atmospheric pressure due to the passage of a tornado</td>
</tr>
<tr>
<td>Rate of pressure drop</td>
<td>10 000 year return period; tornado having a 0.01% annual frequency of exceedance (10 000 year mean recurrence interval)</td>
<td>This parameter is used to evaluate the capacity of ventilated structures to withstand a drop in atmospheric pressure due to the passage of a tornado</td>
</tr>
</tbody>
</table>
### Design Parameters

<table>
<thead>
<tr>
<th>Design parameter</th>
<th>Frequency of occurrence/return period</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Massive tornado missile</td>
<td>10,000 year return period; tornado having a 0.01% annual frequency of exceedance (10,000 year mean recurrence interval)</td>
<td>The mass and velocity of a massive high kinetic energy missile that deforms on impact (for example, an automobile) resulting from the passage of the maximum wind speed tornado; this parameter tests the resistance of tornado barriers to gross failure</td>
</tr>
<tr>
<td>Rigid tornado missile</td>
<td>10,000 year return period; tornado having a 0.01% annual frequency of exceedance (10,000 year mean recurrence interval)</td>
<td>This parameter tests the resistance of tornado barriers to missile penetration</td>
</tr>
<tr>
<td>Small rigid tornado missile</td>
<td>10,000 year return period; tornado having a 0.01% annual frequency of exceedance (10,000 year mean recurrence interval)</td>
<td>This parameter tests the configuration of openings in tornado barriers</td>
</tr>
</tbody>
</table>

*Source:* IAEA (2011)

The values of the design-basis parameters for design purposes are derived by statistical treatment or by associating them to a given annual frequency of exceedance (or return period) for each of the different meteorological hazards in relation to their potential effects on the plant.

If relevant to the site, the design-basis parameters for other site-specific meteorological phenomena that have been identified and assessed for the plant design basis are the following:

(a) Duststorms and sandstorms:

   (i) Total dust or sand loading (kg m$^{-2}$);
   (ii) Duration (h);
   (iii) Average loading (mg m$^{-3}$);

(b) Hail:

   (i) Historical maximum hailstone size;
   (ii) Concurrent terminal velocity;

(c) Freezing precipitation and frost-related phenomena:

   (i) Nominal ice thickness;
   (ii) Concurrent wind speed.

The derivation of the design-basis parameters and the relevant loading scheme should be carried out consistently with the level of detail required for the design limit assessment (for example, structural integrity, leak tightness and functionality) and to the accuracy level associated with the design procedures to be applied.

### 5.2 HYDROLOGICAL PARAMETERS

All significant parameters and their foreseeable changes should be taken into account. The following parameters need to be taken into consideration:

- Rainfall at the site
Guidelines on Meteorological and Hydrological Aspects of Siting and Operation of Nuclear Power Plants

- Runoff of water from off-site precipitation
- Snowmelt – seasonal or due to volcanism
- Failure of water-retaining structures (hydrological, seismic and from faulty operation)
- Failure of natural obstruction created by landslides, ice, log or debris jams and volcanism (lava or ash)
- Sliding of avalanches and/or landslides into water bodies
- Rising of upstream water level due to stream obstructions (see scenarios above)
- Changes in the natural channel for a river
- Storm surges due to tropical or extratropical cyclones
- Tsunamis
- Seiches, also combined with high tides
- Wind-induced waves

For the specification of flood protection measures, the dependency of flood runoff and flood level on the frequency of occurrence should be evaluated. *Meteorological and Hydrological Hazards in Site Evaluation of Nuclear Installations* (IAEA, 2011) provides assessment methods for hydrological hazards.

The design robustness and margin against floods rely primarily on the safety margin considered in the design base flood level and in the way that uncertainties associated with flood hazard assessment have been considered. Active equipment and electrical systems lose their functionality when they get wet or when the power supply elements are affected by water, producing short circuits and ground faults. There is a relatively limited safety margin associated with SSC capacity in relation to the flood impact. Active equipment and electrical systems lose their functionality when they get wet or when the power supply elements are affected by the water, producing ground faults.

5.2.1 **Local flooding**

Flooding of the site produced by local intense precipitation is used to design the site drainage system. The conditions resulting from the worst groundwater level at the site constitute the design-basis groundwater parameters.

The return period for local intense precipitation/local flooding is 100 years or as prescribed by the national regulations.

5.2.2 **Design-basis flood**

The design-basis flood level for a given site may result from the simultaneous occurrences of more than one severe event, not just from the occurrence of one extreme event. In deriving the design-basis flood for a plant site, all sources of flood and credible combined events should be considered as well as the single events for which the corresponding hazards should be assessed in accordance with *Meteorological and Hydrological Hazards in Site Evaluation of Nuclear Installations* (IAEA, 2011).
The maximum water elevation that the water surface reaches during one single hydrological event or a combination of hydrological events, including the increase of water due to simultaneous wind and wave phenomena, constitutes the design-basis flood parameters. When relevant, such as for tsunamis or wind waves, the associated run-up height and inundation horizontal flood should be included in the design-basis parameters for such phenomena.

The design-basis flood characterized by the maximum water elevation is needed for design of the flood protection for the safety-related SSCs using the dry site concept, permanent barriers or a combination of both.

The return period for the design-basis flood is 10,000 years or as prescribed by the national regulations.

The minimum water elevation that the water surface reaches during one single hydrological event or in a combination of hydrological events, such as tsunamis and seiches and the associated duration of the drawdown, constitute the design-basis low-water parameters. These parameters are needed for designing the water intake for providing ultimate heat sink capabilities.

The interdependence or independence of the potential flood-causing phenomena should be examined in relation to the specific characteristics of the site. In addition, appropriate sensitivity analysis should be conducted to ensure that the design-basis flood incorporates all the uncertainties involved in the natural events. In many combinations of flood-causing events, the distinction between dependent events and independent events is not sharp. For example, sequential meteorological events are only partially dependent on or are fully independent of each other. Seismic events and wind events are independent.

Combinations of events should be carefully analysed with account taken of the stochastic and non-linear nature of the phenomena involved as well as any regulatory requirements or guidance applicable for such cases.

Furthermore, the ambient conditions that are relevant for the important flood-causing event or for each event of the selected combination should also be taken into account.

Appropriate combinations of extreme events with wind waves and reference water levels should be taken into account, by considering:

(a) Extreme events (such as storm surges, river floods, seiches and tsunamis);
(b) Wind waves related to or unrelated to the extreme events;
(c) Reference water levels (including tides if significant).

The annual frequency of exceedance for each combination should be estimated. In this estimation, the duration of each event should be considered.
6. MEASURES FOR SITE PROTECTION

For practical reasons, most protective measures on the site deal with flooding hazards rather than low-water hazards or meteorological hazards. Such measures for protection are included in *Meteorological and Hydrological Hazards in Site Evaluation of Nuclear Installations* (IAEA, 2011)

External barriers and natural or artificial plant islands should be considered as features important to safety. They should be designed, constructed and maintained accordingly.

A study of the measures for protection should be performed after a complete understanding of the hydraulic and geological environment of the site has been gained. *External Events Excluding Earthquakes in the Design of Nuclear Power Plants* (IAEA, 2003) and *Meteorological and Hydrological Hazards in Site Evaluation of Nuclear Installations* (IAEA, 2011) provide detailed guidance on site protection.

6.1 TYPES OF PROTECTION

An NPP should be protected against the design-basis flood by one of the following approaches:

- The “dry site” concept. In this case, all items important to safety should be constructed above the level of the design-basis flood, with account taken of the effects of wind waves and the potential accumulation of ice and debris.

- Permanent external barriers such as levees, sea walls and bulkheads. In this case, care should be taken that appropriate design bases (for example, for seismic qualification where relevant) are selected for the design of the barriers. The permanent external barriers should be considered items important to safety.

For both approaches, as a redundant measure against flooding of the site, the protection of the NPP against extreme hydrological phenomena should be augmented by waterproofing and by the appropriate design of all items necessary to ensure the fundamental safety functions in all plant states. All other SSCs important to safety should be protected against the effects of a design-basis flood.

A warning system should be provided that is able to detect conditions indicating the potential for flooding of the site with sufficient time to complete the safe shutdown of the plant together with the implementation of emergency procedures.

All items important to safety (including warning systems powered by a protected off-site power supply) should be designed to withstand the flood-producing conditions (for example, wind and landslides, but excluding highly unlikely combinations) that are considered characteristic of the geographical region in which the site is located.

6.2 ANALYSIS OF PROTECTION

Flood hydrostatic and hydrodynamic pressures in combination with other relevant effects should be considered. In many cases, the effects of ice and debris transported by the flood are important variables in the evaluation of pressure. Erosion by floods can also affect safety.

Other factors relating to hydrological issues should be considered in site evaluation, mainly for their potential effects on water intakes and thereby on safety-related items:

- Sedimentation of the material transported by the flow

- Erosion
– Blockage of water intakes by ice and/or debris

Water ingress of water into safety-related structures through poor sealing in structural joints or cable conduits and openings should be prevented.

The two approaches to flood protection outlined in section 6.1 are the basic ones for protecting an NPP from the consequences of a flood. Protection can be achieved by a combination of both approaches. Groundwater level and any work on or around the site, such as construction, that may influence the level of flood water at the site should be carefully analysed.

In this framework, structures for flood protection should be analysed in a manner similar to that for the other structural items important to safety.

6.3 STABILITY OF THE SHORELINE

The stability of the shoreline near the site should be investigated together with the effects of the prospective NPP on the stability of the shoreline. Any changes that may affect the drainage of rivers, such as the construction of barrages or bridges, should be considered in the flow patterns of water from the river and the sea.

For a river site, the stability of the river channel in extremely heavy flood conditions should be considered.

For a coastal site, two aspects should be properly considered: (a) the long-term stability of the shoreline and (b) its stability against severe storms. An analysis should be performed to determine the potential for instability of the shoreline at the plant site and for any possible consequences for items important to safety. Severe storms can cause significant modifications of the littoral zone, particularly the profile of a beach. Although the long-term profile of a beach in equilibrium is generally determined by its exposure to moderately strong winds, waves and tidal currents rather than by infrequent events of great magnitude, events of both types should be considered. Meteorological and Hydrological Hazards in Site Evaluation of Nuclear Installations (IAEA, 2011) provides more guidance on stability of the shoreline.
7. CHANGES IN HAZARDS WITH TIME

7.1 CLIMATE CHANGE AND HAZARDS

7.1.1 Synthesis of recent Intergovernmental Panel on Climate Change findings

The IPCC reports give comprehensive synthesis on the subject of climate change (IPCC, 2013, 2014a, 2014b, 2014c).

The summary for policymakers in the synthesis report (IPCC, 2014c) contains important conclusions, the following of which are important with regard to siting and operation of NPPs:

(a) Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen.

(b) Continued emission of GHGs will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems. Limiting climate change would require substantial and sustained reductions in GHG emissions, which, together with adaptation, can limit climate change risks.

(c) Cumulative emissions of carbon dioxide (CO$_2$) largely determine global mean surface warming by the late twenty-first century and beyond. Projections of GHG emissions vary over a wide range, depending on socioeconomic development and climate policy.

(d) Surface temperature is projected to rise over the twenty-first century under all assessed emission scenarios. It is likely that heatwaves will occur more often and last longer, and that extreme precipitation events will become more intense and frequent in many regions. The ocean will continue to warm and acidify, and global mean sea level to rise.

(e) With regard to projecting changes in the water cycle, changes in precipitation in a warming world will not be uniform:

(i) Under the baseline scenario without additional effort to constrain emission of GHGs, the high latitudes and the equatorial Pacific are likely to experience an increase in annual mean precipitation by the end of this century. In many mid-latitude and subtropical dry regions, mean precipitation will likely decrease, while in many mid-latitude wet regions, mean precipitation will likely increase.

(ii) Extreme precipitation events over most mid-latitude land masses and over wet tropical regions will likely become more intense and more frequent as global mean surface temperature increases.

(iii) Globally, in all four scenarios (RCPs) considered for GHGs, it is likely that the area encompassed by monsoon systems will increase, monsoon precipitation is likely to intensify and ENSO-related precipitation variability on regional scales will likely intensify.

(f) With regard to projecting changes in ocean, cryosphere and sea level:

(i) The global ocean will continue to warm during the twenty-first century. The strongest ocean warming is projected for the surface in tropical and northern hemisphere

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These conclusions are inevitably much generalized and should not be applied uncritically to site-specific conditions and investigations. Many national organizations have defined their own guidelines on applying adjustment factors for climate change.
subtropical regions. At greater depth, the warming will be most pronounced in the Southern Ocean (high confidence). It is likely that the Atlantic Meridional Overturning Circulation (AMOC) will weaken over the twenty-first century, with best estimates and model ranges for the reduction from 11% to 34% on the mean. Nevertheless, it is unlikely that AMOC will undergo an abrupt transition or collapse in the twenty-first century.

