Guidelines on Implementation of a Coastal Inundation Forecasting–Early Warning System

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Guidelines on Implementation of a Coastal Inundation Forecasting–Early Warning System
EDITORIAL NOTE

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This publication contributes to the Early Warnings for All: the United Nations Global Early Warning Initiative for the Implementation of Climate Adaptation, led by WMO. This publication is also a registered activity of the United Nations Decade of Ocean Science for Sustainable Development, 2021 to 2030.

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PREFACE

This publication, *Guidelines on Implementation of a Coastal Inundation Forecasting–Early Warning System*, is the result of a resolution of the World Meteorological Congress at its eighteenth session in 2019 to assist vulnerable countries to implement their own Coastal Inundation Forecasting–Early Warning System (CIF–EWS). These Guidelines are based on the successful implementation of demonstration systems in four countries between 2009 and 2019 through the Coastal Inundation Forecasting Demonstration Project (CIFDP) (Swail et al., 2019). Additionally, these Guidelines can be used as a valuable planning tool for coastal zone management, to build resilience to inundation through reduced exposure and vulnerability of coastal communities.

The CIFDP and the two other projects that WMO oversaw from 2009 to 2019 – the Flash Flood Guidance System (FFGS) and the Severe Weather Forecast Demonstration Project (SWFDP) – were subject to independent reviews (Barrett and Canterford, 2018; Barrett et al., 2018; Young, 2018). Subsequently the reviewers considered these three projects, with the aim of recommending efficient and sustainable CIFDP, FFGS and SWFDP, which may also, if appropriate, be integrated or “twinned” into new Multi-hazard Early Warning Systems (MHEWSs).

At its eighteenth session, the World Meteorological Congress, in particular through Resolutions 15, 16 and 29, supported this approach and referred to the ongoing systems as the Coastal Inundation Forecasting Initiative (CIFI), FFGS and the Severe Weather Forecasting Programme. Through Resolution 29, the Congress requested continued support to develop CIFI as a key component of marine and coastal services. Through Resolution 16, the Congress decided and then requested guide(s) for mechanisms/procedures in support of multi-hazard warning procedures (including hazard-cluster guidelines, with tropical cyclones as an example of a hazard cluster). Additionally, Resolution 15, in the paragraph “Noting further” states: “(3) An incremental development of the current systems’ approach (CIFDP, FFGS and SWFDP) be adopted rather than a brand new MHEWS development starting from the initial principles of the three demonstration projects” (WMO, 2019a). In this regard, these Guidelines provide a stand-alone CIF implementation that may also be combined, as appropriate and if necessary, with other systems into a new MHEWS.

WMO has given a high priority to Early Warning Systems (EWSs), especially for small island developing States (SIDS) and other developing countries that are particularly vulnerable to these coastal hazards. As explained in Chapter 1, it is critical to recognize that coastal inundation can result from single or multiple hazards, and that it is being exacerbated by the impacts of climate change, especially associated with sea-level rise. Coastal inundation events are an increasing threat to the lives and livelihoods of people living in low-lying, populated coastal areas. Furthermore, the issues for most countries that have vulnerable coastlines are the increasing level of development for fishing, tourism and infrastructure, and the sustainability of their communities.

To make such EWSs available to Members, especially SIDS and least developed countries, the World Meteorological Congress at its eighteenth session recommended the development of guidance material for coastal inundation systems, which resulted in these Guidelines. These show how an effective end-to-end coastal inundation warning system – a CIF–EWS – can be established in a country or region.

For Members considering establishing a CIF–EWS, external sponsorship is critical and can come from international organizations or initiatives. WMO supports and facilitates various mutually beneficial public–private engagements to optimize service delivery. MHEWSs, such as a CIF–EWS, are part of emerging WMO services. As an example, the World Meteorological Congress at its eighteenth session highlighted such initiatives through Resolution 74. Furthermore, the announcement of the United Nations Secretary-General, on World Meteorological Day 2022, that the United Nations will “spearhead new action to ensure every person on Earth is protected by early warning systems within five years” has recently recognized the leading international role of WMO in early warnings (United Nations, 2022).
During the development of these Guidelines, it has become clear that, while there is a large amount of excellent technical information and background documents available, there is certainly a need to prepare single “recommended practice” or “one-stop” implementation guidelines that countries can follow to prepare and implement their own CIF–EWS.

As a result, these Guidelines provide a straightforward 10 step process with templates featuring policy, management and technical processes that countries or regions can use to build their own EWS, from vision through to “go-live” implementation. As such information is not always readily available in many countries, these Guidelines have concentrated on these features in developing and building a system, including necessary information for sponsors and advice on the resources necessary for success.

These Guidelines are careful to emphasize best practices through establishment of a project development plan, accessing international experts to assist and initiating in-country governance arrangements suitable for implementation of the CIF–EWS. As each country implementing such a system will have its own unique set of coastal inundation hazards, the Guidelines provide a flexible approach to a “system build”, based on well-established risk analyses. Additionally, reference is made where appropriate to quality management systems and other WMO standards such as for instrumentation and networks. Also included is a comprehensive explanation of the hazards and the range of models used for their forecasting and warning, along with appropriate reference material.

The Guidelines are structured to include an introductory chapter that outlines the range of coastal inundation hazards and emphasizes the importance of building a CIF–EWS to minimize potential disasters for vulnerable coastal communities. The increasing impact of climate change is also discussed as it directly affects these coastal communities. A background chapter follows that outlines the fundamental nature of coastal inundation and how it is scientifically modelled to provide forecasts, warnings and impacts of the inundation. The third chapter is designed to take the user through a step-by-step project to build and implement a CIF–EWS. Several appendices, with templates, are provided for clear guidance on what is needed for agency officials, experts and sponsors to achieve a successful outcome.

Sincere thanks are expressed to the authors, Dr Ray P. Canterford (Australia) and Dr Yuri A. Simonov (Russian Federation) for their dedication and the high quality of these new Guidelines. These Guidelines reference the extensive material and scientific expertise of Mr Val Swail (Canada), founding Chair / Co-Chair of CIFDP. As per standard WMO publication processes, this work underwent independent peer review by four internationally recognized experts: Mr Curtis Barrett (United States of America), Mr Leandro Kazimierski (Argentina) and two that remain anonymous. The WMO Secretariat staff involved in the review of these Guidelines were Mr Misaeli Funaki, Dr Sarah Grimes, Mr Cyrille Honoré, Dr Hwirin Kim, Mr Nakul Prasad and Mr Giacomo Teruggi. Funding for the development of these Guidelines was supplemented through extra-budgetary sources: the Climate Risk Early Warning Systems initiative and the Korea Meteorological Administration.

These Guidelines were approved in May 2022 by the WMO Commission for Weather, Climate, Water and Related Environmental Services and Applications (Services Commission or SERCOM) Management Group, with the support of the Standing Committee on Marine Meteorological and Oceanographic Services, in collaboration with the Standing Committee on Hydrological Services. The Guidelines are a contribution to the Early Warnings for All: the United Nations Global Early Warning Initiative for the Implementation of Climate Adaptation, led by WMO. The Guidelines are also a registered activity of the United Nations Decade of Ocean Science for Sustainable Development.
1. **INTRODUCTION**

The purpose of this publication, *Guidelines on Implementation of a Coastal Inundation Forecasting–Early Warning System*, is to enable at-risk countries and/or regions to undertake a step-by-step process to establish a Coastal Inundation Forecasting–Early Warning System (CIF–EWS). This is especially important for small island developing States (SIDS) and least developed countries (LDCs) with vulnerable coastal communities. These Guidelines are based on the successful implementation of four such demonstration systems during the period 2009–2019 (Barrett and Canterford, 2018) through the Coastal Inundation Forecasting Demonstration Project (CIFDP) (Swail et al., 2019). CIFDP was a joint initiative between the former Joint WMO–Intergovernmental Oceanographic Commission (IOC) Technical Commission for Oceanography and Marine Meteorology (JCOMM) and the former WMO Commission for Hydrology.

The severity of the impacts of disasters, especially on coastal communities, is well known and documented. A contributing factor is the increasing intensity and frequency of meteorological and oceanographical hazards caused by climate change, including sea-level rise, which can seriously affect SIDS and other coastal nations. Scientists, engineers, emergency specialists and governments are working together to mitigate the impacts of major natural hazards such as those caused by oceanographical, meteorological, hydrological and geophysical events. United Nations entities such as WMO, the IOC of the United Nations Educational, Scientific and Cultural Organization and the United Nations Office for Disaster Risk Reduction support coastal communities as a top priority, and are implementing coastal initiatives. Often, these are complemented by global funding mechanisms such as those of the Climate Risk Early Warning Systems (CREWS) initiative, the World Bank and the Green Climate Fund.

Over the last 200 years, at least 2.6 million people are estimated to have drowned due to coastal inundation, particularly caused by storm surges (Dilley et al., 2005). A later publication concentrating on recent decades (1970–2019) highlights the major loss of life during this 50 year period alone: 2 million people, from over 11 000 weather-, climate- and water-related disasters, as well as economic costs estimated at US$ 3.6 trillion (WMO, 2021a). The 10 worst reported disasters in terms of lives lost were mostly in LDCs and developing countries. This emphasizes the need for these Guidelines, which are applicable to all coastal areas, and which are especially important for SIDS and coastal communities of LDCs.

1.1 **Coastal inundation**

The definition for coastal inundation used in these Guidelines is the following:

> Coastal inundation – on various timescales – occurs from multiple sources, including from storm surges, waves and swell, seiches, riverine and flash floods near the coast, tides, sea-level rise and tsunamis.

Box 1 provides a summary of the causes of coastal inundation. These are due to a number of climate, weather, hydrology, ocean and geophysical hazards. Coastal inundation can result from each of these hazards individually or in combination, which is often the case. A coastal inundation forecasting and early warning system multi-hazard approach for this group of hazards is therefore needed to design and implement a CIF–EWS.
Box 1. Coastal inundation hazards

Hazards that can cause coastal inundation include:
- Storm surges due to cyclones and other weather systems
- Riverine floods and flash floods near the coast
- Tsunamis from geophysical and other events
- Remotely generated swells
- Locally generated waves
- Tidal influences
- Sea-level rise due to climate change
- Inundation due to land subsidence
- Large-scale sea surface height anomalies (SSHAs)

The WMO report *State of the Global Climate 2021* includes a section dedicated to sea level, which states: “In 2021, GMSL [global mean sea level] reached a new record high. Compared to previous El Niño and La Niña years (for example in 1997/1998, 2010/2011, 2015/2016), during which the GMSL displayed temporary positive or negative anomalies of several millimetres, 2021 was marked by an increase of the GMSL that was close to the long-term trend” (WMO, 2021b).

With the changing climate, storms and extreme maritime weather are becoming more intense, which is resulting in more frequent and more severe coastal flooding and erosion events. The accelerated sea-level rise will increase the potential for larger areas of coastal land to be flooded during these events, thus increasing coastal erosion and loss of land with direct impact on property, infrastructure, livelihood and life along the coast.

Coastal inundation is therefore one of the priority areas being addressed by WMO. The aim is to assist Members to improve resilience to coastal flooding while reducing the impact of disasters. WMO has developed these Guidelines within the framework of this priority area.

The issue of sea-level rise and its impacts is also being addressed by the United Nations through its United Nations Decade of Ocean Science for Sustainable Development (2021–2030), adopted as a resolution on 5 December 2017 at the seventy-second session of the United Nations General Assembly (United Nations, 2018). Consideration of coastal inundation and other ocean hazards is critical within this Decade. These Guidelines will therefore be important in enabling all coastal communities, and SIDS in particular, to adapt to the impacts of sea-level rise through Early Warning Systems (EWSs) while the issue of climate change is being pursued. In this regard, a CIF–EWS will also be an important planning tool for coastal communities to reduce exposure and vulnerability through coastal zone management.

To save lives, protect health and sustain economic viability, WMO has developed and initiated EWSs in conjunction with countries and major sponsors in recent years (mainly 2009–2019). These can now be implemented in other at-risk countries and regions, and are designed to mitigate the effects of disasters through preparedness and risk reduction. One such EWS, the CIF–EWS, was recognized by the World Meteorological Congress at its eighteenth session (2019) as important for strengthening country capacities and capabilities to respond to coastal hazards, enabling a more proactive approach to these changing hazards (WMO, 2019a).

Coastal inundation is a multi-hazard phenomenon that occurs on the world’s vulnerable coastlines and can frequently lead to major loss of life. Some countries may already have systems that provide EWSs for one or other of these hazards, but usually not in combination. Therefore, WMO established the CIFDP in 2009 to test such a combined approach of warning services. The demonstration project was successful, and is the basis for these Guidelines.

The CIFDP and the two other EWS projects that WMO oversaw between 2009 and 2019 – the Flash Flood Guidance System (FFGS) and the Severe Weather Forecast Demonstration Project (SWFDP) – were subject to independent reviews (Part A: Barrett and Canterford, 2018; Barrett et al., 2018; Young, 2018). Subsequently, Part B, *Concept for an Integrated, Efficient, Sustainable,
and Adaptive MHEWS for FFGS, CIFDP and SWFDP (Barrett et al., 2019), considered these three projects, with the aim of recommending efficient and ongoing sustainable CIFDP, FFGS and SWFDP that can also be integrated into a Multi-hazard Early Warning System (MHEWS). All these projects were considered successful by the independent reviews and the word “demonstration” was removed by the World Meteorological Congress and replaced by alternative titles where appropriate. They were changed to the Coastal Inundation Forecasting Initiative (CIFI), FFGS and the Severe Weather Forecasting Programme (SWFP). This terminology is used in these Guidelines.

1.2 General considerations for building a Coastal Inundation Forecasting–Early Warning System

As a result of the acceptance of the World Meteorological Congress of the completion of the demonstration phase of CIFDP, WMO initiated production of these Guidelines, which are based on the following general considerations:

- The number of national agencies globally that utilize storm surge, wave and hydrological models and coupled coastal forecasting systems is limited, and is rare in developing countries. Hence, these Guidelines are designed to work with responsible national agencies to support them in utilizing forecast products operationally and linking them to coastal flood management programmes and related activities. This is undertaken, where appropriate, within the WMO Global Data-processing and Forecasting System (GDPFS) framework, as shown in Step 1 (section 3.1) in these Guidelines. This requires substantive and substantial training in the use of these products, under different hydrometeorological and risk situations.
- Of special concern is the need to establish sustainable future governance options and resource availability for carrying out further development efforts and ongoing operations in a sustainable manner in developing countries, again within the WMO GDPFS framework shown in Step 1.
- The key to successfully developing a comprehensive CIF–EWS is the cooperation of different scientific disciplines and user communities. An integrated approach to streamflow, storm surge, wave and flood forecasting, as well as for tides, is the strategy for building improved operational forecast and warning capability for coastal inundation.
- There is a need to incorporate another hazard that has a major impact on coastal inundation: tsunamis. This should be considered in early planning because the critical “last mile” of distribution to the public is similar, even if the hazard origin (geophysical) is different, often with a much shorter lead time.

While Box 1 describes the hazards that can result in coastal inundation, there are many fields of expertise and associated scientific models to describe these hazards, as well as their interaction at the coast, to determine what is known as the total water level envelope¹ and its interactions with the riverine environments and communities. Coastal inundation can be described and predicted using the following scientific models: ocean response models (including wave, surge, tide and sea-level anomaly), nearshore marine meteorology modelling, parametric tropical cyclone modelling, hydrodynamic riverine modelling, rainfall run-off hydrological modelling (used in flash flood and riverine flood forecast techniques) and numerical weather prediction (NWP) modelling.

Expertise in the fields of storm surge, waves, and riverine and flash flooding is fundamental to determination of coastal inundation. Additionally, because of the complex coupling among these hazards, and their models, an integrated approach is required for building improved operational forecast and warning capability for coastal inundation. Another important factor supporting this integration is that all these hazard models share common geospatial datasets such as digital elevation model (DEM) data, bathymetric data and land-use data, which are discussed in section 3.3.3.