(ii) Year-round reductions in Arctic sea ice are projected for all scenarios considered. The subset of models that most closely reproduce the observations projects that a nearly ice-free Arctic Ocean in the month of September is likely for the baseline scenario without additional constraint on GHG emissions, before mid-century (medium confidence). In the Antarctic, a decrease in sea ice extent and volume is projected with low confidence. The area of northern hemisphere spring snow cover is likely to decrease by 7% to 25% by the end of the twenty-first century for the multi-model average (medium confidence). It is virtually certain that near-surface permafrost extent at high northern latitudes will be reduced as global mean surface temperature increases. The area of permafrost near the surface (upper 3.5 m) is likely to decrease by 37–81% for the multi-model average (medium confidence). The global glacier volume, excluding glaciers on the periphery of Antarctica (and excluding the Greenland and Antarctic ice sheets), is projected to decrease by 15–85% (medium confidence).

(iii) Sea-level rise will not be uniform across regions. By the end of the twenty-first century, it is likely that sea level will rise in more than about 95% of the ocean area. Sea-level rise depends on the pathway of CO$_2$ emissions, not only on the cumulative total; reducing emissions earlier rather than later, for the same cumulative total, leads to a larger mitigation of sea-level rise. About 70% of the coastlines worldwide are projected to experience sea-level change within ±20% of the global mean. It is likely that there will be a significant increase in the occurrence of future sea-level extremes in some regions by 2100.

In addition, *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (IPCC, 2012) covers the following issues:

- Climate change: new dimensions in disaster risk, exposure, vulnerability and resilience
- Determinants of risk: exposure and vulnerability
- Changes in climate extremes and their impacts on the natural physical environment
- Changes in impacts of climate extremes: human systems and ecosystems
- Managing the risks from climate extremes at the local level
- National systems for managing the risks from climate extremes and disasters
- Managing the risks: international level and integration across scales
- Towards a sustainable and resilient future
- Case studies

Figure 27 summarizes some of the climate-related drivers of impacts and associated risks.

7.1.1.1 Implications in terms of design parameters

The typical design lifespan of NPPs is 30–40 years. However, it is now widely accepted that with proper management, vigilance and safety enhancements, it is feasible that many new NPPs will be able to operate in excess of their design lives, typically up to 80 years. During such a period,
it is obvious that climate can no longer be considered as stationary. This has a deep impact on the estimates of design parameters and operations. This is especially the case for estimates of the return period of extreme events.

Major advances in the last few years, detailed in IPCC AR5 (IPCC, 2013), are an important potential support to decision-making. These include: climate prediction at the regional scale, including extremes; implementation of a global archive giving access to individual and ensemble results of climate simulations (CMIP archive); assessment of extremes from time series presenting a trend; and use of internationally recognized climate indices.

Figure 27. Some climate-related drivers of impacts and associated risks

Source: IPCC (2014c), Table 2.3
7.1.1.2 Changes in extreme events with time

In the context of the changing climate, it is important to assess the potential for changes in extreme events as a function of time given the long design life of NPPs.

Roth et al. (2012) state that design values for infrastructures in general are often based on characteristics of extreme precipitation. These characteristics may have changed over time owing to climate change, which contradicts the stationarity assumption that is usually made in hydrologic and hydraulic design. Wrongly assuming stationarity generally leads to systematic errors in design values, and might have a considerable impact on the risk of failure of hydraulic structures.

Hence, research is ongoing on how to assess the changes in extreme events; for example, the Coordinated Regional Climate Downscaling Experiment of WCRP to advance and coordinate the science and application of regional climate downscaling through global partnerships or the Extreme Events and Environments – from climate to Society project of Future Earth.

Changes in extreme events with time can be identified by calculating the extreme quantiles for different periods of time (for example, successive 30 year reference periods for the evaluation of climate normals), assuming that non-stationarity over these periods is small enough. Better and more sophisticated methods exist in which the parameters in the statistical models such as GEV and POT vary over time (Laurent and Parey, 2007; Roth et al., 2012).

Many statistical packages are available to perform extreme value statistical analysis and provide the necessary guidance. The Extreme Value Analysis Software (https://www.assessment.ucar.edu/toolkit/) is particularly well suited for analysing extreme value data. Important additional information that can be derived is the confidence interval. The software is able to manage linear trends in any of the three parameters of the GEV distribution.

7.1.1.3 Datasets for indices of climate extremes derived from in situ data

Climdex is a project that produces a suite of in situ and gridded land-based global datasets of indices representing the more extreme aspects of climate. Indices are derived from daily temperature and precipitation data using the definitions recommended by ETCCDI. Some of them are relevant to the objectives of these Guidelines, and are useful as a first guess of expected regional extremes.

Climdex provides access to:
- Station-based indices calculated from datasets such as the Global Historical Climatology Network and European Climate Assessment & Dataset
- Data available from regional workshops coordinated by ETCCDI
- Global gridded datasets such as HadEX, HadEX2, GHCNDEX and HadGHCND (Donat et al., 2013); descriptions of all the datasets are provided at the Climdex website (https://www.climdex.org/index.html)

Datasets for indices of climate extremes derived from climate models

Projected changes in return periods of extremes have also been derived from global climate models participating in the Coupled Model Intercomparison Project Phase 3 (CMIP3) and Phase 5 (CMIP5) (Kharin et al., 2007).

The climate extremes indices defined by ETCCDI were computed for global climate models participating in CMIP3 and CMIP5 (see https://esgf-node.llnl.gov/projects/esgf-llnl/), contributing to the climate projections described in the IPCC Assessment Reports, and reanalyses. They can be downloaded at ftp://ftp.cccma.ec.gc.ca/data/climdex/.
Currently, ETCCDI recommends 27 core indices, known as the ETCCDI indices, which are calculated for the globe using the RClimDex/FClimDex software and defined at http://etccdi.pacificclimate.org/list_27_indices.shtml. Sillmann et al. (2013a, 2013b) present validation of climate extremes indices and analysis of their projected future changes simulated by the CMIP5 models.

The following are relevant databases:

- WMO Weather & Climate Extremes Archives (https://wmo.asu.edu/)
- EM-DAT, created in 1988 by the Centre for Research on the Epidemiology of Disasters at the University of Louvain, Belgium (https://www.emdat.be/)

### 7.1.2 Tropical cyclones and storm surges

Resio and Irish (2015) give an assessment of operational aspects of surge prediction and of potential effects of climate change on tropical cyclones. This section summarizes the latter part of their publication dealing with the effects on tropical cyclone hazards. As noted, tropical cyclone surge hazard can be influenced by long-term, anthropogenic GHG-driven climate change in two ways: (a) a mean increase in sea level (sea-level rise) upon which storm surge is generated and (b) a change in storm intensity and frequency. Both processes potentially increase the expected magnitude of the flood hazard as well as the uncertainty associated with projecting the hazard, yet changes in tropical cyclone intensity and frequency are also spatially variable. For example, Kossin et al. (2014) show a poleward migration of maximum cyclone intensity over the last 30 years, of the order of 50–60 km decade\(^{-1}\). While global occurrence of tropical cyclones is expected to decrease in the future, modelling studies yield decreases in frequency in the range of 6–34% globally by 2100 (Knutson et al., 2010), and there is wide variation in regional cyclone frequency projections (Bender et al., 2010; Villarini and Vecchi, 2012, 2013; Knutson et al., 2013). For example, Bender et al. (2010) reports projections for the twenty-first century with a dramatic rise in tropical cyclone frequency in the western North Pacific with less activity in the south-western Pacific.

Projecting future tropical cyclone frequency remains an evolving research topic. However, there is community consensus that future cyclones will likely be more intense (for example, Webster et al., 2005; Elsner et al., 2008; Emanuel et al., 2008; Kim et al., 2014). Knutson et al. (2010) report projections using theory and dynamic models yield a 3–21% global increase in tropical cyclone central pressure differential during the twenty-first century, and more recent studies continue to be consistent with these projections (for example, Kim et al., 2014). Long-term shifts in storm track and changes in storm size are also important for understanding future surge hazard. The impact of global warming on these parameters requires further study.

Future anthropogenic-induced changes in tropical cyclone frequency and intensity will change the surge hazard. The magnitude of impact of cyclone intensification on the surge hazard can be examined via the simple model of Knutson and Tuleya (2008), where tropical cyclone wind intensity increases by approximately 4% for every 1 °C increase in SST combined with the momentum conservation argument for surge generation, where surge at a given location is proportional to wind speed squared. It thus follows that surge will increase of the order of 8% for every 1 °C of SST warming (Woodruff et al., 2013). This means that a temperature rise of 1–5 °C over the next century (for example, IPCC, 2013) could translate to an increase in storm surge hazard of 8–40%. For example, a 2.0 m surge (of the order of the 100 year event in New York city; Lin et al., 2012) increases by 0.2 m to 0.8 m while a 5.0 m surge (of the order of the 100 year event in greater New Orleans, Louisiana; Niedoroda et al., 2010) increases by 0.4 m to 2.0 m.
While the impact of future changes in tropical cyclone intensity and frequency on future coastal flooding may be important in many local areas, it is expected to be less significant overall than the expected impact of future sea-level rise, especially in areas characterized by low-lying sedimentary coastlines (Woodruff et al., 2013 and references therein). Considering only a static rise in mean sea level, the total depth across the full range of return periods is likely to increase by of the order of 1 m by the end of this century (Parris et al., 2012). For example, Lin et al. (2012) consider projected future tropical cyclone ensembles and static increases in baseline mean sea level to project the future flood hazard in New York city. Their projections over a large range of extreme value probabilities show the dominating contributor to the accelerating flood hazard is sea-level rise (exhibiting an increase in flood level of the order of 1 m under 1 m of sea-level rise), with impacts from future changes in tropical cyclone climatology playing a secondary role. Yet, projections of global sea levels over the twenty-first century carry great uncertainty, with projections ranging from 0.2 to 2 m (for example, Vermeer and Rahmstorf, 2009; Parris et al., 2012 and references therein; National Research Council, 2014 and references therein), with the IPCC reporting a modest range of 0.26 m to 0.82 m (IPCC, 2013 and references therein), with significant additional contributions to local sea-level rise in many locations, for example due to sediment compaction or tectonics. Despite this uncertainty in the future rate of sea-level rise, that there will be future sea-level rise is certain, and its magnitude is expected to be significant enough to be the dominating contributor to future changes in the surge hazard.

Sea-level rise raises the mean sea level upon which surge is generated and propagates, and also facilitates long-term changes to the coastal landscape, potentially resulting in changes in tidal dynamics (Hagen et al., 2012) and enabling larger surges to propagate further inland (for example, Bilskie et al., 2014; Irish et al., 2014). For example, barrier island degradation induced by sea-level rise reduces the ability of these natural features to prevent ocean surge and waves from entering back-barrier areas (Irish et al., 2010). Likewise, sea-level rise induces changes to natural ecosystems, such as wetlands, and alters surge and wind-wave generation and propagation (Ferreira et al., 2014; Hu and Wang, 2015). These processes are highly non-linear; for example, Loder et al. (2009) show decreased resistance arising from wetland degradation (facilitating surge propagation) may be offset by increased water depths created as wetlands erode (inhibiting surge generation). Studies to assess the future surge hazard have largely ignored these dynamic shoreline and land-cover dynamics, mainly due to the difficulty and uncertainty in predicting and modelling these future changes.

Some specific regional effects expected in future climates from the IPCC summary for policymakers (IPCC, 2013) are given below.

7.1.2.1 **North America**

Monsoon precipitation will shift later in the annual cycle; increased precipitation in extratropical cyclones will lead to large increases in wintertime precipitation over the northern third of the continent; the frequency of tropical activity in the western North Pacific will increase, while decreasing in the southwestern North Pacific; the frequency of overall tropical cyclones will decrease slightly along the Gulf of Mexico, and the eastern coast of the United States and Canada; and the frequency of intense tropical storms will increase globally.

7.1.2.2 **Central America and the Caribbean**

Reduction in mean precipitation and increase in extreme precipitation; and more extreme precipitation in tropical cyclones making landfall along the eastern and western coasts.

7.1.2.3 **East Asia**

Enhanced summer monsoon precipitation; increased rainfall extremes of landfall typhoons on the coast; and reduction in the midwinter suppression of extratropical cyclones.
7.1.2.4 **South Asia**
Enhanced summer monsoon precipitation; and increased rainfall extremes of landfall cyclones on the coasts of the Bay of Bengal and Arabian Sea.

7.1.2.5 **Australia and New Zealand**
Summer monsoon precipitation may increase over northern Australia; more frequent episodes of the zonal South Pacific Convergence Zone may reduce precipitation in north-eastern Australia; increased warming and reduced precipitation in New Zealand and southern Australia due to projected positive trend in the Southern Annular Mode; and increased extreme precipitation associated with tropical and extratropical storms.

7.1.2.6 **Pacific islands**
Tropical convergence zone changes affect rainfall and its extremes; and more extreme precipitation associated with tropical cyclones.

7.2 **OTHER CHANGES**

7.2.1 **Introduction**
In addition to the impacts of global and regional climate changes, hazards may change over time due to natural and human-induced factors that may affect the safety and security of NPPs. These have to be considered over the entire lifetime of the facilities, including decommissioning, which can represent a period of up to 100 years.

The nature of the needs and risks of NPPs are such that their most common locations tend to be remote from large concentrations of population (safety considerations), and close to coasts or major rivers (for process and cooling water). These preferred sites cover a range of geographical, geological and geomorphological environments. This section will examine particular problems and issues concerning future safety. In some cases, the features will have a connection to meteorological and hydrological phenomena, for example floods and storms, that are detailed elsewhere in this publication. This section will examine some of the aspects that lie outside these major aspects of the report.

Each of the considerations dealt with should be considered within a suitable future time frame, related to the design life of the installation and the change horizons within each focus. Thus, the geographic considerations might relate to the changing human environment, for example, land-use and population changes, as well as plant redundancy and “mothballing” issues (preservation of an NPP without using it for production). Given that geological time frames are mostly long term, these aspects might be considered as somewhat irrelevant, but there are wide differences in the range of geological activities encountered, from the obvious example of earthquake and volcanic activity, to the more subtle changes in the physical environment, which can mostly be considered under the heading of geomorphology. The special nature of nuclear power is such that management of plants can extend well beyond their working life, to ensure safety relating to possible contaminated land and structural security of waste storage.

7.2.2 **Location considerations**
As mentioned above, there is a preference for NPPs to be located in remote sites. Coastal or estuarine locations are obvious choices for nations having a boundary with the sea or island nations. Remote coastline sites have been developed on hard rock shores as well as soft rock areas. Examples from the United Kingdom are Dounreay in the north, where the principal
rocks are hard shales and sandstones, and Dungeness in the south, built on an extensive gravel foreland or spit. For landlocked countries, remote sites may not be a problem, but the availability of sufficient water has to be dealt with.

Nuclear power sites have usually been constructed on government-owned land, which allows a high level of security and gives full control in terms of central, national planning. Thus, exclusion zones can be set up to limit how close private development (commercial and residential) can take place, and transport access, such as road or rail links, can be maintained. Contaminated land controls can be implemented that further limit redevelopment for a prolonged period, or set requirements for controlled site clearing, for example, in the case of asbestos construction material and waste material. Some change of land use after decommissioning can be considered, if, in the view of the appropriate government agencies, adequate measures of decontamination, health and safety and environmental monitoring have been undertaken.

7.2.3 **Earthquakes**

This topic will not be dealt with in depth here, as it is not directly relevant to meteorological and hydrological extremes. Earthquakes and tectonics are covered extensively from a comprehensive background of specialist studies, and many revised approaches have been developed since the tsunami and earthquake destruction of the Fukushima Daiichi NPP in 2011.

This incident was the result of a deep-seated earthquake immediately offshore from the NPP. However, there are situations where major tectonic disturbances, occurring remotely from the site, may have a significant influence on hydrological behaviour and river morphology. It is well documented that a major earthquake in the Assam region of India in the late eighteenth century released a vast load of sediment into the Brahmaputra River, destabilizing its lower course and drastically changing many river courses, for example the Teesta and Atrai, and partially closing the original course, which is now known as the “Old Brahmaputra” in present-day Bangladesh. Subsequent major earthquakes in Assam, in 1897 and 1950, rated at 8.3 and 8.6, respectively, on the Richter scale caused flooding from landslip blockages and subsequent collapse on major tributaries of the Brahmaputra. The underlying cause of these major events was the presence of a major zone along subducting tectonic plates, which extended along the south of most of the Himalayan range. The uplift and movement along such active tectonic zones in mountain areas, associated with steep slopes developed on unconsolidated superficial deposits, make associated downstream areas prone to flash floods and rapidly changing sediment loads (see the discussion in section 7.2.4 on mobile-bed rivers). Any planned nuclear power installations in these types of areas will need to take consideration of regional as well as local tectonic risks.

It is recommended that the hydrological investigations for a site should include a catchment-wide consideration of possible seismic and tectonic risks, particularly if headwater areas lie in active mountain zones. It is also recommended that some investigation be carried out on large historical floods to identify if tectonic-induced landslips have been a contributory cause.

7.2.4 **Geomorphology of river behaviour**

Although flood level and discharge are key considerations in hydrological studies, the fact that rivers, channels and catchments are part of an active physical continuum should also be taken into account. Given the preferred location of sites adjacent to rivers, the physical nature of the course of the river is important.

Rivers developed on hard rock strata will be the most stable, but even in these geological areas, rivers will develop a flood-plain to some extent. Meanders are a common feature of rivers in upland and lowland areas, and the potential for meanders to migrate is well documented. The main risk involved with a river course that shifts as it meanders is that intakes and outlets for process and cooling water will be exposed or silted up over time. The process of meander migration is mostly on a timescale of several years or decades; it may not be gradual, but subject to significant rapid change after the passage of a major flood.
River banks in alluvial deposits are likely to be prone to erosion; in conjunction with cycles of erosion and deposition, they can cause banks to shift laterally. The resultant realignment of the river channel, which may also be accompanied by widening or narrowing of the channel, can affect the site itself or ancillary structures. The tendency for channel variations can be identified from analysis of mapping over a period of years, and the need for bank protection and stabilization identified. Conversely, the effects of deposition may well require the need for river training works or a regular programme of maintenance by dredging. In highly seasonal rivers, such as in areas where there are major annual changes in flow volumes and velocities, for example, in monsoon-influenced rivers, the effects of erosion and deposition cycles can be significant. In addition to identifying these characteristics in feasibility, planning and design, the ongoing management of the site may require regular topographic and hydrographic surveys to monitor and identify changes.

Mobile-bed rivers present problems for river flow gauging, as the continually changing cross-sectional area will require more frequent measurement and modification of the stage (depth–discharge relationship) – also known as the rating curve. Where a river has a largely stable channel, the rating curve can be established over a few years, as long as a reasonable range of flows are encountered. However, with mobile-bed rivers, a regular programme of measurement has to be conducted on a permanent basis. Rating relationships, particularly for high flows, can change after floods, and in areas with a highly seasonal climate regime (for example, monsoon areas or those subject to extensive snow-thaw conditions), rating curves may need to be reconstructed annually.

A feature of large, alluvial rivers is the existence of hard points, which are stable locations on one or both banks, and which have a history of persisting when other parts of the river channel are subject to migrational change. These points can be identified by examination of mapping over time or by analysis of aerial photographs. Aerial photographs and latterly lidar surveys can identify historical former positions of abandoned meanders, past watercourses, flood levees and so forth. Hard points are used in the selection of stable sites for critical infrastructure like bridges, ferry termini, and powerline and pipeline crossings. There is a long history of identifying hard-point sites for bridge crossings in the Indian subcontinent, with the Bangabhandu road and rail bridge crossing the Brahmaputra River in Bangladesh being the latest.

A particular type of mobile-bed rivers that can give site problems are gravel bed rivers, which are prone to rapid changes during the course of a flood. The size range of gravel can extend from small stones through cobbles to boulders. These rivers are typical of areas where steep mountain rivers reach flatter river valley areas, where the sudden drop in kinetic energy causes the large-sized debris load to be deposited. In extreme cases, the river may have historically deposited an extensive alluvial fan, across which the river channel will migrate from time to time. Gravel bed rivers are widely encountered in mountainous areas with rainy climates, for example, New Zealand, Scotland and British Columbia.

Wadis and ephemeral streams are another specific type of fluvial morphology feature, and typical of desert and arid/semi-arid areas. Wadi channels are normally dry, and carry flow only at infrequent intervals due to intense localized rainfall, resulting in flash floods. They are typically formed at the base of steep hillsides where streams emerge onto flat areas, and usually carry a large sediment load of sands and gravels. The spate flows from wadis spread out at this change of slope, and deposit the sediment as an alluvial fan, across which short-lived channels may develop. Desert and arid area sites may be attractive for the location of NPPs because of their remoteness. However, the unpredictable and violent nature of wadi floods could produce serious problems if the site location were wrongly selected.

### 7.2.5 Coastal erosion and deposition

Like rivers, the coastal geomorphological environment is one of erosion and deposition. The erosion–deposition balance is a feature of soft rock and coastlines of unconsolidated strata. NPP sites need to be safely located to avoid direct erosion, or the risk of deposition and a shifting coastline compromising the safety and operational effectiveness of ancillary structures, for example, outfalls.
Many coastlines on soft strata are characterized by areas where erosion predominates, adjacent to areas where the main morphological activity is deposition, producing features like spits (sand or shingle), sand dunes parallel to the coast or offshore sand and shingle bars. In many cases, for example, the North Sea coasts in eastern United Kingdom and in the Netherlands, the arrangement of erosion and deposition on the shoreline is linked to offshore, submerged features of tidal ebb and flood channels. In this instance, the offshore structures originated as branching channels of the Thames–Rhine delta following the retreat of glaciers and rising sea levels after the last European Ice Age.

As with rivers, the identification of the presence of hard points as stable sites along a coastal or estuary shoreline should be considered as locations for possible NPP construction. Sites need not be hard in terms of localized strata, but rather one of stability between actively changing locations. Thus, the Sizewell nuclear power station on the coast of eastern United Kingdom, where the geology comprises unconsolidated sandstone and fluvioglacial sands and gravel, is located between sites of active coastal erosion to the north and a complex of highly mobile deposition of shingle bars and a major spit feature to the south.

7.2.6  **Groundwater**

The preferred types of site for NPPs (lowland areas close to rivers or coasts) are also areas where the presence of shallow groundwater may be expected. Construction of major infrastructure, such as buildings, roads and major bridges, as well as some NPPs, has enabled a high level of expertise in foundation work to be developed. This includes deep foundations, exclusion of groundwater by curtain walls in saturated subsoil conditions and building in the presence of significant aquifers with variable water tables. However, there may be specific hydrogeological conditions present that need special consideration, for example artesian influences (where the head of the groundwater body will cause water rise to rise up to or above the ground surface). As such, groundwater flooding can be generated remotely from the site of interest, and high water levels are transferred over often considerable distances through the aquifer. Therefore, flooding may occur days or weeks after the causative event, which is usually heavy and prolonged rainfall. Groundwater flooding can also persist over an extended duration.

Unanticipated changes in groundwater levels can introduce stresses on existing foundations through changes of pressure in the subsoil around foundations. Extensive groundwater lowering can occur naturally during severe and extended drought, though this tends to be a slow process, thus lessening the risk of impact to foundations. Rapid groundwater lowering can also be caused by overabstraction from surface and shallow subsurface aquifers. River valley bottoms and flood-plains are frequently used for irrigated agriculture, especially in areas subject to a strongly seasonal climate. Dangerously low groundwater levels have been widely reported from areas in monsoon Asia and Africa.

7.2.7  **Other factors**

Hazards may change over time due to other factors such as:

- Changes in the physical geography of the concerned drainage basins, including estuaries, for example, due to the construction of dams or storm surge barriers.

- Changes to the land use around the site, for example, due to wildfires, deforestation, urbanization, erosion and sedimentation, which will have effects on runoff.

- Changes to the offshore bathymetry, for example, by dredging.

- Land subsidence, either natural or human induced, resulting, for example, from extraction of oil, gas or water.

- Biological hazards that may affect cooling water systems, causing: (a) potential for the colonization and excessive growth of algae or shellfish within these systems, and clogging
of intake structures by large quantities of biological material such as aquatic plants, fish or jellyfish and (b) potential for unusual weather events to increase the risk of ventilation and cooling intake systems being clogged by biota. For example, flooding or large storm events can dislodge large biomasses of aquatic macrophytes that will foul the intake structures (CNSC, 2008).

The combined effects of the hazards resulting from climate and human-induced events should be considered.

Periodic re-evaluation of design parameters should be performed using appropriate means (such as in situ ground and aerial surveys, remote-sensing and modelling).
8. MONITORING, FORECASTING AND WARNING SYSTEMS FOR THE PROTECTION OF INSTALLATIONS

Meteorological and Hydrological Hazards in Site Evaluation of Nuclear Installations (IAEA, 2011) gives general recommendations on monitoring, forecasting and warning systems. These are aimed at regulatory bodies that are responsible for establishing regulatory requirements, at designers of nuclear installations and at operating organizations that are directly responsible for the safety of installations and for the protection of people and the environment from the harmful effects of ionizing radiation.