¹ Determined by superimposing the tidal amplitudes, set-up wind waves, flood levels, sea-level anomalies, surge amplitudes and so forth. See also the Guide to Storm Surge Forecasting (WMO, 2011a).
These Guidelines cover the scientific and predictive fields of oceanography for ocean response modelling (storm surges, waves and so forth), hydrology (riverine and flash floods) and marine meteorology, as they are key to this multidisciplinary and multi-hazard approach to coastal inundation. The Guidelines also cover the critical fields of community education, communication, impacts, preparation and response, for a total end-to-end (E2E) system.

Additionally, the Guidelines refer to the forecasting expertise “on the ground” as associated with marine meteorology forecasters and hydrology forecasters. Of course, in many National Meteorological and Hydrological Services (NMHSs), these forecasters work side by side or are often multidisciplinary, such as hydrometeorologists. In this regard, meteorologists and hydrologists in NMHSs who are operational will require additional competency training, which is addressed in section 3.9. Furthermore, because some countries have meteorological and hydrological expertise in different agencies, coordination and communication between these agencies and the emergency agencies is paramount.

These Guidelines are based on four fundamental recommended actions:

1. **Technical**: In the areas of implementation, conduct a formal assessment of coastal impacts and historical prevalence of storm surge, ocean waves and swell, tides, riverine and flash floods, sea-level variations, climate change and geophysical events (tsunamis and inundation from land subsidence). Include a needs analysis to determine the requirements to support a suitable E2E EWS² design (data through modelling and through communications / early action / response) for the identified hazards and vulnerabilities in the country that are directly caused by coastal inundation or exacerbated (influenced) by it.

2. **Stakeholder collaboration**: Establish a high-level interministerial and inter-agency agreement to support an early warning coastal inundation system that ensures all relevant national agencies (for example, NMHSs or national disaster management agencies) collaborate for an effective E2E EWS that reaches all vulnerable coastal communities (the “last mile”).

3. **Financial, expert and volunteer support**: Prepare and present a national CIF–EWS proposal to potential donors to attract the appropriate funding for supporting national CIF–EWS implementation.

4. **Operational readiness**: Formalize a go/no-go assessment for development and funding of the CIF–EWS.

### 1.3 Ten steps to implementation of a Coastal Inundation Forecasting–Early Warning System

For these Guidelines to be of direct value for governments, sponsors, oceanographical, meteorological and hydrological agencies, emergency services agencies and other stakeholders, the aim is to be straightforward with sufficient understandable detail, so WMO can serve countries wishing to adopt CIF–EWS services.

The aims of these Guidelines are to:

- Identify and help countries support end-user needs
- Encourage full engagement of all stakeholders
- Support coastal risk and vulnerability assessments
- Facilitate the transfer of technology (soft, hard and intellectual) to the adopting countries
- Initiate the development and implementation of forecasting and warning services
- Promote capacity-building and sustainability of systems and processes

It is worth noting that the above aims are also in harmony with Figure 1, a schematic of the four pillars of an E2E EWS, modified from the *Multi-hazard Early Warning Systems: A Checklist* (International Network for Multi-hazard Early Warning Systems, 2018), published after the Global Platform for Disaster Risk Reduction in 2017.

An E2E EWS consists of many interconnected components: network analysis for instruments and methods of observation, data collection and transmission to a centre, modelling and manual analysis, preparation of forecast products, dissemination/communication of these forecasts and warnings to users (emergency agencies, media and the public) for appropriate actions and a feedback loop (see Step 8 in section 3.8).
Figure 1 shows the four pillars upon which an MHEWS should be built. The CIF–EWS is designed as an MHEWS that promotes an integrated approach in the enhancement and delivery of early warnings for coastal inundations, no matter what the causes. This is in line with the concept of impact-based forecasting and the United Nations Sendai Framework for Disaster Risk Reduction 2015–2030. The recommended CIF–EWS approach can be followed directly, or it can be integrated, for example, within the existing protocols or procedures of a country’s emergency agency or NMHS.

**Figure 1. Four pillars of an MHEWS**

*Source: Adapted from International Network for Multi-hazard Early Warning Systems (2018)*

These Guidelines provide 10 succinct and clear steps (Box 2) to build the system, from vision to operation (Barrett and Canterford, 2018).
Box 2. Ten steps to implementation of a CIF–EWS

1. Undertake a national risk assessment of coastal natural hazards.
2. Conduct an inaugural stakeholder meeting with ministerial/government agencies and sponsors (including a formal national and/or regional agreement).
3. Undertake a technical assessment of all in-country and regional capabilities and requirements, as a precondition for developing the capability to issue impact-based forecasts and warnings for coastal inundation hazards.
4. Ensure E2E communications, including the “last mile”.
5. Ensure donor and sponsor engagement (internal and external).
6. Establish a Project Steering Group (PSG) with major stakeholders and technical experts, and appropriate PSG links to WMO Regional Centres. Prepare a concept of operations (CONOPS).
7. Build and strengthen all system components using a project development plan (PDP) with associated governance.
9. Ensure critical training for all elements is in place and that they are sustainable.
10. Undertake a go-live assessment in consultation with the PSG and all stakeholders prior to operational implementation.

Note: The order of some of the 10 distinct steps above may be rearranged or undertaken in parallel. The order of steps is based on the experience of the CIFDP subprojects. Countries implementing a CIF–EWS may have circumstances that justify a change in the order of execution. Appendix 4 gives a proposed timetable of the implementation process for these 10 steps.

2. BACKGROUND

Due to the complex nature of coastal flooding, a CIF–EWS needs to be capable of issuing forecasts and warnings related to different types of marine/hydrometeorological hazards, including storm surges, waves and tides, geophysical hazards (tsunamis) and hydrological hazards, such as riverine floods and flash floods. Exacerbated by climate change, all these hazards have a direct impact on coastlines and are the primary sources of damage in many areas of the world, including in SIDS.

These dangerous impacts for vulnerable coastal populations are more prevalent in SIDS because of their small geographical area, isolation and exposure; about one third of their population lives on land that is less than 5 m above sea level (United Nations Development Programme, 2010; United Nations, Department of Economic and Social Affairs, 2019).

A CIF–EWS should predict the above coastal hazards and be capable of interacting with other EWSs for specific hazards (for example, severe weather) through modelling, forecasting and dissemination. In this regard, the CIF–EWS acts as a component of an E2E MHEWS providing severe weather, marine and hydrological services (International Network for Multi-hazard Early Warning Systems, 2018).

The E2E nature of a CIF–EWS should be in line with the description in *Multi-hazard Early Warning Systems: A Checklist* (International Network for Multi-hazard Early Warning Systems, 2018), in which it is characterized as a capability to: provide risk knowledge, monitor coastal inundation hazards, model events, issue forecasts and warnings, and disseminate and communicate warning information to national disaster management organizations (NDMOs) and the community. This last capability is undertaken to mitigate possible adverse consequences of coastal inundation, and to improve national preparedness and response capabilities.

The CIF–EWS should be capable of dealing with natural phenomena that are responsible for flooding in coastal areas, as listed in Box 1. While tsunami warnings are specific due to their geophysical nature, they are typically covered by their own EWS operated usually (but not
always) by the NMHS under IOC intergovernmental arrangements. The IOC-coordinated tsunami EWS has well-established cascading systems similar to WMO meteorological and oceanographical models.

Forecasting of ocean and marine hazards is approached via application of three-dimensional hydrodynamic ocean models, capable of simulating and forecasting storm surges and tidal effects. The CIFDP subproject reports of the former JCOMM and the former WMO Commission for Hydrology give examples of ocean models that can be applied within the CIF–EWS (JCOMM, 2019a, 2019b, 2019c, 2019d).

Inland river floods that affect coastal flooding are typically riverine floods, for which the flood waves can interact with ocean waves, storm surges and tidal effects. This occurs when the river water hits the elevated water level at the coast, creating a natural dam. Such interaction results in complex processes in the estuarine area, including a backwater effect that can exacerbate coastal inundation. For small river basins, flood formation and travel time from upper catchments to the river mouth tends to be relatively short (a few hours). As a result, this mandates the requirement to model the riverine flooding on major rivers that approach the coastal zone, and rainfall run-off processes in the upper catchment of the rivers (Figure 2).

![Figure 2. Diagram of the CIF–EWS main modelling components](image)

*Figure 2. Diagram of the CIF–EWS main modelling components*

*Source: WMO (2013a)*

The need to model rainfall run-off processes is especially vital for SIDS, where upper small river catchments typically experience intense rainfalls from tropical storms. These can generate fast-developing flash floods with short formation and travel time to main rivers, and which rapidly flow in a seaward direction. Thus, modelling of flash floods and riverine floods is critical for SIDS where tropical systems can bring heavy rainfalls to the river catchments, located near the coastal areas, or for other countries with a short travel time from upper catchments to a river’s coastal area.
2.1 **Interface between the ocean and river models near the estuarine zone**

Special attention in coastal inundation modelling and forecasting is given to the estuarine zone, where the “bridge”, or interaction, between ocean and river processes must be modelled to achieve accurate coastal inundation. Rainfall run-off and river routing models are used to model streamflow generation in upstream catchments and then route it downstream to the coastal area, to couple with the sea/ocean model. Models of different complexity are used in planning and operational practices (for example, WMO, 2009a, 2011a); sections 3.1.1 and 3.1.2 below, as well as Appendix 5, present further details.

SWFP provides support to many countries and regions that can be used for ocean and hydrological model input. This is the case for the ocean models that have been implemented through CIFDP. In terms of inland hydrological flooding, there are WMO interoperable platforms and models for advancing flood forecasting (Appendix 5) and the widely implemented FFGS as input to the inundation modelling (Figure 2) for fast-developing flash floods in upper catchments.

2.2 **The atmosphere, ocean and river modelling chain for coastal inundation**

In the chain of modelling of coastal hazards, weather forecast models play a major role in forcing ocean and river models. For instance, FFGS or other forecast systems, which utilize rainfall run-off models, are forced by modelled meteorological forecasts (mainly precipitation and air temperature) of relatively high spatial resolution, depending on the river catchment size. Weather forecast modelling for severe weather is provided to some WMO Members with the help of SWFDP, which has already been successfully implemented in many countries and regions, and is now ongoing as SWFP (WMO, 2022a).

2.3 **Tsunami coastal inundation as an input to a Coastal Inundation Forecasting–Early Warning System**

Many countries with vulnerable coastal communities have tsunami warning systems that are tested regularly due to the major loss of life that has occurred, in particular, after the tragic 2004 Indian Ocean tsunami. In the immediate period after this tragedy, IOC worked with WMO, and IOC has taken responsibility through regional Intergovernmental Coordination Groups to coordinate the continued development and sustainability of tsunami warning systems. There are opportunities to leverage the successful international tsunami efforts in collaboration with the CIF–EWS, especially for community warning and the “last mile”. If users of these Guidelines are not aware of tsunami warning arrangements in their country, they should consult the IOC website (Intergovernmental Oceanographic Commission, n.d.) to determine the tsunami service provider for their country. IOC has a wealth of information available to ensure countries have the best available tsunami warning services.

These Guidelines do not specifically detail how such warnings are integrated into coastal inundation, but like the other coastal hazards listed in Box 1, consideration should be given as to how public information via the warning arrangements of the CIF–EWS can be promulgated. These Guidelines suggests that the public information chain developed for many tsunami warning systems may be leveraged for the CIF–EWS. The international experts who will need to be engaged in building the CIF–EWS will be best placed to determine the linkages. In the simplest approach, it may be the tsunami warning from the country’s agency charged with that responsibility ensuring it is shared with the agency issuing the CIF–EWS forecasts and warnings. In many cases, this is the NMHS with both responsibilities, so there is no reporting redundancy or delay. In other countries, there are different agencies and public warning systems (like sirens) that should be shared for both purposes. Unfortunately, this is not always the case; CIF–EWS stakeholders should rectify this position (via the PDP), or agree to a suitable sharing of observational data and warning systems.
3. **BUILDING THE SYSTEM: 10 DETAILED STEPS TO IMPLEMENTATION**

Sections 3.1–3.10 detail the 10 steps to build and implement a CIF–EWS recommended in these Guidelines. The steps are designed to be of a form that allows WMO Members and relevant Regional Associations to quickly commence the implementation of a CIF–EWS that utilizes the successful benchmark of the CIFDP outcomes, endorsed by the World Meteorological Congress at its eighteenth session.

The 10 steps involve NMHSs, National Meteorological Services (NMSs), National Hydrological Services (NHSs), government agencies, sponsors, emergency agencies and usually many other stakeholders. They are designed to provide simple guidance so WMO can assist countries, especially SIDS and LDCs with vulnerable coastlines, wishing to adopt CIF–EWS services.

As mentioned in Box 2, the order of undertaking the steps may be rearranged or undertaken in parallel. The particular order of the steps in these Guidelines is based on the experience of CIFDPs (2009–2019). Implementing countries may have circumstances that justify a change in this order.

3.1 **Step 1: Coastal natural hazards, modelling and inundation risk analysis**

When considering the implementation of a CIF–EWS, this first step is critical to ensure the focus is on the appropriate hazard(s) for the country and its vulnerable coastlines. As shown by Swail et al. (2019), and above in Chapters 1 and 2, coastal flooding is a multifactorial event, induced by the combined action of ocean, marine and inland hydrometeorological hazards, as well as geophysical hazards such as tsunamis. Understanding the nature of such hazards, their contribution and the associated risk in coastal areas is a first step towards building an effective human-oriented E2E MHEWS (International Network for Multi-hazard Early Warning Systems, 2018), of which the CIF–EWS is a good example.

Analysis of coastal inundation, whether by storm surge, distant swell, tidal influence and riverine or flash flooding – or indeed a combination of these hazards – requires understanding of the individual risks of each hazard, as well as the joint probability. Of course, all the hazards are often not independent, as they may occur from perhaps a tropical cyclone (hurricane/typhoon) that produces storm surge as well as heavy rainfall conducive to riverine and flash flooding. In this regard, coastal inundation can be seen as an integrating event that can be informed by marine and flood risk assessment.

In addition to hazard assessments, consideration of community impact risks on the ground is vital. Risk assessment from a financial, political and organizational perspective is also critical. Appendix 1 provides a table of community and infrastructure impacts. These impacts can assist in the determination of coastal inundation risk assessments from community, national governmental and responsible agency viewpoints. Such risk assessments should be fundamental to the formulation of the PDP (see section 3.7).

When commencing, indeed before deciding on, the implementation of a CIF–EWS, a full assessment should be undertaken of all potential coastal hazards, using historical records of physical variables as well as any recorded impacts or evolving vulnerability of the coastal areas and communities. Ideally, statistical analysis can be performed on the data to assess critical impacts. For SIDS and LDCs, historical data are often limited or difficult to access, thus restricting statistical analysis. In this regard, meteorologists, hydrologists and oceanographers can use alternative techniques such as scenarios of hazard phenomena based on regional information and experience. Modelling of recent events with adequate data can also assist, as well as extrapolation of known documented events where good data are available. Examples of such techniques are the probable maximum precipitation (PMP) and probable maximum flood (PMF) approaches, used in conjunction with any existing records that can help identify areas at risk (WMO, 2009a, 2009b).
3.1.1 Ocean and marine models for risk assessment

Examining the general risks of inundation, as well as the capability of various models for mitigation, will guide which areas or locations within a country should be improved through CIF–EWS implementation. It will be important to dedicate some time and effort to undertaking such risk analyses. Appendix 1 provides information that should guide this process.

Storm surge from wind forcing for a coastal inundation modelling system can be caused by intense storms including tropical cyclones (or hurricanes or typhoons), extra-tropical storms and other wind systems. For the case of tropical cyclones, a parametric model of winds and pressure within the moving tropical cyclone vortex can be developed from a forecast set of storm characteristics. A typical set of such characteristics includes:

- Storm track
- Storm intensity (usually defined by the pressure differential between the centre of the tropical cyclone and the peripheral pressure)
- Storm size (usually defined in terms of the radius to maximum wind for wind field estimation)
- Forward speed of the storm

Statistical analyses of historical marine hazard systems should be undertaken where data are available. If they are sparse, modelling of recent events with adequate data can assist risk assessments. Many SIDS and LDCs are vulnerable to tropical cyclones/hurricanes/typhoons, and modelling of these systems is mature and undertaken in specialized WMO Regional Centres. There are six tropical cyclone Regional Specialized Meteorological Centres (RSMCs) as well as six Tropical Cyclone Warning Centres having regional responsibility. These centres provide up-to-date guidance products, advisories and bulletins as an agreed set of meteorological information on all tropical cyclones/hurricanes/typhoons everywhere in all ocean basins affected by these phenomena. It should be noted that a wider range of products and data are provided by some of these centres, including storm surge model output. Additional modelling or interpretation can be undertaken locally using these models. Similarly, RSMCs for marine products can provide storm-related information such as on winds, waves and storm surges.

The RSMCs can also provide information about the models used to assess risk, as well as related uncertainty. Countries can access these models and associated metadata through the WMO cascading Earth-system modelling processes (Figure 3 provides a simplified diagram). WMO GDPFS encompasses all NWP systems of WMO Members. The WMO Information System (WIS) exchanges and delivers GDPFS products. Tropical cyclone RSMCs and established centres providing SWFP information assist developing countries in accessing the NWP model outputs, in basins and areas where they have been established. Distant swell modelling is also undertaken by RSMCs and can be complemented in-country with bespoke models that also use boundary conditions from the WMO specialized centres.
As discussed later in Step 7 (section 3.7), which focuses on the CIF–EWS PDP, Regional Centre models provide wind fields, pressures, temperatures and precipitation, as well as data from large-scale ocean circulation and wind wave models (providing information on large-scale SSHAs and on waves generated outside the region). These models have improved considerably in recent years, including their resolution, and can be sustainably utilized in a country’s CIF–EWS.

It is important when examining the country’s vulnerability to meteorological, oceanographical and hydrological hazards, as well as to tsunamis, to determine the risk of each hazard and the level of amelioration or improvement to community impacts and infrastructure impacts that can be provided by a potential CIF–EWS. For example, will a storm surge model (with surge heights and timing) provide sufficient time to allow evacuations of coastal communities, or will a general tropical cyclone or hurricane warning produce the same outcome in terms of community warnings?

3.1.2 Hydrological models for flood risk assessment

Flood risk assessment is necessary for planning and implementing any E2E MHEWS. Several techniques can be used for determination of risk, including flood frequency analysis, the PMF approach, hydrological modelling, and geomorphologic and regression approaches. The Guide to Hydrological Practices, Volume II (WMO, 2009a) gives further details. A key characteristic to be calculated is the design floods of a particular annual exceedance probability (AEP) for a particular gauge along the river – for example, the flood of 1% AEP (a “100 year flood”). Care should also be taken to consider any measurable impacts of climate change on the design flood. After calculating design floods of a certain AEP at different river gauges along the river, flood
hazard characteristics can be derived associated with a certain AEP value (for example, spatial extent, depths and velocities). Spatial extent of floods for different AEP values can be derived with the help of hydraulic modelling, based on accurate terrain data and flood discharge. From such spatial extents, or flood hazard maps, the flood hazard at any location in the river basin can be represented as a water surface elevation exceedance probability function. In SIDS and other developing countries, such observations are scant or missing, thus making such calculations difficult at best. Where historical atmosphere and rainfall data exist, assessment of PMP can be used to determine PMF in determining areas at high risk (WMO, 2009b).

There are specific procedures recommended for assessment of flash flood risks due to the distinct flash flood characteristics associated with their formation (such as complex hydrometeorological events and flood generation processes, affected by factors such as slope, and land cover).

This is particularly relevant and valuable for SIDS, as their natural topography is typically causative for flash floods due to:

- The small areas of the islands and river catchments, which often produce fast routing of rainwaters in the downstream coastal areas
- The headwaters of rivers receiving heavy rainfalls due to the orographic effect of mountains
- The tropical climate with frequent exposure to hurricanes and tropical storms, weather depressions and so forth, bringing heavy and/or long-duration rainfalls, quite often accompanied by increased intensity of precipitation in the form of brief but torrential rainfalls
- A combination of the above that often leads to rapid flash flood generation, typically less than 6 hours from commencement of the causative event

While undertaking the risk assessment with respect to flash floods, there are different flash flood indices and guidance used to single out potentially hazardous areas with respect to flash flooding (for example, flash flood potential index, flashiness and flash flood guidance). Such indices are based on the contribution to the possibility of flash flood generation of several physiographic factors, and are calculated based on multicriteria analysis of flash flood conditioning variables like slope, slope length and aspect, soil hydrological properties, land use and others (such as watershed slopes and geometry, soil texture and vegetation classes), which, if combined in a geographic information system environment with average rainfall amounts, provide information about the hydrological response of a watershed and flash flood potential of a specific area. Although these output results may be qualitative, they can still be used for estimating assets and communities at risk.

3.2 Step 2: Stakeholder inaugural meetings with governments, agencies and sponsors

The successful CIFDP implementing countries and region (Bangladesh, Caribbean, Fiji and Indonesia) had interministerial and agency head agreement. These locally tailored agreements, which were termed Definitive National Agreements in the demonstration phase (CIFDP), have been essential to the success of the projects in those countries/region. For CIF–EWSs, these Guidelines present a generic and formal implementation agreement for a national or regional CIF–EWS. This is also referred to in shortened form as a National Implementation Agreement (NIA) elsewhere in this publication. Appendix 2 provides a template for the full documentation for such an NIA, which may be modified as required.

This step (Step 2) of CIF–EWS implementation is critical and is commenced, where possible, through an inaugural stakeholder meeting, to ensure all government agencies and associated departments are aware of the level of cooperation and commitment to make the CIF–EWS project successful, including ongoing commitments. At this meeting, the lead agency (the NMHS, or possibly jointly the NMS and NHS if they are not within the same agency, or the NDMO if appropriate) should lead with the outline of the success of the subprojects in other countries, as recorded in the assessment of Barrett and Canterford (2018).
WMO Regional Associations and relevant RSMCs, as well as future WMO Hydrological Centres, should be involved from the outset and be part of the inaugural stakeholder meeting, and be affiliated in the NIA (Appendix 2). In addition, IOC regional representatives should be invited for potential tsunami hazards. Where possible, prospective donors or sponsors should also be invited. Attendees should be as widely represented as possible and include relevant government agencies, non-governmental organizations (NGOs) and community groups. The subsection below provides such a list.

At the inaugural stakeholder meeting, it will also be important to consider, up front, the extent of WMO involvement. Full WMO involvement in the project development, implementation (including technical expertise and project management) and sourcing of sponsorship is not possible, as this is beyond the resource (staff and financial) capacity of WMO. This first option was the model used for the CIFDP subprojects that were assessed by Barrett and Canterford (2018) and for which they concluded it was not an efficient mechanism for the large number of future implementations being requested of WMO.

The second and preferred approach for WMO involvement is the one recommended by the assessment of Barrett and Canterford (2018) and which was agreed by the World Meteorological Congress at its eighteenth session. It involves an advisory and assistance role for WMO to ensure WMO standards such as for instruments, networks, model guidance and quality management are met in the implementation process, and in the ongoing operation of the service. It also allows and encourages access to WMO experts on a voluntary/contract basis. This is the approach adopted in these Guidelines; all tables and pro forma in these Guidelines are based on this approach.

**National Implementation Agreement**

An NIA is essential for CIF–EWS implementation in a country or region for the first time. These Guidelines therefore provide a template in Appendix 2 that can be customized by the country.

The project and its ongoing sustainability will need to have strong involvement of the NMHS (or NMS and NHS together), in conjunction with the agency responsible for emergency and related services and high levels of government.

In summary, the key agencies from within various ministries should include:

- The NMHS (or NMS and NHS if different entities)
- The NDMO
- The telecommunications agency and State-owned media (which usually has a role in distributing emergency information)
- Navy/Coastguard/hydrographic agencies
- The oceanographical service(s)
- Other agencies with an immediate or long-term role in coastal inundation

All these agencies, as a minimum, should be involved in the establishment of the CIF–EWS.

Appendix 2 includes an expanded list of potential government and other agencies, for the convenience of the users of these Guidelines. These can be modified by users for the preparation of the NIA for their country or region.

Technology transfer and data sharing are critical among the service-providing agencies including the NMHS (or NHS/NMS), and the implementing agencies and beneficiaries including the NDMO.

It is important for potential sponsors that the NIA is in place and supported by the country/region government agencies before the sponsor commits funding. Furthermore, the implementation of a CIF–EWS usually has international involvement through experts in the provision of, for example, numerical weather modelling, tropical storm tracking, flood forecasting or distant swell modelling.
3.3 **Step 3: Technical assessment of country and regional requirements**

There are several technical requirements that need to be assessed on a national level towards the development and implementation of an effective, sustainable and operational CIF–EWS. Such an assessment would include the observational capability of the necessary hydrometeorological variables, historical and additional data and metadata (including access to national and regional products) and data management capacity. Other assessments would be the warning agencies’ existing capabilities in terms of preparedness, coastal hazards forecasting, forecasting product generation, warning policies and practices (including dissemination and community awareness and response). Another critical consideration is the capacity of the warning and other agencies included in the NIA to undertake the additional responsibilities of this new or enhanced system.

The subsections below list the main requirements that relate to hazards which result in coastal inundation. The technical assessment seeks to identify the strengths, weaknesses and gaps of the current practices of all agencies involved in coastal inundation forecasting and warning. It also provides an overview of what needs to be improved with respect to CIF–EWS development, implementation and sustainability.

This approach to technical assessment follows the authors’ experience in building similar systems in their own countries, and the experience of implementation of the CIFDP subprojects described earlier. Similar approaches have been used for severe weather projects through SWFDP and now SWFP (WMO, 2022), the ocean and marine services requirements (WMO, 2011a, 2018a, 2018b, 2018c) and the hydrological requirements (WMO, n.d.a).

### 3.3.1 Institutional mapping

On a national scale, it is necessary to understand the agencies that are responsible for the risk knowledge of coastal hazards, and also their monitoring, forecasting, warning, communication and dissemination, as well as preparedness and response. As coastal hazards are of mixed nature, all the hazards and functions listed should be mapped against the relevant institutions with respect to ocean, marine (coastal waters), hydrological and meteorological phenomena, as well as bathymetric and topographic information.

### 3.3.2 Infrastructure, including backups

Continuity of operations at the forecast centre where the CIF–EWS will be operating is vital for robust operation of the CIF–EWS in a 24/7 mode. Improved infrastructure for operation centres may be required for resilience to natural hazards and for forecasters’ safety and ability to maintain a sustainable and effective service. Technical aspects, including computing power, electricity and communications are vital, as shown in Figure 4 later. Advanced-generation desktop computers are generally required with periphery devices to enable access to products (for example, NWP and satellite) from the Global Telecommunications System of WIS. Electricity and communications backup technologies, as well as a designated backup (or secondary) centre, should be in place to ensure robust operation of a CIF–EWS.

### 3.3.3 Real-time data, historical data and ancillary information

Historical and real-time hydrometeorological data are required to calibrate and validate models, and to run them operationally. Of equal importance is the value of historical data for community-based vulnerability assessment. This addresses the needs of vulnerable members of the community and their response needs (such as evacuation) and infrastructure support (such as safe areas). This type of historical data and analysis ultimately informs the preparation of impact-based forecasts and warnings at a community level. Section 3.4.3 addresses this in more detail.

In addition to the quantity of data, the quality is also of vital importance. Ancillary information, such as DEM, cross sections, soil type, land-use and land-cover information, reservoir information
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(if any) and bathymetry data, are also required to set up hydrological and ocean models. If some or all elements of these data (real time or historical) are not available, system developers will assess the criticality of the various types of data and recommend those that are essential or otherwise. This should be undertaken as part of the PDP (section 3.7).

Appendix 3 provides a comprehensive list of data and other information requirements for implementation of a CIF–EWS. The list is based on the CIFDP national capacity assessment (JCOMM, 2014) and a synthesis of various relevant system implementation requirements (for example, WMO, 2011a, 2011b, n.d.a).

Observational network design is a key characteristic that should be evaluated with respect to its optimal use for sustainable coastal inundation forecasting – number and location of observing stations, their data acquisition processes, and observing frequency and backups and/or redundancy for robustness of the total system. The Manual on Marine Meteorological Services (WMO, 2018c), the Guide to Marine Meteorological Services (WMO, 2018b) and the Guide to Hydrological Practices, Volume I (WMO, 2009a) provide considerations of observational network design and other features.

Real-time observational data (for example, wave characteristics, water level, streamflow, sea level and rainfall) may be a significant source of error in overall CIF–EWS forecasts. For instance, errors in spatially averaged rainfall alone can be significant (WMO, 2011b). Data acquisition instruments are also sources of measurement errors. Data collection should comply with the general guidance for instruments and methods of observation described in the Guide to Hydrological Practices, Volume I (WMO, 2009a). The Manual on Stream Gauging (WMO, 2010) gives some requirements for collecting streamflow. The reliability of remote transmission of real-time data is vital to avoid data loss (for example, in tropical cyclones) when they are most needed.

Some observational errors are related to changes in measurement characteristics of instruments; therefore, regular recalibration is needed to sustain the quality level of data acquisition. Equipment calibration facilities should be defined in advance, and all organizational and logistic paths should be developed and checked. Where critical, backup equipment should be available to substitute for field equipment requiring repair or laboratory calibration (if these cannot be undertaken on site). In some instances, replacement of equipment can be more efficient than extensive maintenance, which should be considered in the logistics sections of the PDP (section 3.7). Vandalism can also require equipment replacement at short notice.

Field transport is another key issue in terms of maintenance of data acquisition equipment. Checks of readiness of the field transport should be made (and further on a regular basis), so it is ready to be used in case of sudden failure or required maintenance of data-collection/transmission equipment. Spare parts, tools and supplies for sustainable operation of the observing equipment should be available and ready for flood and marine instruments (such as sea-level gauges or buoys).

3.3.4 Data management

Real-time data in an EWS should go through quality assurance (QA) / quality control (QC) procedures, and be stored in a relational database within a database management system (DBMS). Data input/output procedures are usually automated for most hazard variables. Local community access to real-time data with feedback processes can also assist QA/QC.

Technologically, the CIF–EWS can be a complex system that contains different computing subsystems ranging from NWP to ocean, marine and hydrological forecasts, connected with continuous real-time data flow. Management of data, including questions related to sustainability, should be carefully included in the system design and examined during overall system checks.

Users of a CIF–EWS should carefully review input data, either by introducing automatic QA/QC procedures, or through manual checking by experienced and knowledgeable staff. These processes should be included in the planning of the PDP (section 3.7). QA procedures should
also be undertaken for data-collection processes and the data management system. WMO recommends a final comprehensive overarching quality management system (QMS) approach (section 3.10).

The DBMS should be well maintained by information technology (IT) specialists; it should also be mirrored on a different server – and be in a ready mode – which will allow the CIF–EWS to continue operation in case of failure of one server within the DBMS.

Backup procedures for estimating missing data in real time should be developed, automated and implemented (for example, in case of missing real-time rainfall data from a certain rain gauge, the value can possibly be filled with the latest rainfall forecast at that gauge as an approximation).