The general recommendations are:

1. When any meteorological event or hydrological event proves to be a significant hazard for the site of a nuclear installation, continuous monitoring of the site is an essential requirement from the initial phase of studies for site selection and site evaluation purposes, continuing throughout the entire lifetime of the nuclear installation, for the following purposes:

   (a) To validate the design-basis parameters, especially in cases for which the series of historical data are poor;

   (b) To support the periodic revision of the site hazards in the light of the periodic safety assessment (this concern is becoming increasingly urgent as a follow-up of the consequences of global climate change);

   (c) To provide alarm signals for operators and emergency managers.

2. For meteorological events and hydrological events, the monitoring and warning measures that should be taken during the operation of the nuclear installation will depend on the degree of protection offered by the selected site and on the consideration of these hazards in the design basis of the installation. Some of these measures should be implemented at an early stage of the project, as they can be useful in validation of the design-basis parameter values.

3. The data to be used for long-term monitoring and those to be used for a warning system should be chosen on the basis of different criteria, because their respective purposes are not the same. The purpose of long-term monitoring is the evaluation or re-evaluation of the design-basis parameters, for example when performing PSR. The purpose of the warning system is the forecasting of an extreme event that may affect operational safety. For the warning system, special care should be taken over its ability to detect any extreme events in sufficient time to enable the installation to be brought under safe conditions. A warning system should be put in place for sites for which hazards are significant for the design of the installation.

4. The warning system should be used in connection with forecasting models since the time period that would be necessary for operator actions to put the installation into a safe status may necessitate acting on the basis of extrapolations of trends in phenomena without waiting for occurrence of the hazardous event.

5. In the case of the occurrence of an event for which the operator relies on forecasting models made available by organizations external to the operating organization, validation of the models and of the communication channels with those organizations should be carried out to ensure their availability and reliability during the event.

6. Specific quality management or management system activities should be carried out to identify the competences and responsibilities for installing the monitoring systems, their
operation, the associated data processing and the appropriate prompting of operator action. These activities should include planning and executing drill exercises at given intervals for all parties involved.

7. In general, the following monitoring and warning networks should be considered:
   (a) A meteorological monitoring system for basic atmospheric variables;
   (b) A meteorological warning system for rare meteorological phenomena (for example, hurricanes, typhoons and tornadoes);
   (c) A water-level gauge system;
   (d) A tsunami warning system;
   (e) A flood forecast system.

8. If the region in which the installation site is located is covered by a warning system for meteorological and flood events, administrative arrangements should be made to receive the warnings reliably and on time. Otherwise, it should be considered whether to set up a dedicated monitoring system and warning system. The extent of the monitoring system and the frequency of observations should be consistent with local hydrological conditions.

9. Similar arrangements can be made with NMHSs, as most also issue watches and warnings (typically for the next few days) on the possible occurrence of severe weather, such as tropical cyclones, heavy rain with risk of flooding, severe thunderstorms with risk of tornadoes or hail, gale force winds, heatwaves, cold spells, snow, ice, severe coastal tides, storm surges, landslides, avalanches, forest fires, fog and sandstorms. Additional information and advice are generally given on the severity and intensity of the hazard, the expected time period for the given event to occur, its possible impact and any action to be taken. Such information and advice are generally made available by different means of communication. For example, specific messages are sent to registered professional users, with periodic updates (generally twice daily) and using different information systems (for example, the WMO Global Telecommunication System and the Internet) and media (for example, television, radio and newspapers).

Role of National Meteorological and Hydrological Services

NMHSs can play an important role to bring these general recommendations to realization through the provision of monitoring, forecasts and warnings to stakeholders. The specifics will vary from one State to another, in accordance with the structure of authority and responsibilities within a given State. NMHSs should therefore be involved early on in the discussions with stakeholders to present their capabilities, to identify the needs and to define the services.

A key element of the active participation of NMHSs is to ensure that stakeholders are informed in real time of present and expected meteorological and hydrological conditions that can affect safe operation of the NPP and ensuing decision-making.

8.1 METEOROLOGICAL MONITORING

Monitoring is identified as an essential requirement in general recommendation 1 above. This is further developed in Site Evaluation for Nuclear Installations (IAEA, 2016a):

The characteristics of the natural and human-induced hazards as well as the meteorological and hydrological conditions of relevance to the nuclear installation shall be monitored over the lifetime of the nuclear installation. This monitoring shall be commenced no later than the start of construction and
shall be continued up until decommissioning. All the hazards and conditions […] that are pertinent to the licensing and safe operation of the installation shall be monitored.

Chapters 2 and 3 of the present publication have already presented the parameters and hazards that require monitoring on a continuous basis. The reader is invited to refer to those chapters for details.

8.2 METEOROLOGICAL FORECASTS AND WARNINGS

8.2.1 Forecasts

A broad range of forecasts are produced by NMHSs on a continuous basis. They cover periods ranging from a few hours to many weeks. Their content should be adapted to the specific needs of stakeholders (see section 8.2.3).

Long-range forecasts (predictions from 30 d up to 2 years) on a global scale are produced by a few centres around the world, known as WMO GPCLRFs (see http://www.wmo.int/pages/prog/wcp/wcasp/clips/producers_forecasts.html). Their production requires huge amounts of computer power along with specialized knowledge. These set the frame or context essential for predicting climate and weather on regional and local scales, and are used by regional and local forecasting centres.

8.2.2 Warnings

Warnings are issued by NMHSs when a hazardous weather event that poses a significant threat to people or property is occurring, or is imminent or has a high probability of occurring. They are based on specific weather criteria and the impact they may have on the population or infrastructure (WMO, 1997). Warnings should also be tailored to stakeholder needs (see section 8.2.3).

In the case of hurricanes, tropical cyclones and typhoons, guidance is produced by six RSMCs together with six Tropical Cyclone Warning Centres having regional responsibility for information (see http://www.wmo.int/pages/prog/www/tcp/index_en.html). Their output consists of advisories and bulletins with up-to-date first-level basic information, and comprises reliable advice from a clearly defined source on storm location, size, and its present and forecast movement and intensity. NMHSs of individual countries provide advisories and bulletins with information and forecasts of current hurricanes, tropical cyclones and typhoons, which are threatening or could threaten the country. The advisories include, where applicable, official warnings of the impact on their national territory, local areas and coastal waters.

Tsunamis are not strictly hydrological or meteorological phenomena. However due to their importance and high-impact potential, it is important to mention that tsunami warnings are issued in real time by designated centres that are part of the International Tsunami Information Center (see http://itic.ioc-unesco.org/index.php).

8.2.3 Support to nuclear power plant operations

8.2.3.1 Normal operation

An NMHS should work in close partnership with other government agencies and stakeholders to identify what meteorological parameters and potential impacts are important to the normal operation of a specific NPP. A risk matrix can be developed (WMO, 2015c) to define quantitative criteria for the issuance of regular or special forecasts as well as warnings. Some are obvious, such as tornadoes, but there could also be a combination of factors that will have a major impact, for example heavy rainfall in a situation where the ground is already saturated.
8.2.3.2 **Emergency situation**

Criteria for additional special forecasts and warnings should also be determined with stakeholders in case an emergency situation develops at the NPP. There may be a need for additional temporal information such as 24 h forecasts of hourly wind direction and speed or precipitation. In the case of a potential or actual release of radioactive material to the atmosphere, RSMCs designated for the provision of atmospheric transport modelling produce specialized forecasts (see section 8.5).

In all cases, administrative arrangements, including backup options, should be made to receive the information reliably and on time.

8.3 **HYDROLOGICAL MONITORING**

The types of instruments involved in cases of extreme events are the same as those used for routine monitoring, as detailed in Chapter 2. The emphasis is that the networks used for extreme event monitoring, particularly floods, must be equipped with data logging and transmission capabilities, and be of sufficiently high quality to ensure accurate and reliable performance. Where an NMHS or NHS operates a broad-based monitoring and warning system, NPP operators should be recognized as a principal user, but if the network does not meet the operational need, then the operators should install their own system. A situation is envisaged where the NMHS/NHS can provide catchment-wide forecasts and warnings, but the NPP installation requires more localized information on rainfall and river conditions for more accurate timing and water-level information to help situation management. Instruments used need to be compatible with, or of higher specification, than NHS equipment, as the information obtained will be operation critical. All instruments should be automatic and linked to a central control room to operate in real time during a critical situation. The NPP information in these cases is to be used in conjunction with the storm and flood alert and warning services, which is discussed in the next section.

Important requirements should be the reliability of instruments and data-transmission facilities. A minimum requirement is to have 95–98% of reporting data available over an extended period (a month or year), with a stringent limit on the maximum duration of downtime of instruments, say not more than 6 or 12 h, as these are the usual intervals for quantitative precipitation forecast (QPF) updates. These stringent operational demands will require:

- A guaranteed power supply to instruments and operational headquarters, through reliable connections to main electricity networks and on-site generating equipment for emergency backup
- An ample supply of spares, replacement instruments and parts, to provide instant replacement
- Operational staff available to quickly identify faults and malfunctions, and to instigate repairs
- Adequate financial provision to support operation, maintenance and long-term viability of the system
- Periodic replacement or upgrade of instruments to use more recent technologies and standards

Having local and on-site instrumentation can be of significant importance to relate the developing and real-time conditions at the NPP with the forecast and warning information received from the NMHS. This will develop skill in the operators to interpret forecasts, understand developing situations and implement emergency procedures. Typical arrangements might include:

- A network of automatic telemetry raingauges within a short distance of the site
– An on-site radar with dual polarizing capability, most probably an X-band instrument to identify local rainfall patterns with more precision than that provided by a national weather radar network

– Water-level recorders for rivers at the site and an upstream location suitably sited to give a short lead-time warning

– Where relevant, a tide gauge to relate local conditions to forecast tidal conditions

8.4 HYDROLOGICAL FORECASTS AND WARNINGS

The production of flood forecasts and warnings requires a high level of coordination between meteorological and hydrological services. A specialist forecasting and warning unit for severe events is now common in NMHSs and NHSs. In some countries, there are dedicated joint operations for flood forecasting and warning provision, to the public and to particular clients. The latter can include weather warning services for highway agencies, railways, and power and shipping industries. It is recommended that NPP operators make special arrangements for their forecast and warning requirements.

Rainfall intensity and duration, precipitation forecasts, and past data for calibration of rainfall–runoff models are all necessary prerequisites to develop and operate a successful model-based flood forecasting and warning system. Meteorological data and forecasts are required in real time, to maximize the lead time for flood forecasts and warnings. The principal item of meteorological data used is rainfall. This is required from a network of raingauges or radar coverage, to provide a best estimate of rainfall over the area modelled, whether over a grid or to obtain a distributed basin average.

The traditional techniques for rainfall forecast estimation based upon ground-based telemetering raingauges and meteorological radars (for indicating spatial distribution) are still widely used. This is because networks have been progressively developed from conventional and broad-based hydrometeorological networks and are deemed cost-effective (Todini, 2001).

The three major benefits claimed for using radar data are:

– A finer spatial resolution of the precipitation field than normally possible from raingauges

– Real-time data availability

– The ability to track approaching storms even before they reach the boundary of the catchment or area of interest

In particular, where raingauges are sparse and/or storms are localized, radar has advantages. However, if storms are of large areal extent, simultaneously covering the sites of many raingauges, then raingauges tend to produce more accurate estimates of the rainfall amounts while the radar still gives a better indication of the spatial distribution than that achieved by classical methods such as Theissen polygon or kriging interpolation.

Global, regional and local area NWP models are utilized where available, to provide rainfall forecasts as inputs to flood forecasting models, or as added-value products to assist decision-making in a flood warning operation. Although QPFs have considerable uncertainty, and thus may have limited value in hydrologic models, their use can extend lead time significantly when combined with the skill and expertise of the forecaster. In a similar way to radar applications, QPFs have perhaps not been as successful as anticipated, but hold considerable potential for the future, if sufficient accuracy can be realized. They therefore have to be treated with caution, and are perhaps best interpreted by those with some hydrometeorological expertise.
8.4.1 Hydrological forecasting

A hydrologic forecast is an estimation of future states of hydrologic phenomena, principally river flow and level. Such forecasts are essential for mitigation of natural disasters such as floods and droughts. They are becoming more important in supporting integrated water resources management approaches and for reducing losses to floods, operational outages and untoward secondary impacts (for example, fish kills, pollution incidents and navigation disruption).

When developing a new flood forecasting and warning system, it is more likely that a pre-existing or commercially available model will be used, rather than developing a new, specific model from basic principles. However, these available models have to be customized to meet requirements, along with the need for calibration and verification, and a full understanding of the hydrology of the catchment. Flood forecasting and warning systems are usually operated by national or regional catchment management agencies, which are also usually involved with collection and processing of routine hydrological data. It is often the case that historical data have not been collected for the purposes of flood studies. This problem may need to be separately addressed, to provide a sound basis for calibrating flood models.