3.3.5 **Existing capabilities in ocean, marine, hydrological and weather models and forecasts**

Before planning a CIF–EWS in a country, it is necessary to understand the current capabilities of the NMHS (or other provider(s) of such forecasting products) in terms of coastal hazard modelling and forecasting. This subsection and Appendix 5 outline the types of modelling necessary. Country reports, as well as information from national experts on existing models and platforms used for this purpose, will be helpful for system development and set-up. Details of the types of services provided should be part of the baseline information.

One factor for consideration is the capacity gap in many NMHSs in the delivery of flood and coastal marine forecasts and warnings to users. The design and building of a CIF–EWS must consider this gap in developing an interoperable environment that can function adequately in low-capacity situations, yet deliver acceptable coastal hazard forecast and warning products using limited data and fit-for-purpose modelling.

Coastal inundation forecasting and warning is based on the following: ocean (wave, surge, tide, sea-level anomaly) modelling, nearshore marine modelling, hydrodynamic riverine modelling, rainfall run-off hydrological modelling (used in flash flood forecast techniques) and NWP modelling (Appendix 5). Computational resources need to be considered when wishing to approach the solution using, for example, a multimember ensemble for tropical cyclones. Combining these with NWP outputs, ocean and marine, and hydrological and hydraulic models requires extensive computing power. However, particular hazard modelling, such as that applied to produce storm surge forecasts based on tropical cyclones (or hurricanes and typhoons), can be undertaken off site by agencies with access to large computing capacities (such as the National Oceanic and Atmospheric Administration (NOAA) National Hurricane Center (NHC) storm surge system). Through this mechanism, inundation scenarios can be stored on a local desktop computer and selected based on real-time track and intensity forecasts provided by NOAA NHC or other agencies operating comprehensive forecast systems. A similar approach is also used for tsunami modelling, where forecasts can be required within minutes, and even facilities with large computing resources cannot resolve forecasts rapidly enough.

Therefore, the technical assessment needs to consider if the national service has the computational resources to run the entire system, or if the national service needs to consider using a third-party solution for computational resources and for provision of the numerical prediction function (as a cloud-based service). Cascading from RSMCs endorsed by WMO is important. Sustainability will remain an issue to consider. These questions should be included for relevant expert consideration in the system’s PDP.

It may also be possible to consider pre-computed inundation and flood hazard maps for affected communities. In pre-processing, archived maps are selected for the forecast events. For ocean and marine coastal modelling, storms, waves, tides and coastal impacts are modelled. Coastal sea-level gauges and offshore wave buoys provide input to the models, as well as verification of the model predictions.
To assist countries and regions, WMO has implemented over many years a cascading process of modelling that can be utilized locally and adapted with local input (Figure 3). NMHSs in a region can access information from RSMCs including products related to severe weather, tropical cyclones and marine meteorology. These products can be used as the basis for the coastal inundation forecasts (JCOMM, 2019a, 2019b, 2019c, 2019d), including:

- Regional meteorological models (providing wind fields, pressures, air temperatures and precipitation)
- Inputs from large-scale ocean circulation and wind wave models (providing information on large-scale SSHAs and on waves generated outside the region)
- Integrating coastal inundation models (using information from wind wave and wind stress, tidal and large-scale anomalies)
- Hydrological models to handle inflow into the coastal domain from the largest rivers, from which streamflow significantly contributes to coastal flooding, as well as to cover flash flooding in upper catchments

All these dynamic models must be set up on a DEM for topographic information at an appropriate accuracy and resolution, as well as for bathymetric data.

Each country will be unique, depending on the primary causes of coastal inundation in the country (as determined through the risk assessment in Step 1 in section 3.1) and the specific user requirements identified in the user requirements plan in the PDP described in Step 7 in section 3.7. As a result, customized forecast and warning interpretive products will be identified and developed for each country separately in consultation with the local user community (Step 2 in section 3.2 on stakeholder consultation and Step 7 in section 3.7 on PDP development).

The financial and sustainability aspects of available and proposed models and software must be considered, along with the necessary skills for operation and maintenance. It is highly recommended that the CIF–EWS uses freely available NWP and hydrological modelling software (and preferably open source), to avoid additional costs on maintaining the system (licensing).

### 3.3.6 Warning dissemination and communication systems

Communication systems for ocean, marine, hydrometeorological and inundation forecasts and warnings should be fully equipped to effectively disseminate warnings to the entire population in the risk area, including seasonal populations (tourists) and remote locations through multiple communication channels (for example, social media, the Internet, radio, television and alarm systems). Section 3.4 provides analysis of warning dissemination systems.

### 3.3.7 Staff capabilities

The CIF–EWS should be designed to be operated jointly by marine meteorologists and hydrologists for the essential product content and by emergency communication specialists for dissemination and community action. Thus, the following minimum knowledge and expertise is necessary for the system operators, working as a team:

- Ocean response models
- Marine meteorology and hydrology
- Operational forecasting in the region
- Quantitative analysis of marine, meteorological and NWP products
- IT for the system’s server administration
- Emergency management for on-the-ground community response

Section 3.9 details training for the wide range of professionals and support staff. This should include interpretation of technical products by emergency management staff who are primarily responsible for the final and critical phase of the CIF–EWS: community response.
3.3.8 **Sustainability**

Budget continuity for support of the CIF–EWS in the future should be allocated for: appropriate “hours-of-coverage” operation of the system, ongoing staff training and component maintenance (for example, replacing ageing computing and communications resources and associated hardware, maintaining networks of buoys, sea-level gauges and river gauges, and resampling bathymetry data). Of course, there are many components of the system that will require ongoing funding. The development of the PDP (section 3.7) must take this into account.

3.4 **Step 4: End-to-end communications including the “last mile”**

Dissemination and communication are crucial CIF–EWS elements, which must be targeted to ensure people and coastal communities at risk receive warnings before possible coastal inundation events. These elements can be through different mechanisms, including the development of “last-mile” connectivity. This connectivity means that emergency agencies and the public can receive rapid updates on forecasts and warnings through various mechanisms such as radio, mobile telephone and the Internet (if available), police and emergency service personnel, so that that coastal communities can respond to a flood threat to save lives and/or mitigate negative consequences. In the warning process, it is important to disseminate warnings to target audiences (such as those with a disability), to ensure warning information is well understood and that effective protective actions are taken.

Provision of warnings is often seen as a one-way process of delivery of warnings from an EWS to target audiences (without direct feedback), while communication is a two-way process that implies interpretation of the warning messages and then feedback from end users. User engagement and feedback is a major principle, which helps to shape warning information and means of delivery according to the changing needs of the users.

The most important aspect of the communication process is to be sure that users of coastal hazard warnings from the CIF–EWS receive these warnings in a timely manner, with clearly understood warning information containing appropriate action statements or reference to emergency agencies. Section 3.4.3 provides more information on impact-based forecasts and warnings.

According to the *Multi-hazard Early Warning Systems: A Checklist* (International Network for Multi-hazard Early Warning Systems, 2018), the warning dissemination and communication element should include the following components: organizational and decision-making processes, communication systems and equipment, and impact-based early warning communication.

For CIF–EWS warnings, including for tsunamis, the dissemination and communication process structure and informational chain are not the same everywhere, as they depend on country-specific governmental distribution functions, historical arrangements and existing requirements. For example, it may be the role of the ministry of emergency planning, or other high-level governmental agency to establish and coordinate the E2E communication process. The major requirements of the multi-hazard dissemination and communication process, which should be met nationally in a coordinated manner to get full effect from the CIF–EWS, are discussed below.

3.4.1 **Organizational and decision-making processes**

The NMHS, or other agency responsible for running the CIF–EWS and issuing coastal inundation forecasts and warnings, must develop a list of recipients of coastal hazard warnings. This traditionally includes governmental sectors, such as the NDMO, local government authorities, civil and military authorities, media, private companies in vulnerable areas, community-based organizations, public information, press and media, and others. The private companies...
mentioned in this list should include any hotels or resorts that can provide shelter to tourists and vulnerable members of the local community. Requirements, roles and responsibilities of these partners in the E2E process of coastal inundation management should be clearly defined.

Knowledge about the end users of CIF–EWS warnings and their structure is important, as it will define the type and means of dissemination and communication systems and equipment.

Communication strategies of CIF–EWS warnings at different levels (national, subnational and local) should be developed and followed, to ensure a high level of coordination among CIF–EWS warnings and dissemination channels (such as the Internet, television, radio and social media networks).

A feedback mechanism with users should be set up, for example, regular coordination, planning and review meetings (including post-event debriefs and surveys). It is valuable to hold meetings before the high-risk coastal inundation seasons (if this is the case) and to pay attention to the current prerequisites for possible adverse events, review existing product effectiveness and service delivery, and review the introduction of new products.

Coordination between the NMHS (or another agency) and the local at-risk communities is important and should be developed and sustained throughout system development and operation. People in the field can add value as local observers and spread information to the community leader(s) and further up and down the communications chain on unexpected coastal environmental changes such as: rapidly rising seawater or sea waves, increasing sea swells, rapidly rising river water levels or a colour change in a riverbed. Social media networks can also provide valuable situational awareness and should be monitored where possible.

Training and education of the local population (see section 3.9.4) should also be part of the inundation warnings communication strategy. Training sessions can significantly shape the perception of the flood and inundation risk among the population, and improve the understanding of warning messages and actions needed to mitigate inundation consequences. Mass media could play a much more effective role than simply broadcasting flood warnings, by also shaping the perception of a flood and inundation risk prior to events and promoting and reinforcing the warning and community response messaging of the responsible agencies.

### 3.4.2 Dissemination and communication systems and equipment

The goal of dissemination and communication systems is that CIF–EWS warnings have to be tailored to all groups of users, especially accounting for their possible specific needs, for example, urban and rural populations, different genders, the elderly and youth, people with disabilities, seasonal population (tourists) and others. It is vital to reach effective last-mile connectivity by understanding which population groups can be reached by which means and services of CIF–EWS dissemination systems and equipment.

The following are traditionally used for warnings dissemination in EWSs: websites, radio, telephone (automatic calls and short message service (SMS) text messages), television, press conferences, social media, sirens/alarms, emails and others. Use of these methods of dissemination should be analysed to ensure all population groups are reached with CIF–EWS warnings.

There are numerous standards and protocols that can be used by CIF–EWSs to transmit warnings. One of the most advanced is the Common Alerting Protocol (CAP). This is an international standard format for emergency alerting and public warning, adopted as an International Telecommunication Union recommendation to address long-standing needs to coordinate dissemination mechanisms for warnings and alerts (WMO, 2013b). One of the major benefits of CAP is that it can serve as an alerting media for all hazards and can be used for all dissemination media (Figure 4). Thus, different warning systems can be activated via a single input. Other benefits include standardized alerts from many sources, consistency in the information delivered over multiple systems and CAP messages being compatible with all kinds of alerting information.
systems (such as radio or television). The CIF–EWS authority can follow the Guidelines for Implementation of Common Alerting Protocol (CAP)-Enabled Emergency Alerting (WMO, 2013b) to implement CAP-enabled alerting.

![Dissemination and communications architecture](image)

**Figure 4.** Dissemination and communications architecture; CAP serves as a “universal adaptor” for alert messages

*Source: Adapted from WMO (2013b)*

### 3.4.3 Impact-based early warnings

Warning messages should enable appropriate actions, either within the warning or in collaboration with emergency agencies. To ensure this occurs, it is highly recommended that coastal inundation early warnings are communicated in an impact-based way, so target groups can take prompt, appropriate actions. The WMO Guidelines on Multi-hazard Impact-based Forecast and Warning Services (WMO, 2015a) details the best state-of-the-art approach to such impact warnings through consideration of vulnerability and exposure mapping. The warnings should not be based solely on meteorological, hydrological or inundation thresholds, but also on the impacts on communities and infrastructure. Appendix 1 on community impacts provides a detailed approach to such considerations. It should be used in conjunction with the WMO Guidelines on Multi-hazard Impact-based Forecast and Warning Services (WMO, 2015a).

It should be emphasized that effective communication of warnings to end users is a vital issue that should be seriously considered. For example, information in warning messages should clearly describe actions that should be taken (such as moving to higher ground or full evacuation). In case of fast-developing inundation in a coastal zone (for example, flash floods, storm surges and tsunamis), it would be ideal if automated systems should be installed to mitigate impacts (for example, the automatic cessation of public transport and activation of red lights in tunnels). However, depending on the infrastructure available, this type of automation may be limited. Care should be taken to ensure unwanted impacts are avoided (for example, stranded people). The role of the media in promulgating community risk prior to events and highlighting the impacts of the events is extremely valuable (WMO, 2015b).

Finally, as discussed above, coastal inundation early warning impact-based messages should be capable of dealing with the specifics of different groups of population, in particular their risk and needs, including different vulnerabilities. To ensure these are fully effective, there needs to be close, real-time operational coordination between the NMHS (or NMS and NHS if different agencies) and emergency services.
3.5  **Step 5: Donor and sponsor engagement (internal and external)**

Section 3.2 of these Guidelines provides advice on establishing the necessary stakeholder involvement in the CIF–EWS in the country or region. A critical component of that engagement is the recognition that donors or other sponsors are essential to the success of the project, and its sustainability.

This section, Step 5, outlines the key points to achieve successful engagement of sponsors, including what they need to contribute significant funds. It is worth noting that sponsorship can come from internal or external sources, or both. By establishing an NIA (section 3.2), internal sponsorship can be identified early in the implementation. It may come in the form of in-kind contributions (such as communication networks or support for maintenance) or financial contributions from government.

3.5.1  **WMO support for public–private engagement and resource mobilization**

External sponsorship can come from international organizations or initiatives. WMO supports and facilitates various mutually beneficial public–private engagements to optimize service delivery and add value to society. Additionally, MHEWSs such as CIF–EWSs are part of emerging services that are attracting an increased focus.

To assist in “closing the capacity gap” (see also section 3.9), the World Meteorological Congress at its eighteenth session, through Resolution 74, highlighted the announcement that the World Bank and WMO jointly created an Alliance for Hydromet Development in 2018 (WMO, 2019). This is supported by a declaration of the WMO Regional Associations on the importance of the Country Support Initiative for increased WMO responsiveness. These initiatives are important in seeking donor support for CIF–EWS implementation. The leadership team of the stakeholder engagement (section 3.2) should consider all of these WMO initiatives and partnership agreements, including CREWS (which is represented within the WMO Secretariat structure) and the Green Climate Fund. In particular, the implementation team should reach out to WMO Regional Associations to explore opportunities for the region or their own country. Often, projects are under way or in formative stages that may allow additional countries to be engaged.

3.5.2  **Presenting the case to a potential sponsor**

For a country wishing to implement a new CIF–EWS, the goal of the project will be to develop and implement a system that strengthens with time, builds confidence and gains capacity. Significant external (to country) resources will be needed during implementation (over some years). Ideally, this external support should reduce over time after implementation. When the system is finally operationalized, it should be independent of significant external support and have a sustainability strategy mapped out and signed up to by all stakeholders. However, it will often need to utilize the well-established WMO cascading processes for weather and ocean models (Figure 3). These will need to be identified during building of the system.

It will be ideal for the country to seek support from the appropriate Regional Association, RSMC or future WMO Hydrological Centre.