Hydrological forecasts essentially require input data that relate to precipitation, river flow and level measurements and other data (Table 2), and flood forecast models (see section 2.3.2.3) for hydrological and hydrodynamic simulations within channels and flood-plains. Flood forecast models are developed from a full understanding of the hydrology of the catchments. They utilize historical data, augmented by flood studies carried out to develop the models. The fundamental requirement for flood forecasting and warning models is that they should accurately and robustly reflect ongoing changes in time over a river system and provide estimates of flow magnitude and timing with sufficient lead time for response actions to be initiated.

Meteorological forecasts are an integral part of hydrological forecasting arrangements, as they can provide early alert information of potentially hazardous conditions, and additional lead time for critical situations to be identified and warnings provided. Meteorological and flood forecast models must be capable of frequent updating to reflect changing conditions over short periods.

As a flood forecasting and warning system is most likely to be operated by the NHS, NPP operators should consider how appropriate/relevant the existing system would be, particularly with regard to whether or not the locations of warnings are local enough. Forecast points are usually coincident with a stream gauge location, partly due to the modelling approach, and partly to give operational verification. However, forecast points can also be designated for a specific reach of a river where flood impact is high, such as near towns, cities or agricultural areas where flooding can cause significant economic losses or disruption. With NPPs being important national assets, it would be appropriate that the flood forecasting and warning agency make special arrangements for the site to be a prime forecast location.

8.4.2 Coastal surge forecasting and warning

Storm surge forecasting and warning are a national responsibility. To assist NMHSs with this task, guidance for hurricanes, tropical cyclones and typhoons, and their storm surges, is produced by designated centres (see section 8.2.2).

The Guide to Storm Surge Forecasting (WMO, 2011c) and the JCOMM web page (https://www.jcomm.info/index.php?option=com_content&view=article&id=175&Itemid=37) provide information and guidelines on this topic. However, assembling forecast information for operational applications remains a challenge in many areas of the world today. Annex 2 presents a major WMO effort towards alleviating this problem and for enhancing national capabilities for storm surge forecasting and warning.
8.4.3 Basis for a flood warning system


The technical requirements of a river flood warning system can be concisely summarized as (Bruen, 1999):

(a) A real-time data-collection subsystem for receiving and processing the relevant meteorological information, the discharge data at appropriate gauged sections in rivers (or water levels and rating curves), impoundments and so forth, and soil moisture measurements if required. These may involve manually recording gauges, automatic recording gauges, terrestrial data-collection platforms, ground-based radars, satellites, airborne sensors and so forth, and extensive use of GIS to present such information in a useful format.

(b) Access to the outputs of a numerical meteorological forecasting subsystem (NWP models for forecasting meteorological inputs, for example, QPFs) over the required lead time of the flood forecasting model.

(c) A subsystem for optimally combining the data from various sources and for providing a feedback mechanism for recalibration of the measuring tools and techniques, and for initialization of model error correction.

(d) A catchment modelling subsystem, embedded in a user-friendly interface, to estimate the total discharge at the catchment outlet, at the required time intervals, along with a corresponding statement of uncertainty.

(e) A subsystem comprising a hydrodynamic or a hydrological channel routing model to estimate the movement of the flood wave along the channel, the water levels, the effects of dyke breaches and reservoir operation, and the interaction with the flood-plain and flooded areas, giving a flood inundation forecast.

(f) An error correction subsystem having an algorithm for improving the estimates of discharge based on recent feedback from river gauge data.

(g) A subsystem for tide/estuary modelling in the case of backwater effects influencing the flood.

(h) Appropriate communications, GIS networks and decision support systems, producing forecast details at various levels, map forecasts showing flood inundation in real time and so forth.

The details of the several items listed above are dealt with in the Manual on Flood Forecasting and Warning (WMO, 2011a). Some further considerations of particular concern to NPP installations are examined in the remaining sections of this chapter.

The nature of the forecasting services that can be provided by a typical NMHS is dependent on the type of flooding process occurring in the basin. Table 15 illustrates these processes.

Upper basins are often characterized by a quick response to heavy rain, which would be exacerbated if infiltration were reduced because of catchment wetness due to previous rain or snowmelt. The reduction of infiltration due to urbanization is also a consideration in smaller catchments with rapid response. The main processes are thus infiltration and runoff, which can produce high flow concentration in lower reaches of rivers and low-lying topographic areas. These processes can be monitored and predicted by a combination of observation and modelling, and it is possible to design a flood forecasting and warning service based on this. Other types of basin flooding will require different approaches to the monitoring and modelling facilities, each having a variable capacity for the most suitable type of forecasting and warning.
needed. Urban catchments present particular problems, as built-up areas lead to rapid response flooding, and the occurrence of localized, high-intensity rainfall and capacity of drainage structures become important considerations. Both require special effort for monitoring and modelling to produce a successful flood warning system.

An important consideration is the interfacing of meteorological warning with the catchment model. Meteorological forecasts, including QPFs, are usually issued for a geographic area (for example, part of a country or region), which rarely coincides with a catchment area or river basin on which the flood forecasting model operates. An algorithm is therefore required to relate the two by distribution of rainfall in time, space and quantity. This can be done by interpolation routines, or where a grid-based QPF is available, relating the grid to point or area quantities. This is a complex issue, and an area where forecaster and operator experience, judgement and even local knowledge are required. This dictates that meteorological and flood forecasters should have a thorough professional and technical background, and that models should not be run as “black boxes”.

Table 15. Interaction of basin size and physical processes on flood response

<table>
<thead>
<tr>
<th>Basin type</th>
<th>Physical influence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>Infiltration</td>
</tr>
<tr>
<td>Urban</td>
<td>X</td>
</tr>
<tr>
<td>Upper</td>
<td>XX</td>
</tr>
<tr>
<td>Long river</td>
<td>X</td>
</tr>
<tr>
<td>Estuary</td>
<td>XXX</td>
</tr>
<tr>
<td>Aquifer</td>
<td>X</td>
</tr>
</tbody>
</table>

Note: XXX = dominant effect; XX = direct effect; X = minor effect.

8.4.4 Operational requirements of a flood forecasting and warning system

This section is an overview of operational requirements for a flood forecasting and warning system. The Manual on Flood Forecasting and Warning (WMO, 2011a), Chapter 8, gives complete coverage of this topic. A flood warning turns a prediction or forecast into information on which many actions are dependent. The fundamental purpose of the warning is to enable individuals and communities to respond appropriately to a major flood threat to reduce the risk of death, injury and property loss. Warnings for an NPP installation need to be focused and tailored to its specific needs.

The basic requirement is for people to have time to take necessary actions and make arrangements, which can range from putting protection or proofing arrangements in place, to evacuation to a place of safety. Flood warnings are therefore required to inform those at risk on the timing and extent of the flood, so they know how long they have in which to act, which areas will be affected by the flood, and, most importantly, what emergency actions to instigate, and ultimately which escape routes or accesses to shelter are available.

Flood behaviour in a river, either with floodwaters moving downstream, or lower reaches being affected by high tides or drainage congestion, lends itself to the preparation and issuance of flood warnings on the basis of river reaches. The size of reach depends on the size of catchment, but the time of travel also has a bearing. Thus, on a major river, such as the Rhine or the Ganges where flood travel takes several days, reaches may be a few hundred kilometres in length. In smaller catchments, where flood passage takes 1–2 d, suitable reach length will be of the order of tens of kilometres. A reach may be identified by a flood warning gauge at its upstream and downstream extremities. This approach is useful only when there is knowledge of how riparian areas may be affected by the flood, or if there are any flooding “hot spots” along the reach.
There are no fixed and definite rules regarding the provision of lead time for warnings. The requirement depends on specific operational needs and rests on a number of considerations, principally:

(a) The size of the catchment and nature of flooding: large catchments with extensive flood-plains are slow to respond, while, conversely, headwater catchments in steep hilly areas afford little potential to provide advance warning of flooding;

(b) The nature of the risk and impacts, and whether or not evacuation or physical protection (for example, sandbagging and embankment strengthening) or operational responses (such as plant shutdowns) need to be provided;

(c) If staged alerts and warnings are required;

(d) Lead times are dependent on the appropriate action related to the flood warning and also on the type of information available.

Figure 28 shows the timeline covering the forecasting process. Proceeding from top left, the meteorological forecast is derived from a general circulation model, which can produce a reasonable forecast for a period of 5–10 d. The source of the forecast, principally the scale of the model used, is shown along the top of the diagram and the type of forecast produced in the next horizontal sequence of boxes. A timing scale (logarithmic) is in the centre of the diagram, while the appropriate actions from the flood forecasting and warning provider are shown in the two lower lines of boxes.

Once the event starts to happen on the ground, with the onset of the forecast rainfall event and the commencement of rivers in the catchment beginning to respond, the situation develops to a warning process, which is depicted in Figure 29. As in Figure 28, the linear sequences of warning and response actions are shown, and also the numerous activities involved in a central management organization.

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**Figure 28. Schematic of flood-forecasting lead time (here and later, the terms “Flood Watch” and “Flood Alert” refer to pre-warning and warning levels, respectively)**

*Source: WMO (2011a)*
Flood warning “triggers” are set by the service provider (or in the case of an NPP, defined in collaboration with the user) by careful study of local conditions. They relate to critical river levels or rainfall amounts which indicate that flood states are approaching or worsening. The triggers initiate certain actions or provision of information to external users. They are used to decide when to undertake certain actions during a flood event, and should be designed to give enough time to undertake the response action. For example, if a river water level reaches a certain trigger level, it might mean that an area or community will flood in a few hours and the response action could be to evacuate. In the case of an NPP, the trigger may be linked to process actions. Triggers relating to rainfall include:

(a) Accumulations exceeding a threshold in a given period, for example 100 mm in 12 h or less (this threshold may need to be changed according to season);

(b) Rainfall accumulation and catchment wetness condition;

(c) Rainfall intensity exceeding a given rate (this is particularly important in urban areas or industrial complexes, where drainage capacity can be exceeded and flash floods or localized inundation can occur).

Triggers relating to water level include:

(a) The river level rising to within predefined warning levels;

(b) The rate of rise of level is faster than a threshold level, for example 25 cm h$^{-1}$.

Triggers for river levels are linked to local conditions and features of risk, for example:

(a) The level at which water flows out of a channel onto the flood-plain;

(b) The level of water that submerges areas of land used for livestock, or at which low-lying roads become flood;

(c) The level at which major areas (including residential and business properties) and communications are affected;

(d) The level at which water depth and velocity combined pose a threat of structural damage and danger of loss of life.

Figure 30 illustrates the general arrangement of triggers for flood warning stages. Figure 31 provides a schematic of a progressive forecast and warning situation, from rainfall forecast to downgrading of a warning.

Triggers for flood warnings are set so they are not reached too frequently, thus creating unnecessary responses or disruption. A high frequency of warnings can also lead to a negligent attitude by users where warnings are not heeded. A similar problem exists if too many false alarms are given. The provider has to strike a balance between a precautionary approach and an unwillingness to issue warnings for fear of them being wrong. A phased alert-warning system goes some way to overcoming these problems, as long as the various stages and their implications are understood by the user. The system should also allow for the alert-warning situation to be downgraded if conditions improve or forecasts change.

False alarms are inevitable given the nature of meteorological and hydrological events. Over time, they should be a small proportion, for example 20% of the forecasts that are issued, or of the number of correct forecasts. An indicative number of no more than five warning events per year in a given location, averaged over a period of years, is considered to be of the correct order where flooding is an irregular occurrence, but in more flood-prone areas (for example, monsoon climates), the warnings will be more frequent.
GUIDELINES ON METEOROLOGICAL AND HYDROLOGICAL ASPECTS OF SITING AND OPERATION OF NUCLEAR POWER PLANTS

INFORMATION SOURCES

- METEOROLOGICAL FORECASTS
- RAINFALL RADAR
- TELEMETRY RIVER GAUGES AND RIVER GAUGES
- LOCAL OBSERVERS

ALERTING FACILITIES

- RAINFALL TRIGGERS
- FIRST STAGE RIVER LEVEL TRIGGERS
- HIGHER STAGE TRIGGERS

FLOOD STATUS

- River rise commences
- Out of bank flow
- Extensive inundation
- Damage and threat to life
- Decline of river levels

RESPONSE ACTIONS

- ALERT INITIATED
- FLOOD WARNING
- SEVERE FLOOD WARNING
- EMERGENCY MOBILIZATION
- DOWNGRADING OF WARNINGS

Figure 29. Flood warnings and responses

Source: WMO (2011a)

Figure 30. Arrangement of trigger levels for various flood warning stages

Source: WMO (2011a)
8.4.5 Presentation of warnings to users

Experience has shown that non-specialist users often find that the distinction among alerts, warnings and severe situation warnings can be confusing and misunderstood. Colour codes (for example, yellow, amber and red) commonly used for weather warnings on their own are not necessarily appropriate, and many agencies now use symbols, which are explained with the meaning or implication of the symbols. The system that is used in the United Kingdom is a combination of a symbol with a simple illustration, to which specific instructions are related. Awareness and information on the symbols and instructions are disseminated periodically, for example, annually, to the public by advertising, leafleting and public information centres. The symbols are used as part of television and press weather forecasts and on the NMHS websites when warning situations arise. Box 5 shows the symbols and explanatory instructions.
Box 5. United Kingdom flood warning symbols

**Flood alert**
This is the first stage of the warning. If your area is issued with a flood alert, it means flooding is possible so preparedness is required. It advises you to be prepared to act on your flood plan, to prepare a flood kit of essential items, to avoid walking, cycling or driving through flood water. Farmers should consider moving livestock and equipment away from areas likely to flood.