The inaugural stakeholder meeting with government, agencies and potential sponsors (section 3.2) will establish the scope and mandate for the CIF–EWS project. In approaching sponsors, it will be important to provide:

- A set of critical information to reflect the importance of the project to the coastal communities in terms of loss of life and infrastructure
- The capacity and capability of the in-country weather, marine and flood forecasting service agencies (this should be realistic and factual)

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3 The Concept for the Alliance for Hydromet Development refers to cooperation and partnerships that strengthen meteorological, climatological, and hydrological capacity and services (WMO, 2019).
- The high-risk hazards
- The level of involvement of emergency services agencies as partners
- The level of support from the government for establishing the CIF–EWS

To assist in this process, Appendix 4 provides templates that will be of value in presenting the right information for sponsors. The key elements should include the following fundamental information:

- Agencies involved in the proposed CIF–EWS such as:
  - The lead agency in the country, usually the NMHS,4 or co-lead agencies if separated (NMS and NHS) and other partner agencies (such as emergency services and ports);
  - Implementing agency/ies, which may include local staff, contracted experts or WMO contracted representatives;
  - The Project Manager;
  - The Project Executive.
- A strong statement of justification (which should include historical community and infrastructure vulnerabilities) that highlights the contribution to the government’s strategic and policy goals.
- A project summary including:
  - Impact(s)/outcome(s)/output(s);
  - Project budget;
  - Funding source(s).
- Project activities and roles and responsibilities, including:
  - Reporting and evaluation through a formal PDP with accountability to government and sponsors.
- Sustainability of project achievements once implemented, including:
  - A proposal for a CONOPS.
- A project implementation schedule, containing:
  - Timing of proposed phases of the project, including instrumentation installation, critical bathymetric and topographic dataset compilation, forecasting model building and implementation, staff training, public education and field testing.
- Proposed building and integration of forecast models for the following elements:
  - Wave (swell);
  - Storm surge;
  - Tide;
  - SSHA;
  - River flooding;
  - Flash flooding;
  - Total integrated inundation model;
  - Output from tsunami models, which are usually from IOC-designated countries (see Chapter 2).
- Risk identification and management matrix, including:
  - Political/institutional risks;
  - Financial/resources risks;
  - Human resources risks;
  - Technology risks;
  - Environmental risks.
- Cost breakdown for all phases with targets of dates and performance.

For further details, see Appendix 4, which also includes a suggested schedule for implementation.

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4 In some instances, it can be more appropriate for the lead agency, or implementing agency, to be located within another arm of government. However, the NMHS must be a major stakeholder.
3.6 Step 6: Establishing the Coastal Inundation Forecasting–Early Warning System project, concept of operations and links to WMO

A major programme of consultation with technical experts and policy experts from WMO, IOC and other relevant agencies should be undertaken from the start of implementation. WMO has a range of experts to call upon, through its Technical Commissions and Research Board. In particular, the Commission for Weather, Climate, Water and Related Environmental Services and Applications (or Services Commission, SERCOM) has lead responsibility. The WMO–IOC Joint Collaborative Board and the Hydrological Coordination Panel will be important linkages in the implementation. WMO Regional Associations, RSMCs and planned future Hydrological Centres will need to be actively engaged throughout. The key role of GDPFS in providing relevant global and regional model input to the CIF–EWS will be essential.

A PSG (discussed in section 3.7) will need to be formed, and should have technical, policy and project management expertise. The PSG will drive the project from start to finish. The group members will mainly be external experts selected in consultation with WMO. A PDP (section 3.7) should be prepared and shared with sponsors for validation and possible funding of some experts in ocean, marine and hydrology activities, as well as communications systems and project management. These funded experts should supplement the local teams (section 3.7) and be engaged on specific tasks. Where appropriate, there may be additional volunteer experts to assist or provide advice. In particular, sponsor/donor funding for a Project Manager needs to be front and centre in the PDP. This funded position may be co-located within the WMO Secretariat (extrabudgetary) on a full- or part-time basis depending on the complexity of the project.

As part of the establishment process, there needs to be a comprehensive assessment of needs, incorporating suitable gap analysis, and a detailed CONOPS. This will identify the type and number of experts to be involved.

CIF–EWS functionality should be consistent in terms of following the 10 steps of these Guidelines. In this way, the CONOPS should allow sharing of governance principles, instrument specifications, data networking techniques, forecast models, training material and so forth, for all countries that wish to establish a CIF–EWS E2E (or indeed a wider MHEWS) capability.

With regard to sustainability, the twin main drivers will be funding and political/agency support (section 3.2). It is likely that both these will be achievable, especially given evidence of the capabilities and benefits of the demonstration subprojects undertaken by CIFDP (Barrett and Canterford, 2018). Further, if there have been no recent major coastal impacts or historical impacts that have been archived for the country, a socioeconomic benefit–cost analysis should be undertaken. WMO and/or external experts could provide further advice on this approach. Potential impacts of future sea-level rise should be included in such an analysis.

3.6.1 The role of WMO in the Coastal Inundation Forecasting–Early Warning System: Members and constituent bodies

For the proposed CIF–EWS to be successfully implemented by a country or region, the NMHS (or NMS/NHS) will require advisory and technical support from WMO Technical Commissions and the Research Board, Working Groups, Regional Associations, Global Meteorological Centres and RSMCs, as well as future WMO Hydrological Centres. In defining the specific components for the CIF–EWS, the cascading of models and data from global to regional to national (and below) level is critically important for implementation and sustainability. The Project Board and the Project Team, supported by the PSG (see section 3.7), must use this approach in building the CIF–EWS model of operations in the country/region seeking implementation.

SERCOM has the lead responsibility for guiding CIFI. From a user and services perspective, the Project Board, Project Team and PSG must consider the CIF–EWS to be in harmony with...
developments and standards of SERCOM, as well as the relevant Regional Association, which should ensure standards for, and guidance on, dissemination of the information to users in the country and region. The Commission for Observation, Infrastructures and Information Systems (or Infrastructure Commission, INFCOM) is responsible for the networks and modelling systems. Within this Technical Commission, the role of GDPFS is to set standards and processes for cascading of relevant data and products to RSMCs or directly to NMHSs. Where appropriate, it can provide oversight of the standards and processes for the technical aspects, such as product and data flows and cascading models, if these components are necessary for the implementing country’s CIF–EWS.

3.6.2 **The role of the WMO Secretariat in implementation of Coastal Inundation Forecasting–Early Warning Systems**

As the CIFDP has been completed, any WMO Secretariat roles will now be predominantly for advice and minimal guidance. These Guidelines will be the major source of detailed implementation information. The CIF–EWS PSG and sponsor(s) for a particular regional implementation should seek advice from the WMO Secretariat on the optimum implementation and sponsor arrangements. Resolution 29 of the eighteenth session of the World Meteorological Congress on strengthening marine and coastal services outlines the requirement for these Guidelines. In the first instance, the Marine Services Division (mmo@wmo.int) can provide this advice and direct queries to the relevant areas in WMO for the variety of issues to be addressed.

The WMO Secretariat can advise on documented examples of the benefits of CIF–EWSs for the inaugural stakeholder meeting. These can be used to demonstrate clearly the benefits of CIFI in saving lives and to improve resilience for communities from adverse environmental events in the country implementing a CIF–EWS through these Guidelines.

3.7 **Step 7: System build – the project development plan to establish all components**

Establishing a PDP is essential for successfully designing and building the E2E system. The PDP will have detailed implementation procedures and ongoing governance arrangements to ensure success of the CIF–EWS and provide an attractive proposal for donors, especially noting the success of the previous CIFDP subprojects (Barrett and Canterford, 2018). The PDP should include a process of community engagement right from the outset to garner community, political and cross-agency support. If properly promoted, it should emphasize the minimization of community disruption and loss of life and infrastructure. Throughout these Guidelines, the governance structure and project implementation processes follow a simple PRINCE2 methodology (Axelos, 2017). There are many good tutorials available on this methodology, through search engines, at no cost. However, other generic project methodologies can also be used, depending on the preferences of the project developer, but the governance, structure and processes discussed in these Guidelines should be followed. These include the governance, scope, risk assessment, project stages, financial targets and so forth that are outlined below, and in the checklists and pro forma in the appendices.

As described in earlier sections, the *Multi-hazard Early Warning Systems: A Checklist* (International Network for Multi-hazard Early Warning Systems, 2018) based on the outcomes of the Multi-hazard Early Warning Conference, 22–23 May 2017, Cancun, Mexico, outlines the fundamental elements (checklist) for an MHEWS based on many natural hazards and capabilities of nations. It is a modern, well-thought-out set of criteria and includes four elements with the component attributes shown in Figure 1:

- Disaster risk knowledge
- Monitoring, analysis and forecasting of the hazards
- Warning dissemination and communication
- Preparedness and response capabilities
It is clear from analysis of the fundamental elements and the component attributes that the CIF–EWS meets all requirements for an MHEWS (stand alone or integrated with other EWSs).

### 3.7.1 Analysis of capacity gaps with respect to future Coastal Inundation Forecasting–Early Warning System design

As noted in Chapter 1, the purpose of the CIF–EWS is to help countries with issues of coastal inundation from oceanographical and/or hydrological phenomena, resulting from severe hydrometeorological events and some geophysical triggers, to operate and maintain a reliable forecasting system that helps national decision-making for coastal management.

Having established a country's needs for such a system (section 3.1), the initial stages of a PDP are to review and analyse the existing technical capacity and capability within the country (section 3.3) and what can run in the national operational environment. This will form a basis for the system design.

This analysis should not be viewed as a general assessment of forecast capability within the country, or a general assessment of the scientific adequacy of forecast models and techniques (for example, tropical cyclone track and intensity forecasting) that are global research issues investigated in other programmes. Rather, it is the capability of the country to adapt and run these systems, or access them and other bespoke systems developed by experts, from an operational viewpoint. Sustainability in terms of human expertise, IT system upgrades, forecasting models and funding will be a key consideration.

Training – a critical element of the PDP – should be high priority. Indeed, it should have its own distinct funding component in the financial proposal of the CIF–EWS project. The level of funding should take account of current capacity gaps and future requirements of the new system. Section 3.9 provides full details.

### 3.7.2 Scope of implementation of the Coastal Inundation Forecasting–Early Warning System project

In defining the gaps for implementation of the integrated CIF–EWS, it is useful to precisely define the scope of the project.

At the inaugural stakeholder meeting outlined in Step 2 (section 3.2), it is important to consider the scope of implementation such that it can be well documented in the PDP. This stakeholder meeting should analyse the key areas or locations for implementation in the country, such as:

- Coastlines vulnerable to storm surges and distant swells
- Key river basins with downstream flooding that affects coastal communities
- Coastlines vulnerable to tsunamis

In this way, the CIF–EWS can be restricted in implementation, and all parties will agree at the commencement of the project on where and at what level implementation will occur. Scope is important in the PDP because sponsorship will be determined on this basis. This also mitigates against scope creep, where additional unfunded activities are undertaken. Of course, this is not to limit further extension later, after the success of the first implementation and with the agreement of sponsors.

### 3.7.3 Implementation governance

Although many countries such as SIDS will have limited resources, the inaugural stakeholder meeting (section 3.2) will need to identify in-country or regional expertise that can work with sponsors and external experts (volunteer and/or contracted) to establish the CIF–EWS. There may be only a small number of in-country staff that can work a limited amount of time on the project, but they must be able to advise external volunteers, contractors and WMO experts.
on the local needs and current forecast systems. The latter may be limited, but the CIF–EWS implementation can be a catalyst to close the capacity gap. This has been shown to be successful in the demonstration projects in several countries under the CIFDP (Barrett and Canterford, 2018). Figure 5 is an example of a governance structure that can be put in place under the PDP. The listed positions are not necessarily full time (so the country or regional agencies are not overwhelmed and detract from existing operations). With appropriate sponsor funding, most of the system development, observational equipment and model development can be undertaken by selected volunteer experts and/or contractors. Again, this was found to be the case in the CIFDP. The following governance arrangements may require modification or simplification, but the overarching caveat is that a formal reporting structure is needed as outlined in Box 3.

![Figure 5. Example of the governance required for CIF–EWS implementation that can be adapted to in-country requirements (for modification and/or simplification, see Box 3)](image-url)
Box 3. Minimal governance requirements

These Guidelines recognize that in some countries, professional staffing levels in NMHSs and other agencies can be low and preclude adoption of a fully developed formal governance structure. However, a simplified but formal reporting structure, adapted from that presented in this section, will be essential to maximize benefits from funding by and accountability for sponsors. It will also enable efficient and sustainable implementation.

The simplification of the governance elements in Figure 5 and the accompanying role descriptions of the Board, PSG and so forth can be adopted if appropriate. As an example, the Stakeholder Issues Panel can be replaced with informal reporting to the Project Director, and the PSG may consist of only one or two key people (such as part-time WMO experts and meet only every 6 months). Membership of the Project Board, PSG and Project Team can also be reduced as necessary.

The Project Board (with membership from the executive, senior users and senior suppliers) is the body with responsibility for the overall CIF–EWS implementation in the country/region. It should be chaired by the NMHS Director or a delegate (or co-chaired by the NMS and NHS Directors), depending on the governmental arrangements in the country. Alternatively, the inaugural stakeholder meeting (Step 2 in section 3.2) may have decided that the lead agency for the project, or the implementing agency, should be within another senior level of government or the NDMO. The Project Board should also include senior user representatives of all agencies that will benefit or be affected by the project. Similarly, the Project Board should also include senior suppliers, who contribute expertise, systems infrastructure, instruments and so forth, or who contribute in other critical data areas (for example, bathymetry and topography). It is wise to include at least one to two technical or model experts in hydrology and in marine meteorology, so that technical know-how is available to the Project Board.

The PSG has a project advisory role and should consist mainly of international volunteer experts that have agreed to contribute their expertise, experience or advice for CIF–EWS implementation for a particular country or region. The WMO Secretariat will be able to nominate the right level of expertise for membership of the PSG, which should include experts in ocean response models (especially for storm surges and ocean waves), marine meteorology, hydrology, NWP, instrumentation and social sciences. An in-country or regional high-level official should also be a member for coordination with the Project Board.

The CIF–EWS Implementation Project Director will need to be dedicated on a part-time basis, as required, during the implementation. They will need to have experience across the coastal inundation hazards and an ability to direct the project. This position would most likely need to be funded by the sponsor. Alternatively, if WMO has the need to oversee many such E2E CIF–EWSs, it could be more efficient for sponsors to fund one position within the WMO Secretariat with appropriate travel funds to visit countries during implementation.

The Project Team will be responsible for the technical and communications work, and consist of local country or regional service experts and external model experts. There will need to be flexibility in this team, depending on the local capacity and level of expertise.

A Stakeholder Issues Panel is optional, but best practice will allow this panel to engage with local communities and government agencies to ensure the right outcomes are being achieved during the project.

3.7.4 System and model requirements

A comprehensive PDP will include consideration of the level of modelling required for particular hazards and country/regional implementations. This will depend on the availability of models such as storm surge, distant swell and flood models, and whether they are needed and feasible, given the capability of the country, and the risk for a particular location or coastline.

Appendix 5 provides a summary of the types of models that can be considered, some of which were also utilized in the CIFDP. Engagement of technical experts in the stakeholder meeting and in discussion with WMO will provide guidance on applicability to the country or region in question.
3.7.5 **Objectives and milestones for the system build**

In establishing the PDP, it is critical to detail the main objectives and milestones for different phases of the system build for all components. Experience from the CIFDP suggests four phases over the entire E2E system build and implementation. This is usually undertaken in a 4–5 year time frame. The PSG described in section 3.7.3 will provide the experience and advice on the best way to split the implementation project. As one possibility, the first phase may be the detailing of the PDP in consultation with high-level agency heads and community representatives, with the engagement of sponsors. This should include a detailed CONOPS (see section 3.6). Appendix 4 provides a suggested project implementation schedule for all 10 steps in these Guidelines.

The second phase may be the design of instrument networks and procurement of instruments such as river gauges (for water-level and streamflow measurements), rainfall gauges, sea-level gauges and offshore wave buoys. Consolidation and improvements to the local bathymetry (where possible) and coastal topography would also be included in this phase. In parallel would be the development of hydrological and marine models. The third phase may be the building of models utilizing the various instrument networks and acquiring data required for the modelling such as bathymetric and geospatial data, and the fourth phase the establishment of the E2E service.

No matter how the Project Board and PSG decide to undertake the implementation, specific milestones with financial targets must be established from the outset and included in the PDP. See Appendix 4 for details on the type of information and schedules that are needed. In this way, most importantly, the sponsors and all other stakeholders will have a transparent view of the total project. Regularly scheduled reviews of progress against the milestones will ensure this transparency is maintained.

The PDP must also include an ongoing functional plan that has sufficient funding for sustainability. Ideally, this will be undertaken in-country, but other mechanisms may be suitable.

Additionally, it is important that the PDP takes into consideration the WMO Quality Policy (Box 4). In the final stages of implementation (section 3.10), this will provide part of the final checklist.
3.8 Step 8: Testing of the Coastal Inundation Forecasting–Early Warning System end-to-end system

Pre-operational testing and/or desktop scenario testing of CIF–EWS components, as well the system as a whole, are essential steps towards implementation into the operational practices of an NMHS, or other agency, responsible for issuing inundation forecasts and warnings in coastal areas.

The major goal is to define the degree of effectiveness and robustness of the system components, as well as an assessment of the status and potential gaps for implementation of the CIF–EWS into operational practices. Another goal is to analyse the structure of CIF–EWS forecast and warning products in the context of their suitability for use in disaster mitigation procedures by end users (such as disaster managers). Testing seeks to ensure the separate components (Figure 6) of the CIF–EWS are operating well together in a robust and sustainable manner under real-life conditions.

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**Box 4. Key extract from the Guide to the Implementation of Quality Management Systems for National Meteorological and Hydrological Services and Other Relevant Service Providers**

**WMO QUALITY POLICY**

WMO programmes and Members are to adopt a quality management approach based on the International Organization for Standardization (ISO) standard ISO 9001:2015, Quality Management Systems – Requirements, to assist in:

- Understanding the purpose and context in the community in which the organization operates
- Planning the strategic direction of the organization
- Identifying and providing appropriate resources to achieve the planned objectives
- Achieving the consistent delivery of high-quality products and services
- Evaluating and reviewing organizational practices, procedures and processes to drive continual improvement

This policy will be underpinned and sustained by practical application of the seven principles of quality management and compliance with national and international regulatory requirements.

The following seven principles have been identified as providing a sound foundation for achieving the organization’s goals and objectives:

- Customer focus
- Leadership
- Engagement of people
- Process approach
- Improvement
- Evidence-based decision-making
- Relationship management

*Source: WMO (2017)*
At the first stage of testing, it is recommended that desktop scenario experiments be undertaken using historical case studies. Under such experiments, severe storm events (historical or scenario based) can be simulated for the first two components shown in Figure 6: (a) input data collection and monitoring and (b) modelling and forecasting.

This is undertaken for the “at-risk” coastal inundation area(s). Ideally, several (a minimum of three) such events should be run through all technical elements of the first two components in Figure 6. The system can then be assessed as to whether the correct or verified forecasts and warnings are being generated for each historical event. Furthermore, for each historical event, it may be possible to assess the sensitivity of model output by restricting some input data (for example, rain or river gauges). This should provide guidance on whether the CIF–EWS is robust in a range of real-time operational situations when input data are not ideal. Additionally, a hypothetical extreme event (using forecaster and expert experience) could be utilized if the records for such events do not exist.

After completion of the desktop experiments, pre-operational testing of all components of the system should commence. The last three components of Figure 6 will require collaboration with other local emergency agencies to avoid public alarm at testing. The period of pre-operational testing, using real-time events, typically ranges from 6 months to 1 year.

During the pre-operational period, it is vital to examine the components of the CIF–EWS and how each reacts to real data and product flow within the system. It is vital that severe weather conditions, which tend to generate coastal flooding, fall within the period of operational testing so all components can be checked under extreme conditions. This may not be possible if the coastal inundation at a particular location is predominantly due, for example, to storm surge from tropical cyclones or extra-tropical storms. These may not have affected the locations under consideration during the testing period, and therefore the desktop scenario testing described above may be the only fallback. In this situation, where there is minimal pre-operational testing, it will be critical for ongoing post-event studies to rigorously incorporate lessons learned in future years, to optimize operation of the CIF–EWS.

All technical requirements discussed in section 3.3 and detailed in Appendices 3 and 5 should operate in a sustainable manner without failure. If a failure occurs at any step, an investigation should be undertaken to find the source of any error and to rectify it before the next event.

The main components (Figure 6), which must be checked during the pre-operational testing period or desktop exercise, are provided below as a checklist in the following subsections.

3.8.1 **Data collection and monitoring**

- Instruments are installed with adequate resolution and ranges, and without significant interferences
- Instruments are calibrated, operate in the normal regime and demonstrate sensor technical characteristics, as well as measurement elements values
IMPLEMENTATION OF A COASTAL INUNDATION FORECASTING–EARLY WARNING SYSTEM

- The power supply is stable
- Backup equipment is in place and ready for transport (in case of sudden failure of equipment, and repairs can be undertaken safely)
- The data transmission system has no failures (even under severe weather conditions)
- The acquisition of static data such as bathymetric and DEM data

3.8.2 Data management

- Data ingestion procedures operate well, real-time data reach the DBMS and are readily available (in appropriate volumes for all stations), with appropriate timing
- QA/QC procedures and routines operate well: all ingested data are within limits of QA/QC quality data limits and metrics (in case of deviation from the limits, the sources of observational errors or data failure should be fully tracked and eliminated)
- Databases operate well, and real-time data are processed according to the requirements of forecasting and warnings methods and models

3.8.3 Models and forecasts

- NWP and other forecast parameters are ingested into the system in a timely manner
- Ocean and hydrological model software operates in a stable and sustainable manner
- Forecast fields and values are manually checked by experienced staff to confirm suitable outputs against historical events
- Objective forecast verification is undertaken and errors fall within projected forecast uncertainty intervals

3.8.4 Forecast and warning product dissemination and communication to users

During the pre-operational testing period or desktop exercise, it is important that all stakeholders (if possible, but at least the primary users) provide feedback on forecast and warning products they receive, with response on whether all information is understood (including uncertainty information) and the format of products. Critically, primary users such as the NDMO should report back on the value of the products in enabling them to issue community alerts and mitigation measures, such as evacuations (section 3.8.5). Appendix 6 presents examples of the output of a CIF–EWS: a public forecasting and warning text product, and a graphical representation of model prediction of a distant swell wave field. Barrett and Canterford (2018) provide other examples.

The following should be stressed at the stage of pre-operational testing:

- Forecast and warning products are generated in a robust and sustainable manner according to the recommended procedures, including those highlighted in section 3.4
- Forecast and warning channels (for example, web, SMS, phone, fax, bulletins and sirens) are provided in the lead time and at the accuracy required by users determined as part of the PDP
- All different users (all target groups) receive products they need (in a customized way)
- Users can easily understand the format of forecast products
- The warning communication strategy operates well
- Warning dissemination systems reach the intended community groups (at-risk coastal areas, disability groups and so forth).

3.8.5 Decision support and response to warnings

After the above-mentioned checks of the technical aspects of the CIF–EWS components, it is necessary to examine the most important aspect: how well do end users convert coastal
inundation forecasts and warnings into appropriate actions? As discussed in section 3.4, it is preferable to introduce impact-based warnings where possible to optimize the decision-making process for the target end-user groups.

Ideally, all recommended response actions should be checked as a whole and for consistency of message (alarm systems, activation of alert signs and so forth). In undertaking this checking of response actions and their consistency, the following features should be considered:

- CIF–EWS warnings should contain information regarding location, time and possible impact of the coastal inundation.
- Each element of the response chain from the forecasts and warnings relayed to the NDMO, to local and regional offices (which may also receive direct information from the media) and finally to the community, should be considered in the testing. Each party needs to fully understand and be able to interpret and understand the warning information. Although the response to warnings is usually the responsibility of the NDMO, the NMHS should partner with the NDMO in undertaking such checks or assessments.
- All relevant target groups of the population, including those with a disability, should be aware of what actions they need to follow to save lives and mitigate consequences and how to successfully follow them.

Overall, the success of the CIF–EWS requires substantial cooperation with users during pre-operational testing to ensure efficient community actions are taken to mitigate the consequences of a real (or scenario) coastal inundation.

3.9  **Step 9: Critical training for all Early Warning System elements, including public education**

Without appropriate training in all aspects of a CIF–EWS, serious limitations will affect the key delivery organizations and the public. The initial training is necessary for correct implementation, and then continuous or ongoing training will be required to maintain standards of service developed through the PDP.

Public awareness and education are also fundamental requirements, and must be undertaken at the time of launch of the system and subsequently on a regular basis (perhaps annually before high-risk coastal inundation seasons).

During the implementation period, training of forecasting staff needs to focus on the understanding of the new system, including models, forecasting and service delivery skills, and understanding of applications and responses to coastal inundation forecasting and warning. Disaster managers should also be trained to a level such that they can understand all elements of the system’s products. The training needs should be specified for all participants in the E2E forecasting and warning system design proposed in the PDP (section 3.7).

There are some fundamental aspects to the training across:

- Physical processes leading to hazards
- Components in the E2E forecast services chain (see Box 5)

<table>
<thead>
<tr>
<th>Box 5. Major categories of training required for system operators</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physical processes for hazards:</strong> Storm surges, ocean waves and swell, riverine and flash floods, significant waves, tidal influences, sea surface height variations, tsunamis and a combination of all these hazards at any one time and/or location.</td>
</tr>
<tr>
<td><strong>Forecast services chain:</strong> Instruments, data collection, models, forecaster interpretation of model outputs for public products and warnings, emergency services management and first responder awareness and public education on how to respond to warnings.</td>
</tr>
</tbody>
</table>
3.9.1 **Training on hazard processes**

As the CIF–EWS is a multi-hazard system, a forecasting team approach is best used for the determination and issuance of warnings. However, if the staff numbers are too low due to various pressures, available staff should be trained at least to a basic level in all coastal inundation hazards, while retaining expertise in their own field. This has been done in many countries and in the CIFDP implementations (Barrett and Canterford, 2018).

This section will outline these areas of training. The additional references and other material provided here are substantial, and official WMO training documents and courses should also be actively sought. All training activities should be undertaken with consideration to WMO guidelines, but some additional consultation with the WMO Secretariat may be necessary to ensure the latest training is being followed and where there is comprehensive knowledge available from WMO experts in each field. If additional WMO expert resources are necessary, these should be included in the proposal to sponsors (section 3.5) so suitable training funding can be obtained.

Training can be considered as the core professional training of forecasters (meteorology, marine meteorology/oceanography and hydrology) enhanced by competency training for the forecasters in specific aspects of the hazard processes of the CIF–EWS being implemented in the country. This competency training needs to be undertaken at a regular refresher schedule, as recommended in the relevant WMO training guidelines.

Overall, the CIF–EWS is designed to be operated jointly by meteorologists and hydrologists, in cooperation with emergency management experts. It is preferable for this to occur in one organization or forecasting office, but this is not essential, provided high-quality communication links are established and clear processes are in place to avoid overlap or confusion.

The system operators (as a team) must have suitable capability in:

- Marine meteorology, including ocean response models (waves and storm surges), and oceanography (tide and sea-level variations)
- Tsunamis and warnings
- River hydrology with specific understanding of riverine and flash floods
- Operational hydrometeorological forecasting in the country and region (if appropriate)
- Responding to extreme weather-related hazards in collaboration with emergency response agencies
- Analysing marine meteorological, oceanographical and NWP products
- IT for the system’s models and server administration
- Human communication skills to tailor technical information in warnings to easily understood non-technical information, impacts and action statements, in consultation with NDMO experts

The combination of hazards training with the forecast services chain leads to a matrix of training requirements.

3.9.2 **Ocean and marine forecasting training and competencies**

Core training of meteorologists usually includes some training in marine meteorology and oceanography. However, additional specific training and competency in marine meteorology and oceanography is usually needed to build on this core training.

As waves and storm surges are usually dominant in coastal inundation, training in the interpretation of ocean response models used for waves (for example, distant swell) and storm surges, as well as SSHAs, is fundamental for operators of CIF–EWSs.

Storm surge forecaster training is usually available through various online courses (including COMET storm surge training modules, which were translated from English into Spanish and French through the CIFDP, funded by the United States Agency for International Development).
and workshops. A definitive source is the *Guide to Storm Surge Forecasting* (WMO, 2011a). Additionally, training should be organized through the experts or organizations implementing the modelling for the CIF–EWS in-country. The funding for this training should be incorporated into the PDP.

At its eighteenth session, the World Meteorological Congress highlighted marine services capacity development (Resolutions 15, 29, 71 and 73) as a major initiative by the WMO marine and training areas. A full course titled WMO Marine Services Course also exists (WMO, n.d.b).

The structure of the course covers some specific marine weather competencies and in particular includes the following online and workshop initiatives:

- Phase 1: Marine services delivery context analysis
- Phase 2: Workshops on impact-based marine meteorological service delivery

These can be facilitated by WMO Regional Training Centres or other certified training providers.

In particular, the marine and ocean forecasting competencies related to CIF–EWSs are addressed in the following publications: *Manual on Marine Meteorological Services* (WMO, 2018c), *Guide to Marine Meteorological Services* (WMO, 2018b), *Guide to Wave Analysis and Forecasting* (WMO, 2018a) and *Guide to Storm Surge Forecasting* (WMO, 2011a).

The *Compendium of WMO Competency Frameworks* (WMO, 2019b) summarizes the competency requirements for marine weather forecasters, who should be able to:

1. Analyse and monitor continually the marine weather situation;
2. Forecast marine weather phenomena, variables and parameters;
3. Warn of hazardous marine meteorological phenomena;
4. Ensure the quality of marine meteorological information and services;
5. Communicate marine meteorological information to internal and external users.

These competencies were included in the *Assessment of the Coastal Inundation Forecasting Demonstration Project (CIFDP)* (Barrett and Canterford, 2018), and are necessary in the implementation and sustainability of a new CIF–EWS described in these Guidelines.

### 3.9.3 Flood forecasting training and competencies

Training and competency in hydrology is well established in various WMO documents and courses, which are gathered under one of the major WMO hydrological initiatives – Capacity building in hydrology and water resources management (World Meteorological Congress, eighteenth session, Resolution 25). Manuals, Guides and distance-learning courses have been developed within this initiative. Several hydrological competencies are particularly important for the flood forecasting team member(s), in the framework of development and sustainable operation of CIF–EWSs, as well as for core training:

- Hydrometry
- Hydrometeorological data networks; data collection, transmission and sharing; and establishing and maintaining database systems
- Flood modelling, forecasting and warning
- Flash floods


There are several distance-learning courses, including on advanced topics in hydraulics, hydrological sciences and hydrometeorology, as well as hydrometry, developed specifically for SIDS (WMO, 2020a).
There is also an extensive training programme developed by the Hydrological Research Center on flash floods and FFGS applications. For further information about FFGS, see WMO (2022c).

The Associated Programme on Flood Management, which is a joint WMO and Global Water Partnership initiative, provides valuable resources for improving CIF–EWS competencies, such as extensive publications and tools and capacity-building exercises, as well as a help desk on integrated flood management through which external expertise from more than 30 specialized institutions (the so-called “support base partners”) can be obtained.

Finally, the WMO Community of Practice for Flood Forecasting offers a wide variety of resources for the E2E EWS for flood forecasting development and implementation, covering the whole chain of the process, with special attention to the assessment of current capabilities of the NMHS in terms of flood forecasting and interoperable model and platform applications for operational hydrological forecasting.

### 3.9.4 In-country specific training

The services chain (Figure 6) requires additional training of technical experts in the siting and network requirements of instruments such as flood and rainfall gauges, wave buoys, assessment of existing radar capability, and location and quality of sea-level and tide gauges. This type of training can usually be undertaken by experts or consultants establishing the system, but ongoing in-country expertise and training are still required and should be factored into the sustainable running of the CIF–EWS.

Staff will also need specialized training in the E2E systems being implemented in the country or region, in addition to core training and competency training for flood and marine forecasting.