**Flood warning**
If a flood warning is issued in your area, it means flooding is expected so immediate action required. It advises you to protect yourself, your family and help others, to move family, pets and valuables to a safe place, to turn off gas, electricity and water supplies if safe to do so, to put flood protection equipment in place. If you are caught in a flash flood, get to higher ground.

**Severe flood warning**
This is the warning issued when flooding poses a significant risk to life or significant disruption to communities. It advises you to stay in a safe place with a means of escape, to be ready should you need to evacuate from your home, to co-operate with the emergency services.

*Source: Environment Agency (2010)*

8.4.6 **Warning information contribution to flood response**

Specific arrangements should be made between NMHS and NPP authorities for the provision of warning services. NMHSs use a wide range of information formats, and these can be adapted to suit specific needs related to the NPP.

The detail of information delivered by flood alerts and warnings varies from one country to another. In general, these include tables of water level and rainfall, sometimes graphical presentations and sometimes interactive mapping, where measurements at data points can be accessed via a website.

As an example, the United States NWS website providing flood warning statements also has links to graphical and map displays. Figure 32 is a typical example, which provides the recent
evolution of the river level along with the forecast and the definition of different warning and
danger levels. This method of illustrating current and forecast information has also been adopted
in Bangladesh. In Figure 32, the blue line indicates the observed river level, and the green
line the model forecast river behaviour. In this case, the river is responding more rapidly than
forecast, so a revised model forecast would be required. The graph also shows the various trigger
and warning levels at the site.

It is important that receivers of warning information understand the meaning and the
implications for their site. It is thus recommended that NPP operators have personnel with
the emergency response unit who have a good understanding of the basics that underpin
meteorological and hydrological forecasts, and of how to use the information in their response
actions. It is recommended that NPP personnel engaged in flood forecasting and warning
activities undergo some training from the NMHS to understand the basic principles of the
science involved and how the deliverables are structured and work. A highly important feature
of the direct arrangement with the forecast and warning services is that a dedicated person-to-
person link is set up, which can be used for general briefings and in critical operational situations.

Some hydrological services use simulators of their forecasting software, which allow professionals
to train, and perhaps test “what-if” scenarios, or to become familiar with new technologies and
new practices. However, they are not used at the same level at which, for example, an airline
pilot would be trained and tested. The simulation approach can be extended to training through
exercises. These can be “desktop” where staff are required to respond to a range of hypothetical

Figure 32. Graphical flood forecast for the Green River at Paradise, Kentucky, United States

situations, or as training exercises carried out in quasi-real time. These training simulations may involve partner organizations, so testing the response actions of both parties to a flooding situation.

In a full exercise, the forecasting and warning service can simulate some or all of the following:

- Begin the process with information from the NMHS that will activate full operational duty
- Continue to maintain a real-time interaction with meteorological services during the event
- Use simulations of catchment and river models to produce realistic situations to allow the flood forecaster to provide information to generate warnings
- Introduce critical situations, for example, loss of data transmissions, computer breakdown and so forth
- Produce a realistic set of warning information that may escalate responses within any receiving organization
- Set up contact with public protection services to keep them informed of the evolution of the situation
- Provide information to inform authorities at national level and the press
- Prepare Internet output material, used to inform public protection services and general public in near real time

An extended exercise must be operated by professionals, and requires a large amount of effort to produce (Environment Agency, 2005). It will therefore be costly, and not something that can be repeated frequently.

8.5 OPERATIONAL SUPPORT FOR EMERGENCY RESPONSE AND ATMOSPHERIC DISPERSION

8.5.1 National Meteorological and Hydrological Services

As discussed in section 8.2, NMHSs should work in close partnership with government agencies and stakeholders to define forecast and warning criteria in support of NPP operations. This is particularly important if an emergency situation occurs with a potential, imminent or actual release of radioactivity into the atmosphere.

For NMHSs that have the capability to model atmospheric dispersion, arrangements should be made for the provision of products and support to appropriate agencies within the State. As part of the arrangements made among NMHSs, government agencies and NPP operators, it should be assured that all atmospheric transport models used in emergency response activities, independent of their scale and purpose, are driven by the best available meteorological input data.

Recognizing the potential for radioactive material to travel great distances and to affect many States, a WMO RSMC global system exists for the provision of dispersion modelling products. It can assist NMHSs that may not have modelling capacity or provide additional and backup assistance. Another important role of this system is to support the IAEA Joint Emergency Management Plan of the International Organizations (IAEA, 2017).
8.5.2 **WMO Regional Specialized Meteorological Centres**

WMO is one of the international organizations that co-sponsor the IAEA-led Joint Radiation Emergency Management Plan of the International Organizations (IAEA, 2017). The plan describes the inter-agency framework for preparedness and response to an actual, potential or perceived radiation incident or emergency, independent of whether it arises from an accident, natural disaster, negligence, a nuclear security event or any other cause. It is intended to support and underpin the efforts of national governments and ensures a coordinated and harmonized international response to radiation incidents and emergencies. It is not intended to interfere with nor replace the emergency response arrangements of international organizations or States.

WMO has designated RSMCs with the specialization to provide atmospheric transport model products for environmental emergency response and/or backtracking (WMO, 2017a). This capability is activated, and products and services are provided within the scope and arrangements described below.

The scope of application for this specialization is the provision of modelling products and services by RSMCs when requested by the delegated authority of a country or the IAEA Incident and Emergency Centre (IEC; see [https://www-ns.iaea.org/tech-areas/emergency/incident-emergency-centre.asp](https://www-ns.iaea.org/tech-areas/emergency/incident-emergency-centre.asp)).

The models used for the RSMC function are complex numerical models of the atmosphere that are capable of simulating long-range transport, diffusion and deposition of airborne tracers or radioactivity in an operational response setting. Outputs from these models are made available within a short turnaround time, at most 3 h, following a request received by the RSMC.

The request (activation) and response arrangements in relation to this RSMC specialization consist of: (a) the identification of a requesting party, (b) the identification of a recipient of the atmospheric transport model products and (c) a basic set of RSMC actions that are established within WMO in agreement with IAEA.

To ensure the authenticity of a request to activate the RSMC, each WMO Member names one delegated authority contact, which is the WMO-recognized authority of that State to make the request. When the request made by a delegated authority is received by the RSMC, the RSMC immediately activates its response procedures. The delegated authority may or may not be part of the NMHS of the Member. A request for RSMC support does not relieve the requesting state of notification requirements with any relevant international organizations.

ATDM products are made available by RSMCs to IAEA IEC and NMHSs of WMO Members. This is done to facilitate immediate and effective meteorological interpretation of the model output products by meteorological experts for their domestic use. The NMHSs are encouraged to make the required arrangements to distribute RSMC products to national agencies involved in emergency response and to provide interpretation to ensure effective use of the products.

*Documentation on RSMC Support for Environmental Emergency Response, Documentation for Meteorologists at NMSSs* (WMO, 1997) gives detailed information on RSMC support for environmental emergency response, including a description of all atmospheric transport, dispersion and deposition models used by RSMCs and specific products.
1. **BASIC COMPONENTS**

In its simplest form, the problem of predicting the concentration of a pollutant in the atmosphere can be expressed as having three distinct components:

- **Source term or emission term.** This component consists of all non-meteorological parameters that characterize the release of a pollutant to the atmosphere. For example, the nature of the pollutant (chemical, radioisotope, volcanic ash and so forth), the amount (mass, activity and so forth) emitted, the horizontal and vertical extent of the release and the release time profile.

- **Meteorology.** This component includes meteorological parameters (pressure, wind, moisture, stability and so forth) that serve as input to the transport and dispersion component.

- **Transport and dispersion.** This component combines inputs from the other two components through the use of atmospheric transport and dispersion models to displace and disperse the pollutant in the atmosphere. Depending on the level of sophistication of the model, the transformation, scavenging and deposition of the pollutant at the Earth’s surface can also be taken into account. Some approaches include the transport and dispersion component directly into the meteorological modelling system.

2. **ADVECTION–DIFFUSION EQUATION**

The advection–diffusion equation governs atmospheric transport and dispersion. The equation emerges as a direct and simple consequence of the conservation of mass principle ($dC/dt = 0$); that is, the rate of change of the total mass $C$ within a closed system is zero if there are no sources or sinks. In Cartesian coordinates, where the mass $C$ is locally distributed, $C(x_i, t)$ can change locally as a function of three-dimensional (3D) space coordinates $x_i$ and time $t$. As molecular diffusion is so small, it is not relevant to atmospheric dispersion and is neglected in the following. If sources ($S_o$) and sinks ($S_i$) are included for the pollutant, the conservation of mass equation becomes:

$$\frac{dC}{dt} = S_o - S_i.$$  

This simply states that the mass of material (pollutant) in a volume (concentration) of the fluid following the fluid motion changes only by the actions of sources or sinks inside the volume. This is known as the Lagrangian form of the conservation of mass. This equation can be developed as follows:

$$\frac{dC}{dt} = \frac{\partial C}{\partial t} + u_i \frac{\partial C}{\partial x_i} = S_o - S_i \tag{1}$$

or

$$\frac{dC}{dt} = -u_i \frac{\partial C}{\partial x_i} + S_o = S_i \tag{2}$$

where:

- $u_i$ is the instantaneous (3D) wind speed
- (1) is the local rate of change of mass (or concentration) as a function of time at a fixed point in space
- (2) is the 3D advection (transport) by the wind
This is known as the Eulerian form of the conservation of mass or concentration.

To describe the behaviour of the mean concentration and possibly get a measure of the statistical deviation from the mean at a specific location, the instantaneous concentration and instantaneous wind speed can be expressed as a mean value and a fluctuation (deviation) from that mean value:

\[ C = \bar{C} + C' u_i = \bar{u}_i + u'_i, \]

where the fluctuating part averages to zero:

\[ C' = 0, \quad u'_i = 0. \]

The Eulerian form of the conservation of mass or concentration becomes:

\[
\frac{\partial \bar{C}}{\partial t} + \bar{u}_i \frac{\partial \bar{C}}{\partial x_i} + \bar{C}' \frac{\partial u'_i}{\partial t} + \frac{\partial \bar{C}'}{\partial x_i} u'_i = \frac{\partial C}{\partial t} + \frac{\partial C'}{\partial x_i} u'_i + \frac{\partial C}{\partial t} + \frac{\partial C'}{\partial x_i} u'_i + \frac{\partial C}{\partial t} + \frac{\partial C'}{\partial x_i} u'_i + \frac{\partial C}{\partial t} + \frac{\partial C'}{\partial x_i} u'_i + \frac{\partial C}{\partial t} + \frac{\partial C'}{\partial x_i} u'_i + S_0 - S_i.
\]  
(1)          (2)         (3)           (4)   (5)

This is known as the advection–diffusion equation, where:

(1) is the local rate of change of the mean mass (or mean concentration) as a function of time at a fixed point in space
(2) is the 3D advection (transport) by the mean wind
(3) is the turbulent flux or turbulent diffusion
(4) is the source term, or emission term, and describes how the pollutant is released in the atmosphere
(5) is the sink term or depletion term and corresponds to the removal and transformation mechanisms for the pollutant

The combination of the advection and turbulent diffusion terms is usually referred to as dispersion. Now, \((x, y, z)\) can be used for the horizontal and vertical spatial coordinates and \((u, v, w)\) for the corresponding wind components. The average bars in the local rate and advection terms are also often considered implicit and dropped from the equation:

\[
\frac{\partial \bar{C}}{\partial t} + \bar{u}_i \frac{\partial \bar{C}}{\partial x_i} + \bar{C}' \frac{\partial u'_i}{\partial t} + \frac{\partial \bar{C}'}{\partial x_i} u'_i = \frac{\partial C}{\partial t} + \frac{\partial C'}{\partial x_i} u'_i + \frac{\partial C}{\partial t} + \frac{\partial C'}{\partial x_i} u'_i + \frac{\partial C}{\partial t} + \frac{\partial C'}{\partial x_i} u'_i + \frac{\partial C}{\partial t} + \frac{\partial C'}{\partial x_i} u'_i + \frac{\partial C}{\partial t} + \frac{\partial C'}{\partial x_i} u'_i + S_0 - S_i.
\]  
(1)          (2)         (2)          (2)           (6)               (7)                (8)       (4)    (5)

Terms (6), (7) and (8) are referred to as turbulent diffusion.