This type of specialized training could be provided by experts implementing the CIF–EWS components for a particular country or region, or independent arrangements can be made in consultation with sponsors and/or WMO. Funding for the training should be included in the full PDP analysis (Step 7 in section 3.7) and be highlighted to the donor/sponsor stakeholders as an essential requirement for implementation.

### 3.9.5 Public education

As well as the E2E communications, including the “last mile” presented in Step 4 (section 3.4), there is a fundamental and critical requirement for public education on any new CIF–EWS service. The original CIFDP has undertaken some excellent examples, especially for Fiji, which are discussed below. Additionally, public education should include information on potential hazards, location vulnerability and pre-event preparedness, often undertaken in conjunction with emergency response agencies.

As outlined in Step 2 (section 3.2), stakeholder engagement is crucial in the implementation. However, further ongoing stakeholder engagement is recommended through existing stakeholder networks in the NMHS and in the country/regional NDMO. These must, for example, include women’s networks and disability support groups.

Awareness education for local coastal communities is considered critical for warnings to be effective in saving lives and property and for local custodianship of local land-based and offshore instruments. One approach to public education is the preparation of awareness videos that are short (several minutes) and easily understood by the community. An example is one originally developed by WMO for Fiji (WMO, 2020b) in English, Fijian and Hindi languages, and subsequently modified for other Pacific SIDS, and the Caribbean region, including translations to local languages, with subtitles. Additionally, valuable community education on the purpose and benefits of ocean buoys and the need to protect them from damage is available in English, French, Spanish and the local languages of the Pacific Islands and Caribbean regions (WMO, 2020c). These animations can easily be utilized by other SIDS and vulnerable coastal communities, and are available to be tailored to other regions/languages in the future.
Public education must also be prioritized during non-event periods. It is advised that dissemination of information to the public is a critical need in ongoing operations. Interaction between the originators of the forecast and warning products (usually the NMHS) and the dissemination agencies (disaster managers and local on-the-ground community leaders) must continue throughout the lifetime of the CIF–EWS, to ensure the “last mile” is established for action on the information such as community preparedness or evacuations.

Information to the public needs to be short, clear and easily understood by people. That means simple tailored messaging with the support of the community in co-design of the communication formats. Required communication systems must be in place, for example, via alarm systems, sirens, SMS texts, Twitter and so forth. There is a strong need for all the partners, across all areas, to be working together and to build trust to do this, including using local champions in the community.

3.10 Step 10: Go-live assessment in consultation with all stakeholders and WMO

To ensure the CIF–EWS is complete and can be launched into operation, it is important to have in place a formal sign-off process that involves all key stakeholders. The first step is to have completed an E2E system check (Step 8 in section 3.8) that includes access to core data, models, robust IT and an informed distribution mechanism to the public and emergency services. This final operational go-live check and endorsement should be flagged in the PDP and must be undertaken before the public receives forecasts and warnings.

However, the go-live assessment goes beyond the operational E2E system check already undertaken (see section 3.8). It should include confirming that public education on products and services has been undertaken, that the full range of training has occurred and will continue at the required intervals in coming years, and that emergency services staff are all trained in the forecast and warning products and their interpretation.

This final assessment for a launch into operations will require acceptance of responsibility by the key stakeholders right up the implementation chain from observational data readiness to product readiness for the community. Therefore, as part of this formal sign-off, all stakeholders in the original national and/or regional CIF–EWS NIA (see Step 3 in section 3.3) should have the opportunity to endorse the system before production and distribution of forecasts and warnings to the public. Additionally, Step 7 (section 3.7), which describes the PDP for development of the system, advises that operation of the CIF–EWS should follow the WMO Policy on Quality Management (Box 4).

The final sign-off prior to launch needs to ensure “acceptance of responsibility” and “confirmation of readiness for operations” by all responsible officers through to the Project Director, and finally the head of the lead agency. The table below provides a suggested final sign-off document.

The areas of responsibility for formal acceptance include:

- Input data from observations are of the necessary quantity and quality
- IT capability is established and platforms are fully operational
- Successful pre-operational testing of all models such as flood, wave, storm surge and inundation modelling has been undertaken
- Coastal inundation numerical results are produced
- Forecasters (flood/marine/ocean/hydrometeorological) are adding value to numerical results with written forecasts and warnings
- Messaging to civil emergency agencies is fully tested and accepted
- Messaging to communities is clear, precise and timely for necessary action
- Coastal communities successfully receive messaging to prepare/evacuate

The table can be used as a guide to a formal sign-off process. Lead agencies in the development of the CIF–EWS may have other mechanisms for formal clearance for operations, but if not, the table can be adapted to the needs of the local country or region. This step may seem obvious,
but due to the large number of disciplines and agencies involved, it is essential. The sign-off of responsibility of the component starts with the first link in the operational chain. By the time all components are signed off, the head of the operational agency issuing coastal inundation forecasts and warnings (usually the NMHS) should be satisfied, and if not, they can check back down the chain.

### Guide to a formal sign-off process for the CIF–EWS project

<table>
<thead>
<tr>
<th>Responsible person</th>
<th>Operationally ready (yes or no)</th>
<th>Signature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Team leads (see section 3.7)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IT platform and communications</td>
<td>Y/N</td>
<td></td>
</tr>
<tr>
<td>Observations network and data</td>
<td>Y/N</td>
<td></td>
</tr>
<tr>
<td>Models – oceans/marine and hydrology</td>
<td>Y/N</td>
<td></td>
</tr>
<tr>
<td>Forecaster training – marine meteorology</td>
<td>Y/N</td>
<td></td>
</tr>
<tr>
<td>Forecaster training – hydrology</td>
<td>Y/N</td>
<td></td>
</tr>
<tr>
<td>Emergency services product training</td>
<td>Y/N</td>
<td></td>
</tr>
<tr>
<td>Community messaging tested</td>
<td>Y/N</td>
<td></td>
</tr>
<tr>
<td>Project Director (see section 3.7 for description of role)</td>
<td>Y/N</td>
<td></td>
</tr>
<tr>
<td>Implementing entity/entities engaged</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NMHS</td>
<td>Y/N</td>
<td></td>
</tr>
<tr>
<td>NHS (if not within NMHS)</td>
<td>Y/N</td>
<td></td>
</tr>
<tr>
<td>In-country Department of Emergency Services or similar</td>
<td>Y/N</td>
<td></td>
</tr>
<tr>
<td>Community education undertaken</td>
<td>Y/N</td>
<td></td>
</tr>
<tr>
<td>Community understands products and messaging and can implement correct response actions</td>
<td>Y/N</td>
<td></td>
</tr>
<tr>
<td>Other concerned ministries and agencies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Government departments</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Response agencies, including police</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ports agencies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marine agencies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrological agencies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Airports</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGOs, other department(s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WMO compliance (Project Director)</td>
<td>Including instruments/training/QMS</td>
<td>Y/N</td>
</tr>
<tr>
<td>Head, lead agency in country</td>
<td>Satisfied that all elements of the CIF–EWS are ready</td>
<td>Y/N</td>
</tr>
</tbody>
</table>

### 3.10.1 Community readiness prior to launch

Before the launch date, it is critical that the community must be fully informed on what to expect from the coastal inundation forecast and warning products, and how to respond to them. This applies even though the scientific and technical aspects may be ready, and is based on experience from the CIFDP subprojects (Barrett and Canterford, 2018).

The new CIF–EWS may result in many improvements above coastal inundation forecasting and warning capabilities, such as information to improve the accuracy of hazard risk assessments and risk maps. However, this may not be ready to be released in the early stages after launch until it is fully validated and QC has been conducted. Therefore, the user community expectations, as presented in the formal community education, should be clear on the type of messages that
can be confidently provided in terms of straightforward forecasts and warnings. Improvements to risk maps and assessment can come at a later stage in consultation with civil emergency service agencies.

In public education, it is important that communities and warning disseminators understand and address the needs of specific user communities, including those with identified special needs based on gender, ethnicity and language, disability and others. Usually, countries will have several community engagement platforms, such as women's information networks and disability support groups, that can work in partnership with the implementing agencies for support in developing user-specific warnings services.

Emergency warning procedures include multiformat messages with multimedia dissemination, but capacity and resources to respond – particularly at the community level – has often been limited. The issue of bandwidth is often highlighted by end users as a limitation to receiving additional information on warnings. NMHS and emergency service organizations often utilize a range of services such as social media (for example, Facebook, Twitter, Instagram and WhatsApp), SMS, very high-frequency broadcasts and high-frequency broadcasts to mariners.

It must also be recognized that the procedures for dissemination of tsunami warnings are often well established and can be a good model also for other warnings, especially to the “last mile” at the community village level. With a CIF–EWS, this essential information will be substantially enhanced for coastal inundation from storm surges, coastal swells and associated river flooding. To promote effective response actions at the grassroots level, it is recommended that simple tailored warning messages should be co-designed with the support of the community and local champions. Stronger partnerships with NGOs at a national level should also be considered. Community education on hydrological and marine causes of coastal inundation is important and was discussed in section 3.9.5.

To ensure sustainability of the new CIF–EWS, NMHSs and associated agencies need to continue modelling and development activities. Donors will be looking for the sustainability strategy being built into the project (see the PDP in section 3.7). Once the systems become operational, there needs to be regular planned re-evaluation of the system using a range of criteria to assess the impact and effectiveness of the CIF–EWS, and propose modifications if necessary. After launch, NMHSs will need to undertake system updates, continued training and regular liaison with all users.

3.10.2  Launch and post-launch review

Once all components and responsibilities are deemed ready and signed off by the responsible officials (see the table above), the new CIF–EWS can be launched.

Community feedback and other lessons learned will need to be documented and fed back to all parties involved in the development and implementation of the E2E system after each major event. This process is referred to as “post-event review management”, and should be incorporated into the QMS procedures (WMO, 2017) of the lead agency (usually the NMHS). In short, the process involves a formal post-event meeting of key staff and end users (usually within 1 month if other serious events are not prevalent). A risk analysis process is adopted (see Appendix 1) to determine the priority of any rectification and improvement actions. The actions should be logged within the formal QMS to enable tracking until they are completed.
APPENDIX 1. COMMUNITY IMPACTS: CONSIDERATIONS FOR RISK ANALYSIS (STEP 1) AND THE PROJECT DEVELOPMENT PLAN (STEP 7)

To assist in the implementation of a Coastal Inundation Forecasting–Early Warning System (CIF–EWS), this appendix gives a risk assessment process for the main features of implementation as provided in Steps 1 and 7 (sections 3.1 and 3.7) above.

Table 1 should be used for consequence, together with Table 2 for likelihood, in the risk assessment (Table 3). The relationship between likelihood and consequence determines the level of risk.

Table 1. Example of the community impacts or consequence assessment of a CIF–EWS that can be undertaken when designing the system (Step 1 in section 3.1) or as a post-event review (to be used in conjunction with Table 2)

<table>
<thead>
<tr>
<th>Consequence (community)</th>
<th>Negligible</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Life</td>
<td>Insignificant danger to life Insignificant injuries/illnesses</td>
<td>Minimal danger to life Minimal injuries/illnesses</td>
<td>Minimal danger to life Few injuries/illnesses</td>
<td>Some danger to life Some injuries/illnesses</td>
<td>Significant danger to life Many injuries/illnesses and loss of life</td>
</tr>
<tr>
<td>Property</td>
<td>No damage to property</td>
<td>Minimal property damage</td>
<td>Localized or minor damage to buildings, structures and property</td>
<td>Widespread damage to buildings, structures and property</td>
<td>Extensive damage or destruction of buildings, structures and property</td>
</tr>
<tr>
<td>Delivery of services/utilities</td>
<td>Insignificant disruption</td>
<td>Minimal disruption</td>
<td>Localized or brief disruption</td>
<td>Widespread disruption</td>
<td>Prolonged widespread disruption</td>
</tr>
<tr>
<td>Emergency services</td>
<td>Insignificant demand for emergency response</td>
<td>Minor demand for emergency service response</td>
<td>Increased demand for emergency service response</td>
<td>High demand for emergency services response</td>
<td>Prolonged peak demand for emergency services response</td>
</tr>
<tr>
<td>Day-to-day activities</td>
<td>No impact on usual activities and routines</td>
<td>Minimal impact on usual activities and routines</td>
<td>Brief disruption to usual activities and routines, including workplaces and schools near the coastal inundation</td>
<td>Widespread disruption of usual activities and routines Coastal school or workplace closures</td>
<td>Prolonged widespread disruption of usual activities and routines Coastal school or workplace closures</td>
</tr>
<tr>
<td>Land/vegetation</td>
<td>No impact</td>
<td>Minimal impact</td>
<td>Some tree damage/trees down Localized coastal erosion Localized landslips</td>
<td>Widespread tree damage/trees down Widespread coastal erosion Significant landslips</td>
<td>Widespread and extensive damage or destruction to trees and landscape Widespread and extensive coastal erosion</td>
</tr>
<tr>
<td>Population exposure</td>
<td>Slight No direct population exposed</td>
<td>Minimal Very low population density</td>
<td>Small coastal dwellings Low population density</td>
<td>Moderate population density</td>
<td>Coastal towns High population density</td>
</tr>
<tr>
<td>Consequence (community)</td>
<td>Negligible</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>Extreme</td>
</tr>
<tr>
<td>-------------------------</td>
<td>------------</td>
<td>-----</td>
<td>--------</td>
<td>------</td>
<td>--------</td>
</tr>
<tr>
<td>Spatial exposure</td>
<td>Minimal number of dwellings affected</td>
<td>Localized area</td>
<td>Wide coastal areas</td>
<td>Multiple coastal areas</td>
<td>Widespread across country</td>
</tr>
<tr>
<td>Hazard duration</td>
<td>&lt; 10 minutes</td>
<td>&lt; 3 hours</td>
<td>3–12 hours</td>
<td>12–24 hours</td>
<td>&gt; 24 hours</td>
</tr>
</tbody>
</table>

Note: The table above may be modified for country-specific consequences.

**Table 2. Likelihood**

<table>
<thead>
<tr>
<th>Likelihood</th>
<th>Negligible</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
<th>Almost certain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rare</td>
<td>Could happen but probably never will</td>
<td>May occur only in exceptional circumstances</td>
<td>Might occur at some time</td>
<td>Will probably occur in most circumstances</td>
<td>Expected to occur</td>
</tr>
</tbody>
</table>

**Table 3. Risk assessment**

<table>
<thead>
<tr>
<th>Likelihood</th>
<th>Negligible</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Almost certain</td>
<td>Significant</td>
<td>Major</td>
<td>High</td>
<td>Severe</td>
<td>Severe</td>
</tr>
<tr>
<td>Likely</td>
<td>Moderate</td>
<td>Significant</td>
<td>Major</td>
<td>High</td>
<td>Severe</td>
</tr>
<tr>
<td>Moderate</td>
<td>Low</td>
<td>Moderate</td>
<td>Significant</td>
<td>Major</td>
<td>High</td>
</tr>
<tr>
<td>Unlikely</td>
<td>Negligible</td>
<td>Low</td>
<td>Moderate</td>
<td>Significant</td>
<td>Major</td>
</tr>
<tr>
<td>Rare</td>
<td>Negligible</td>
<td>Negligible</td>
<td>Low</td>
<td>Moderate</td>
<td>Significant</td>
</tr>
</tbody>
</table>

For further consideration of the development of the risk analysis, see Step 1 in section 3.1 above, and Appendix 9 (risk register template) of the *Guide to the Implementation of Quality Management Systems for National Meteorological and Hydrological Services and Other Relevant Service Providers* (WMO, 2017).