This equation is the basis of all models that calculate the transport and dispersion of a pollutant in the atmosphere. It states that the local rate of change (time variation) of the mean concentration of a pollutant at a point fixed in space is influenced by several different physical processes as follows.

2.1 Advection (or transport) by the mean wind

\[-u \frac{\partial \bar{C}}{\partial x} - v \frac{\partial \bar{C}}{\partial y} - w \frac{\partial \bar{C}}{\partial z} \]

This equation indicates that the concentration at a specific point in space will increase if the wind is blowing from a region where the mean concentrations are higher. It is important to note that for typical mid-latitude weather systems, the characteristic scale of the horizontal wind components \((u, v)\) is 10 m s\(^{-1}\) while it is only 0.01 m s\(^{-1}\) for the vertical wind component \((w)\). This means that the horizontal transport is typically much stronger than the vertical one. However, there are exceptions to this, for example when strong convection takes place in the atmosphere during thunderstorms.

2.2 Turbulent diffusion

\[-\frac{\partial}{\partial x} (u' C') - \frac{\partial}{\partial y} (v' C') - \frac{\partial}{\partial z} (w' C') \]

These terms are also part of the transport process by winds. They are the result of mixing due to turbulent motions and unresolved wind eddies. They cannot normally be solved directly because
they operate at scales that cannot be fully resolved. They must therefore be parameterized in some fashion. Analogous to what is known from molecular diffusion, the turbulent diffusion is often modelled as being proportional to the mean gradient of the concentration field. This is called a first-order closure approach and implies that the turbulent diffusion is assumed to be proportional to a constant of diffusivity, $K$, multiplied by the mean gradient. With a few additional assumptions (not described here), the advection–diffusion equation becomes:

\[
\frac{\partial C}{\partial t} = -w \frac{\partial C}{\partial x} - v \frac{\partial C}{\partial y} - K_x \frac{\partial C}{\partial x} + K_y \frac{\partial C}{\partial y} + K_z \frac{\partial C}{\partial z} + S_0 - S_i.
\]

Terms (9), (10) and (11) correspond to the $K$-theory form of the turbulent diffusion component.

The turbulent kinetic equation offers a more advanced, second-order closure method to determine the turbulent fluxes, but it is beyond the scope of this discussion.

### 2.3 Source term or emission term

$S_0$

This consists of all non-meteorological parameters that characterize the release of a pollutant to the atmosphere. For example, the nature of the pollutant (chemical, radioisotope and so forth), the amount (mass, activity and so forth) emitted, the horizontal and vertical extent of the release, the duration and so forth. It is often difficult to obtain a good quantification of this term. Depending on the nature and magnitude of the uncertainties, it can have a direct impact on the quality of the modelling results.

For example, consider how the release of the pollutant occurs in the vertical. Because of the way winds vary in speed and direction as a function of height, especially in the planetary boundary layer (PBL), a small difference in the estimate of the altitude at which the pollutant is released can sometimes have a big impact on the modelling results. This is why good estimates of the initial height and the vertical extension of the release are required to simulate correctly the evolution of the pollutant cloud.

How the release of the pollutant occurs as a function of time is also a factor of major importance because of the time evolution of the atmosphere (diurnal evolution of PBL, arrival of frontal systems, wind shifts and so forth). The start and duration of the release must be known or at least estimated reasonably to correctly simulate the evolution of the pollution cloud. The timing of the weather systems has a key influence on the direction of motion and pattern of the dispersion. For example, the wind direction and corresponding dispersion of the pollutant will be completely different before and after the arrival of a wind shift line. This information is useful for emergency planners and responders making strategic decisions such as where to place a command centre, when to evacuate the population from a specific neighbourhood or to help decide the best time to have a controlled venting from a nuclear power plant (NPP).

If the vertical structure and the time-release scenario of the source term are well described, then the area of maximum air concentration and deposition to the ground can be qualitatively estimated. In addition, if there is an estimate of the mass of the pollutant released (or mass release rate), quantitative values of air concentrations and deposition can then be calculated. The same applies for accidents at NPPs. Knowledge of the radiological species and quantities involved is of key importance because parameters such as dry deposition, scavenging ratio and half-life are dependent on the pollutant.

Modelling of the source term is a crucial part of atmospheric transport, dispersion and deposition modelling (ATDM). In most cases, the processes by which pollutants are injected into the atmosphere (explosion, fire, high-pressure jet and so forth) occur at scales well below those resolved by ATDM. The source effects have to be parameterized; the type of parameterization will vary as function of the type of model used (for example, Lagrangian or Eulerian).
2.4 Sink term or depletion term

This represents the processes by which pollutants are removed from the atmosphere. It generally takes into account the effects of clouds and precipitation (wet scavenging and wet deposition to the Earth’s surface), deposition on the ground due to the various capturing properties of the surface (dry deposition) and radioactive decay. More sophisticated models may also take into account transformations such as chemical reactions, for example.

2.4.1 Wet scavenging and wet deposition

There are various mechanisms by which a pollutant can be partially captured by moisture and removed from the atmosphere by deposition at the Earth’s surface. The pollutant aerosols can serve as condensation nuclei for water and ice (nucleation scavenging). In-cloud scavenging will cause some additional capture of the pollutant’s aerosols by water droplets, ice crystals and snowflakes. As hydrometeors grow larger, they fall in the form of precipitation that causes the removal of additional aerosols, in and below the clouds. The result of these combined effects is that a portion of the pollutant will be removed from the atmosphere and deposited at the ground. This is referred to as wet deposition. In the case of radioactivity, this can lead to hotspots or regions where the radioactivity at the Earth’s surface is much higher due to the removal of radioactivity from the atmosphere by precipitation. The processes of wet scavenging and wet deposition are usually parameterized with the use of scavenging coefficients.

2.4.2 Dry deposition

This is the process by which a pollutant is captured by the roughness of the Earth’s surface. It can result from gravitational sedimentation (difficult to take into account), interception and impaction by obstacles of various sizes (for example, grass, trees and buildings) at the surface and turbulent eddies. Dry deposition is usually considered by introducing a dry deposition velocity.

In the case of a radioactive pollutant, an important factor to take into account is the depletion that results from radioactive decay (half-life).

3. Atmospheric transport, dispersion and deposition models

3.1 Categories of models

Atmospheric transport, dispersion and deposition models can be classified in categories using three characteristics: (a) their coordinate systems, (b) their wind fields and (c) the type of averaging used in the models to solve the mass-conservation equation.

(a) Two coordinate systems are used: Eulerian and Lagrangian. For the Eulerian system, the flow variables are a function of time and the position in Earth-based coordinates. The Lagrangian system follows individual fluid parcels whose locations depend only on time.

(b) The wind field in transport and dispersion models can be represented in a simple or complex way. In some cases, it is defined by a single value of the average wind at a specified height. This is the case for the simplest Gaussian plume models. A step towards more detailed information is to incorporate time-varying winds measured at several points within the domain. The most sophisticated transport and dispersion models use high-resolution, time-varying, 3D grids of winds obtained from numerical weather prediction (NWP) models.
Averaging is required in the models to simulate parameters that are at spatial and temporal scales too small to be resolved explicitly (for example, small eddies produced by turbulence). The type of averaging applied to the governing equations has important implications for the modelling results.

3.2 Lagrangian and Eulerian models

With regard to the coordinates system, the transport and dispersion of pollutants at local to long-range scales in the atmosphere are simulated by Lagrangian and Eulerian models.

3.2.1 Lagrangian models

Lagrangian models describe fluid elements that follow the instantaneous wind flow. They solve the mass-conservation equation expressed in the total derivative form, such that the change of concentration is computed following the parcel as it is advected by the wind. They include all models in which plumes can be broken down into segments, puffs or particles. The advection is directly simulated by computing the trajectories of the plume elements as they move in the wind field. Some atmospheric transport, dispersion and deposition models use a large number (millions) of parcels, and diffusion is modelled by adding semi-random or stochastic components to the large-scale wind to include the effect of atmospheric turbulence. The trajectory of each parcel is calculated, and concentrations obtained by counting the number of parcels within a certain volume.

A Lagrangian model can be simple or complex depending on what it takes into account. In general, the Lagrangian method has the advantage of providing a better representation of the source term and the concentration near point sources. It does not suffer from numerical diffusion, which is a problem encountered with Eulerian models.

The Lagrangian framework offers a natural way to model turbulence because it is a closer physical analogue to the pathways traced by eddies. The method can also be used to determine source–receptor relationships that help estimate the location and strength of a source based on measurements at one or more locations.

However, a Lagrangian model requires a large number of parcels (hundreds of thousands to millions) to resolve adequately concentrations for long-lived events that cover large domains. This method is also computationally costlier than the Eulerian method.

All WMO Regional Specialized Meteorological Centres designated for emergency response activities use Lagrangian models with complex 3D winds fields that vary in time. The wind fields are provided by the National Centre NWP models with horizontal resolutions that range from tens of kilometres globally to a few kilometres regionally.

3.2.2 Eulerian models

Eulerian models look at how the mass or concentration of the pollutant changes as a function of time at a specific location in the atmosphere by directly solving the Eulerian version of the advection–diffusion equation developed earlier.

The turbulent fluxes are commonly assumed to be proportional to the mean gradient according to the $K$ gradient theory (first-order closure). The horizontal and vertical $K$ coefficients are dependent on the structure of the atmospheric PBL.

These models use numerical techniques that allow specific treatments for each physical process (finite-difference method, splitting, finite-element method and so forth).
The main advantage of the Eulerian method is that it employs a stationary, fixed grid, which makes calculations relatively easy. However, it does not handle point sources well and produces artificial (numerical) diffusion.

### 3.2.3 Gaussian models (Gaussian plume)

Gaussian models are a special, simplified form of Eulerian models that, in their simplest versions, use a single value of the average wind at a specified height. They are based on the assumption that over short time periods and relatively short distances (10 km or so), steady conditions exist with respect to pollutant release and meteorological conditions (this is obviously not always the case).

It can be shown that in the special case of a continuous emission from a point source where the mean wind velocity is constant in the horizontal direction and with height and in the absence of boundaries, the concentration of the pollutant downwind (averaged over a large number of realizations of the given dispersion problem; see Figure 1) for the Eulerian advection–diffusion equation is a Gaussian or normal probability distribution in the vertical and lateral directions (Turner, 1972, 1994; Hanna et al., 1982).

The pollutant is therefore represented by an idealized plume that is dispersed in three dimensions. The dispersion in the downwind direction is a function of the mean wind speed blowing the plume. Dispersion in the cross-wind and vertical directions is governed by the Gaussian plume equations of lateral dispersion, which are a function of atmospheric stability and corresponding empirical dispersion coefficients/equations determined by Gifford and Gibbs using experimental data in the mid-1970s (Hanna et al., 1982). The model assumes that the dispersion takes on the form of a normal distribution Gaussian curve with the maximum concentration in the middle of the plume.

The coordinate origin can be defined as located at ground level (\(x = 0, y = 0\) and \(z = 0\)), beneath the point of the pollutant’s release. The \(x\) axis is the downwind axis, extending horizontally with the ground in the average wind direction. The \(y\) axis is the cross-wind axis, perpendicular to the downwind axis, also extending horizontally. The \(z\) axis extends vertically. The plume travels along, or parallel to, the downwind axis (see Figure 2).

![Figure 1](image.png)

**Figure 1.** (a) Snapshot of the instantaneous plume downwind from a continuous source in a turbulent flow and (b) time-averaged plume

*Source: Environmental Protection Agency Fluid Modeling Facility*
For a continuous emission, the concentration at a point in space for an effective release height $H$ above the ground (see Figure 3) is:

$$C(x, y, z, H) = \frac{Q}{2\pi\sigma_y\sigma_z u} \exp \left( -\frac{1}{2} \left( \frac{y}{\sigma_y} \right)^2 \right) \exp \left[ -\frac{1}{2} \left( \frac{z-H}{\sigma_z} \right)^2 \right] + \exp \left[ -\frac{1}{2} \left( \frac{z+H}{\sigma_z} \right)^2 \right] ,$$

where:

$C(x, y, z, H)$ is the atmospheric concentration of the pollutant at point $(x, y, z)$ for an effective release height $H$ above the ground.

$H$ is the effective release height (m).

$Q$ is the source term (g s$^{-1}$).

$u$ is the average wind speed (m s$^{-1}$) at the effective release height (note: it is assumed that the wind has a single and constant value everywhere; this is obviously rarely the case, especially over a domain that exceeds a few kilometres).

$x, y, z$ are the downwind, cross-wind and vertical distances (m).

$\sigma_y, \sigma_z$ are the standard deviations of the concentration distribution in the cross-wind and vertical directions (m).

Estimates of $\sigma_y$ and $\sigma_z$ as a function of downwind distance and atmospheric stability (Pasquill’s stability classes A to F) were developed by Gifford and Briggs in the mid-1970s based on experimental data (Hanna et al., 1982). Note: These estimates should ideally be recalculated at the location of interest using local meteorological data.

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Figure 2. Coordinates system for a Gaussian plume

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1 The effective release height is the final equilibrium height of the centre line of the pollution plume from a smokestack or some other source. It is the sum of the actual physical height of the top of the stack, plus any plume rise due to buoyancy or initial momentum of the rising plume. See Figure 3.
Wind and atmospheric turbulence are the forces that move the molecules of a pollutant released in the air. As a pollution cloud is blown downwind, turbulent mixing causes it to spread out in the cross-wind and vertical directions. According to the Gaussian model, a graph of gas concentration within any cross-wind slice of a moving pollutant cloud looks like a bell-shaped curve, high in the centre (where concentration is highest) and lower on the sides (where concentration is lower).

At the point of a release, the pollutant gas concentration is high, and the gas has not dispersed far in the cross-wind and vertical directions, so a graph of concentration in a cross-wind slice of the cloud close to the source looks like a spike. As the pollutant cloud drifts farther downwind, it spreads out and the bell shape becomes wider and flatter. See Figure 4.
Gaussian plume models assume continuous and constant emission of the pollutant, flat terrain, no chemical reactions or absorption, and constant mean wind speed and direction with time and height.

4. **GENERAL FEATURES OF LAGRANGIAN MODELS THAT USE THREE-DIMENSIONAL TIME-VARYING WIND FIELDS**

Generally, atmospheric transport, dispersion and deposition models used during emergencies are offline models, to allow for a fast and timely response. This means that the dispersion modelling is usually not integrated within a complete NWP model. Atmospheric transport, dispersion and deposition models require 3D time-varying meteorological data input (for example, winds) from NWP models. The quality of NWP models affects that of atmospheric transport, dispersion and deposition models. NWP models provide data on a grid with a specific resolution. Atmospheric transport, dispersion and deposition models can simulate only phenomena of the same scale as the input data mesh, and subgrid scale phenomena have to be parameterized. That is the main reason why processes such as convection or scavenging are treated in a cruder fashion in operational atmospheric transport, dispersion and deposition models than in research ones.

Atmospheric transport, dispersion and deposition models are, of course, dependent on the quality of the input meteorological data. A source of uncertainty is the precipitation field, and the corresponding wet deposition calculations of NWP models parameterize the complex process of precipitation but with large uncertainties. Precipitation generally only provides rain fluxes at the ground, so estimation of the depth of the wet layer must be done by ATDM. The results for wet deposition may not be accurate, even when the precipitation areas are well estimated.
This is why weather radars, when available, are of great value because they provide real-time quantitative estimates of the actual precipitation amounts. Many national centres also have high-resolution precipitation gridded analyses that can be used as input to atmospheric transport, dispersion and deposition models.

Many studies have evaluated the quality of atmospheric transport, dispersion and deposition models. For example, one of the earlier ones is the ATMES experiment (Klug et al., 1992) that evaluated different models for the Chernobyl accident. It showed that the evolution of a pollution cloud can be depicted fairly well when analysed/observed meteorological fields are used. However, there is a deterioration of the model performance when using forecast meteorological fields, which is not surprising. That is why an evaluation of NWP forecasts by meteorologists is essential so that the quality of the outputs of atmospheric transport, dispersion and deposition models can be assessed.

More recently, ATDM of the releases from the Fukushima Daiichi NPP accident has been the subject of many publications (for example, WMO, 2013a; Draxler et al., 2015; Katata et al., 2015).
ANNEX 2. WMO COASTAL INUNDATION FORECASTING INITIATIVES

Between 2009 and 2019, WMO carried out the Coastal Inundation Forecasting Initiatives (CIFI; WMO, 2013b, 2017d), with the aim to demonstrate the capability to develop and implement predictive systems within a coordinated effort between Regional Specialized Meteorological Centres (RSMCs) and national forecast systems around the world. The approach used in these forecast systems is shown in the figure. The overarching objectives of CIFI were to meet challenges of coastal community safety (which would include operations at nuclear power plants (NPPs) where appropriate) and to support sustainable development through enhancing coastal inundation forecasting and warning systems at the regional scale. Upon completion of national subprojects of CIFI, countries would be able to implement an operational system for integrated coastal inundation forecasting and warning, providing an objective basis for coastal disaster (flooding) management and operational decision-making.

CIFI was focused on facilitating the development of efficient forecasting and warning systems for coastal inundation, based on robust science and observations. In particular, CIFI implementation created synergies with the ongoing regional and global programmes and activities. It also provided technical requirements to develop the regional Storm Surge Watch Scheme in basins subject to tropical cyclones and storm surges, jointly with (fluvial) flood events.

As shown in the figure, information obtained from responsible national/regional agencies, such as the RSMC is used as the basis for these forecasts, including: (a) regional atmospheric models (providing winds, pressures and precipitation), (b) inputs from large-scale ocean circulation and wind-wave models (providing information on large-scale sea-surface height anomalies and on waves generated outside the region), (c) a coastal inundation model (using information from wind wave and wind stress, tidal and large-scale anomalies) and (d) hydrologic models to handle inflow into the coastal domain from rivers and streams when local rainfall is a dominant contributor to coastal flooding. All of these dynamic models must be set upon a digital terrain model that includes bathymetric and topographic information at an appropriate accuracy and resolution. The goal of this system of models is to be able to provide accurate forecasts of inundation from hazardous meteorological forcing in different areas around the world, including storm surges produced by direct wind and wave forcing, wave set-up from large swell events and inundation from high river/streamflows interacting with sea-level variations in coastal areas.

Wind forcing for the overall modelling system comes from tropical cyclones and other wind systems. For the case of tropical cyclones, a parametric model of winds within the moving tropical cyclone vortex may be developed from a forecast set of storm characteristics. A typical set of these are:

1. Storm track;
2. Storm intensity (usually defined by the pressure differential between the centre of the tropical cyclone and the peripheral pressure);
3. Storm size (usually defined in terms of the radius to maximum wind for wind field estimation);
4. Forward speed of the storm;
5. Optional terms to refine the wind distribution along the radials of the storm (for example, the Holland B parameter, double exponential forms and so forth).

Given that it has been shown in several test cases that a purely deterministic forecast can produce large areas in which the surge levels can be underpredicted by 2–4 m, or more, these parameters should be varied to encompass the uncertainty inherent in tropical cyclone forecasts as a function of forecast interval. The entire forecast system should be exercised for a complete set of derived storms. Forecasts of winds other than tropical cyclones will be derived from a combination of global and regional numerical weather prediction models. Including interactions...
among tides, large-scale sea-surface height anomalies and waves propagating into a regional area may be obtained from models run on scales appropriate to those processes. This will provide necessary information along all of the regional-scale model boundaries.

Within the regional model, wind stresses and pressure fields for each forecast are input to the surge and wave models at time intervals appropriate to resolve the physics/processes within these models and will be combined with the effects of wave, tidal and large-scale forcing from larger-scale models to forecast the total inundation levels. The wave and surge models can be loosely or tightly coupled, depending on the specific application and modelling system found to be effective in an area. In areas located on shallow near-shore slopes, a reasonable approximation to the forecast surge may be obtained without needing to run a wave model, since the contribution by wave radiation stresses tends to be small compared to the direct wind-driven tides in such areas. In cases where the wave contribution is small and neglected, a constant value, representing the typical contribution to the overall surge levels due to the wave fields, should be added to the overall forecast surge to avoid underpredicting critical flooding. For much of the globe, a value of 0.3–0.5 m might suffice for this purpose – bearing in mind that such an approximation is inappropriate for regions with steep slopes (such as found in many island areas where waves are often a dominant forcing mechanism for surges).

The inundation model should also be coupled to hydrologic models in locations where inundation is influenced by the combination of river inflows and increased coastal water levels. For such areas, it is important that the inundation model has a capability to consider flooding and drying (inundation) within its numerical framework. The inundation model should include a loose or tight coupling to a hydrologic model that provides the input conditions at the upstream boundary of the inundation model domain. The hydrologic model could be set up to run independently in areas where flows are not influenced by backwater effects due to coastal or tidal inundation; however, it will likely be important to consider both contributions to flooding in some coastal regions. A key question to be addressed by the in-country technical team (National...
Coordination Team) is the dynamic nature of the moving boundary between the incoming river/streamflows into the coastal model domain when the hydrologic and inundation models are coupled.

A critical part of the effort for an NPP will be to provide evidence that the forecast system is suitably validated. This will require: (a) a comparison of modelling system performance relative to available observations in past events, (b) a demonstration that the system is suitably robust to maintain functionality for the complete range of storms (extreme events) and boundary conditions critical to inundation in an area, (c) a demonstration that the system is capable of providing information needed and that this system adequately addresses the uncertainty in the forecast surges and (d) an exercise in an operational mode of the forecast system including interactions with stakeholders.

Observations should be integrated into the operational service system. For the overall inundation system to function effectively, for it to be objectively assessed and to improve its accuracy and value through time, it will be critical to include a set of observations (in situ and remotely sensed, real time and non-real time) into the overall system. These measurements should include information on conditions before, during and after the different inundation events. Pre-inundation information is essential for improved forecasts of the event that generates inundation and to evaluate which models in an ensemble are tracking better with the developing scenario. Other pre-inundation information required is a suitable database of digital bathymetric and topographic information, which should be updated periodically, especially in deltaic regions. Data taken during the event are necessary to enable quantitative comparisons between the modelled inundation being generated by the hydrometeorological forcing and the inundation response to this forcing. It is also important in enabling updated warnings in rapidly changing situations. These measurements should include forcing functions (winds, pressures, rainfall, waves and so forth) and response functions (water level, stream discharge and so forth). Finally, post-event measurements (rate of post-storm inundation abatement, high-water marks, damage surveys and so forth) will be critical to understand and guide on-site recovery efforts and to quantify relationships between inundation and consequences. It should also be noted that continuous, long-term measurements will be important for establishing the overall climatology of extremes in this area and to detect any long-term changes that are occurring.
ANNEX 3. EXAMPLE OF AN INTEGRATED APPROACH FOR EMERGENCY SUPPORT

The integrated approach taken by MeteoSwiss combines a set of ground-based remote-sensing observations of the troposphere and a high-resolution numerical weather prediction (NWP) model.

Automatic profiling of meteorological parameters like wind and temperature are automatically performed at strategic locations chosen as a function of the regional topography and the main wind regimes. This information is assimilated in real time into an NWP model that is therefore initialized with the best possible three-dimensional (3D) meteorological parameters. Then, the necessary input data for the dispersion model are obtained directly as an output of the high-resolution NWP model, at each altitude range above the nuclear power plant (NPP). Local measurements at the NPP sites will then consist of standard surface measurements (wind, temperature, humidity, pressure and radioactivity).

The system combines a specific measurement network (surface measurements as well as remote-sensing upper-air measurements in the boundary layer) together with an NWP model with high spatial and temporal resolution. The input data for the surveillance authorities are delivered by the NWP model output and not by the in situ observations from the meteorological towers located in the neighbourhood of NPPs.

In this system, the measurement network consists of:

- Surface stations at NPPs, including turbulence and radioactivity measurements
- A few ground-based remote-sensing upper-air stations located at strategic sites around NPPs, typically: upstream, downstream of the main wind trajectories and in the centre of the domain providing 3D information to be assimilated into the NWP model

Such a system has been operational in Switzerland since 2009 (see Hug et al., 2009; Ruffieux et al., 2009; Calpini et al., 2011).

The following NWP model forecasts (profiles) are delivered for the domain of interest, typically in a temporal resolution of 10 min covering 30 h in total:

- Wind direction/speed at 10, 70, 100, 110, 200 and 500 m above ground
- Temperature at 10, 70, 110, 200 and 500 m above ground
- Relative humidity at 70 and 110 m above ground
- 2 m temperature
- 2 m relative humidity
- Surface pressure
- Total precipitation
- Global radiation
- Solar radiation at the surface
- Surface sensible heat flux
- Surface momentum flux (zonal and meridional)
- Cloud cover
By assimilating data from dedicated measurement systems into a high-resolution NWP model, it is possible to obtain a full four-dimensional view of the atmosphere in the vicinity of NPPs. The replacement of meteorological towers (limited by their heights) at the location of the plants by a few strategically located ground-based remote-sensing systems (upwind and downwind of the main flows) associated to a high-resolution NWP model is an alternative that allows a better coverage in space and time of the meteorological phenomena. The figure shows a schematic of the former (top panel) and current system operationally used in Switzerland (bottom panel).
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