Note: Appendix 1 is based on the *Guide to the Implementation of Quality Management Systems for National Meteorological and Hydrological Services and Other Relevant Service Providers* (WMO, 2017) and internal quality management procedures in the Australian Bureau of Meteorology (R.P. Canterford, personal communication, 2019).
APPENDIX 2. TEMPLATE FOR A NATIONAL IMPLEMENTATION AGREEMENT FOR A COASTAL INUNDATION FORECASTING–EARLY WARNING SYSTEM PROJECT

**Being concerned** to provide the highest quality public warnings to the coastal communities of _________ (Member or region of interest) in the event of possible inundation from oceanographical and/or hydrological phenomena, resulting from severe hydrometeorological events;

**Noting** that consistent with the Member’s and/or region’s natural disaster management legislation (or similar), the roles and responsibilities of the agencies of the Government(s) of _________ (Member) are to be carried out in such a way that the agencies work in close harmony;

This Agreement describes the commitment of the undersigned agencies to work closely with the National Meteorological and/or Hydrological Service (NMHS/NHS/NMS), to assist all in the fulfilment of roles, responsibilities and missions related to coastal inundation in the context of a Coastal Inundation Forecasting–Early Warning System (CIF–EWS);

**Noting** that establishing an effective forecasting and warning system on coastal inundation, the goal of the CIF–EWS would greatly assist the Member’s activities of disaster mitigation;

**Noting** that CIF–EWS will be built from the combined and sustained implementation, as well as contributions of the signatories, along with substantial multilateral and multidisciplinary cooperation and coordination;

**Acknowledging** that existing operational forecasting and warning arrangements for extreme events already provide information to coastal community, the CIF–EWS would build on the existing capacity while avoiding any duplicated efforts;

The national and regional stakeholders agree to work together in providing support to the CIF–EWS by way of participating in and supporting a CIF–EWS National Coordination Team (NCT), in particular;

**Agree** that they will work together in:

- Assessing user requirements for services related to coastal inundation in the Member(s).
- Exchanging data required for CIF–EWS operational services.
- Supporting the efficient and effective long-term management of data used in operational forecasting, warning system validation, and research and development aimed at improving the CIF–EWS. Such data include:
  - Atmospheric measurements including pressure, wind fields, temperature, rainfall and humidity/dewpoint, in particular, measurements related to cyclones;
  - Radar and satellite weather information;
  - Sea-level height, including those from tide gauges;
  - River water level and streamflow;
  - Satellite data for ocean winds, sea surface temperatures, waves, sea surface height anomalies and so forth;
  - Wave measurements in deep water offshore and shallow water nearshore;
  - Bathymetry;
  - Watershed characteristics;
  - River channel cross sections and properties;
  - Digital land elevation data in the coastal zone;
  - Astronomical tide and coastal currents;
  - Structural information;
  - Land-use information;
  - Coastal inundation vulnerability maps;
  - Other data that, from time to time, the NCT deems vitally important for the CIF–EWS.
Technology transfer among the service-providing agencies including the NMHS/NHS/NMS, and the implementing agencies and beneficiaries including the national disaster management office (NDMO), and from donors to signatory parties.

Training of staff engaged in operational and extension activities related to the work of the CIF–EWS.

This Agreement may be amended at any time at the request of one of the signatories, and any amendment shall be made in writing and decided by consensus among the signatories;

This Agreement shall enter into force upon signature by all parties on __________ (date) and shall continue to be in force for a period of 5 years thereafter or shall continue unless terminated by agreement of the signatories;

Further, any agency of the Member(s) or any other organization involved in the related activities may become a party to the Agreement by the three quarters majority of the Agreement’s initial parties. [Below is a sample list of parties that can be considered for inclusion.]

Signed:

Prime Minister’s Office or similar level of government office*
Ministry of Disaster and/or Emergency Management, or similar*
Ministry of Finance and Budget*
Ministry of Telecommunications, or similar*
Ministry for Fisheries and/or oceans, or similar*
Ministry of Local Government, or similar*
Ministry of Works and Transport, or similar
Ministry of Lands, or similar
Ministry of Defence (Navy), or similar
Ministry of Agriculture, or similar
Ministry of Foreign Affairs, or similar

* Stakeholders/signatories that are considered the essential participants in this Agreement, in order to proceed with the CIF–EWS project implementation.

Annex 1 to National Implementation Agreement

Terms of Reference for the National Coordination Team for the Coastal Inundation Forecasting–Early Warning System for _________ (Member(s))

1. Preamble:
1.1 Members of _________ (country/region stakeholders) have decided to develop an example of cooperative work as a strategy for building improved operational forecasts and warnings capability for coastal inundation that can be sustained by the responsible national agencies:
   • Implementing well-proven and operational end-to-end forecasting and warning systems for coastal inundation. These should preferably be open source wherever possible to allow local modifications by experts and independence from suppliers.
   • Supporting the exchange of data and information among stakeholders.
   • Developing cross-cutting cooperation of different scientific disciplines and user communities.
   • Building communication platforms among researchers, forecasters and disaster managers involved in coastal inundation from oceanographical and/or hydrological phenomena, resulting from severe hydrometeorological events, including those associated with tropical cyclones.

1.2 These terms of reference are applicable to the elements of the CIF–EWS being developed to address the needs of the people of _________ (country/region).
1.3 The NCT comprises the following national stakeholders, while its membership is open to other agencies as necessary and as agreed following paragraph 1.5:

[Technical partners]
NHS/NMS/NMHS
NDMO
Navy
Oceanographical service
Universities
Contracted experts (sponsors)
... others

[Beneficiaries]
NDMO
Coastal communities
Ministries
Government departments
Response agencies, including Police
Ports agencies
Marine agencies
Hydrological agencies
Airports
Non-governmental organizations (NGOs)
... others.

1.4 Each member agency/institution participating in the NCT will appoint a focal point who is responsible for and has the capability to contribute to the CIF–EWS.

1.5 Additional stakeholders may be invited by majority of those stakeholders attending a meeting at which a quorum (60% of the team) is present.

2. Scope of work:

2.1 The NCT will work with the NMHS/NHS/NMS (the agency responsible for the implementation of operational systems) to provide warning for coastal inundation, to develop and implement the project with the guidance of and close collaboration with the CIF–EWS Project Steering Group (PSG), which is to be formed at the commencement of the project and include advice from WMO to:

• Identify and continuously review the requirements of users and stakeholders in [Member] for advice and warnings related to coastal inundation.

• Promote technology development and transfer, through the provision of tools for risk assessment, services from coastal inundation forecasting and warning services; as well as the provision of training material specifically developed based on the progress in project implementation.

• Assist in resolving information exchange and management issues among national stakeholders in the CIF–EWS implementation, in view of establishing a long-term framework for information sharing.

• Encourage and support specialized training programmes, which would enhance the capabilities of all participating agencies to provide coastal inundation forecasting and warning services, including the dissemination aspects.

2.2 The NCT will assist in the development of an operational coastal inundation forecasting and warning system, to be operated and maintained by the National Meteorological and/or Hydrological Service (NMHS/NHS/NMS), once the CIF–EWS is successfully completed. In doing so, the NCT will guide the implementation of a communication platform that will improve interactions with national stakeholders (including government agencies, media and NGOs) for better understanding of user requirements, effective communication of the advisory and warning messages, and user feedback.

2.3 The NCT and PSG will meet at regular intervals as required by the demands of the project (possibly 6 monthly initially).

2.4 The NCT will work with the PSG to develop proposals for further (beyond initial project start-up) donor support for critical CIF–EWS activities throughout the implementation phases.

2.5 The NCT is open and transparent in its functioning, making available to all stakeholders a report of each meeting held, including a summary of the decisions taken, a list of current stakeholders and a list of the meeting’s participants.
2.6 The NCT will work with the PSG to prepare and issue annual reports for the first 4 years of the CIF–EWS implementation, in coordination with the WMO Secretariat, and prepare recommendations to be transmitted to the relevant programmes and projects.

Annex 2 to National Implementation Agreement

Coastal Inundation Forecasting–Early Warning System

Coastal inundation is an increasing threat to the lives and livelihoods of people living in low-lying, highly populated coastal areas. According to a World Bank report (Dilley et al., 2005), at least 2.6 million people have drowned due to coastal inundation, particularly caused by storm surges, over the last 200 years.

Overarching objectives

The purpose of the WMO CIF–EWS is to meet the challenges of coastal community safety and to support sustainable development through enhancing coastal inundation forecasting and warning systems at the regional scale.

Benefits of a Coastal Inundation Forecasting–Early Warning System for implementing countries

Upon completion of national and/or regional implementation of a CIF–EWS, countries will implement an operational system for integrated coastal inundation forecasting and warning, providing an objective basis for coastal disaster (flooding) management, contributing to saving lives, reducing loss of livelihood and property, and enhancing resilience and sustainability in coastal communities.

Upon completion of the CIF–EWS project, countries will be provided with valuable input to the assessment and awareness of the issues of coastal inundation management within governments. Advancing steps towards the integration of other forecasting and warning services would also assist countries.

General financial model of a Coastal Inundation Forecasting–Early Warning System

A national and/or regional CIF–EWS project is generally implemented by either national resources or external funding support from donor agencies. The NCT, led by national operational agencies for coastal inundation forecasting, would be responsible for implementation of the CIF–EWS. The NCT works with the CIF–EWS PSG and takes advice from WMO (where necessary) to identify financial and in-kind resources required for the project’s full implementation over all phases. A project development plan should be prepared and followed throughout implementation.

Upon completion of a national project, operation and maintenance of the CIF–EWS would be the responsibility of national operational agencies with the mandate of coastal inundation (marine and flood) warnings.

Scope and implementation

The focus of the CIF–EWS will be to facilitate the development of efficient forecasting and warning systems for coastal inundation based on robust science and observations.
This appendix provides a comprehensive list of data and other information requirements for implementation of a Coastal Inundation Forecasting–Early Warning System (CIF–EWS). This can be used as a guide in the early stages of development of the project development plan (PDP), but note there will most likely be several gaps in many countries. Therefore, the early assessments of coastal inundation risks by local and international experts should highlight which data are of a higher priority for a particular country. Provision of these data may then be prioritized for sponsorship in the PDP financial considerations.

Real-time observations are required during the operation of a CIF–EWS: to run it effectively, to assess its quality and to improve accuracy while operating. The following data categories are required (for details of frequency or other information, users should refer to the technical references given in section 3.3.3 above):

- Ocean-level data and coastal sea-level and tidal data.
- Hydrometric data (streamflow and water level) – hourly, and sub-hourly for flash floods and routine daily.
- Meteorological data:
  - Precipitation – hourly and sub-hourly for flash floods – air temperature.
  - Radiation, wind and humidity data – hourly and daily.
- Reservoir data (if applicable): inflow (observations and forecast), storage levels, outflows – hourly and daily.
- Radar and satellite information at the best achievable frequency.

Historical data and ancillary information are required to develop different components of a CIF–EWS. The following data and information are required (the length of record should be for as long as historical records exist):

- Metadata for observational stations (ocean buoys, river gauges and meteorological stations).
- Ocean-level data – hourly, daily, monthly, climatologically.
- Hydrometric data (streamflow discharge, stage), in digital format with hourly, daily and monthly resolution (including climatologically).
- Meteorological data in digital format:
  - Precipitation, air temperature – hourly, daily, monthly, climatologically.
  - Pan evaporation – daily, monthly, climatologically.
  - Radiation data –daily, monthly, climatologically.
  - Wind and humidity – daily, monthly, climatologically.
- Soil moisture data (top 1 m of soil) – weekly, monthly, climatologically.
- Rating curves at river gauges (covering different periods of flow – peaks and low-flow periods – regularly gauged and updated).
- River cross-sectional survey data (including cross sections for local streams draining 10–2 000 km²).
- Reports or regional relationships between channel cross-sectional characteristics and catchment characteristics.
- Spatial digital data or maps:
  - Digital elevation model (DEM) (the ultimate accuracy of extent and depth of inundation forecasts will depend greatly on the availability of high-resolution DEM data).
  - Bathymetry data: offshore and nearshore, 100 m horizontal resolution, 1 m – vertical, updated every 5 years. This is critical to the inundation modelling. There are usual data sources available, but they may be deficient in resolution. A key part of the PDP will be to explore and possibly facilitate collection of additional information. The bathymetric datasets will need to be in a gridded format compatible with the models selected.
• Coastal elevation: 5 m horizontal resolution and 0.5 m vertical resolution (updated every 1–5 years if possible).
• Land-use and land-cover data.
• Soils data, including soil texture or Food and Agriculture Organization of the United Nations soil classification or soil properties data.
• Stream network and catchment boundaries.
• Lakes and reservoirs.
• Sewer system design (in case an urban type of flood is relevant).
• Local stream cross-sectional survey.
  – Impact data: vulnerability and exposure data, flood trigger levels and flood maps.
  – Reservoir data and information (if applicable) – inflows, storages and outflows – and reservoir operation rules (historical and present).
APPENDIX 4. PROJECT IMPLEMENTATION SCHEDULE AND TEMPLATE FOR PROPOSALS TO SPONSORS

1. Project building and implementation schedule

Table 1 shows a suggested timetable for a Coastal Inundation Forecasting–Early Warning System (CIF–EWS), and should be prepared as part of the project development plan (PDP) (Step 7 in section 3.7 of these Guidelines).

<table>
<thead>
<tr>
<th>Implementation steps</th>
<th>Year 1 Q1</th>
<th>Year 1 Q2</th>
<th>Year 1 Q3</th>
<th>Year 1 Q4</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Year 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1: Undertake a national risk assessment of coastal natural hazards</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step 2: Conduct an inaugural stakeholder meeting with ministerial/government agencies and sponsors (including a formal national and/or regional agreement)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step 3: Undertake a technical assessment of all in-country and regional capabilities and requirements, as a precondition for developing the capability to issue impact-based forecasts and warnings for coastal inundation hazards</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step 4: Ensure end-to-end communications, including the “last mile”</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step 5: Ensure donor and sponsor engagement (internal and external)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step 6: Establish a Project Steering Group (PSG) with major stakeholders and technical experts, and appropriate PSG links to WMO Regional Centres. Prepare a concept of operations (CONOPS)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step 7: Build and strengthen all system components using a project development plan with associated governance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step 8: Test the CIF–EWS end to end – using technical and scenario-based approaches</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step 9: Ensure critical training for all elements is in place and that they are sustainable</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step 10: Undertake a go-live assessment in consultation with the PSG and all stakeholders prior to operational implementation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Review Steps 8, 9 and 10 for sustainability</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2. Establishing a Coastal Inundation Forecasting–Early Warning System project proposal for sponsors

Tables 2–5 suggest information to provide to donors and/or sponsors for consideration. Sponsors (including government) may request their own formats or additional information.
Table 2. Background information for country/region implementation of a CIF–EWS

<table>
<thead>
<tr>
<th>Target country/region</th>
<th>List country and/or region for implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contributes to government strategic goals</td>
<td>Safety for coastal communities and avoidance of infrastructure losses</td>
</tr>
<tr>
<td>Lead agency in country</td>
<td>National Meteorological and Hydrological Service (NMHS) or National Meteorological Service (NMS) and National Hydrological Service (NHS) if separate, but joint lead including with other agency in a country responsible for coastal inundation forecasting</td>
</tr>
<tr>
<td>Other concerned department(s)</td>
<td>Ministries, National disaster management agency, Government departments, Response agencies, including Police, Ports agencies, Marine agencies, Hydrological agencies, Airports, Non-governmental organizations and others</td>
</tr>
<tr>
<td>Project Director</td>
<td>Nominated person in-country or externally, with experience or knowledge of coastal inundation hazards and an ability to direct the project on a part- or full-time basis</td>
</tr>
<tr>
<td>Project Executive</td>
<td>Includes the NMHS (or NMS or NHS) head and key stakeholders such as Department of Emergency Services and the lead system developer</td>
</tr>
<tr>
<td>Project team members</td>
<td>To be selected by the proposer and relevant in-country agency heads; should include, as a minimum, a project coordinator, information technology (IT) manager, senior meteorologists and hydrologists and a communications manager; external technical experts can also be included</td>
</tr>
<tr>
<td>Implementing entity/entities</td>
<td>NMHS, National Hydrological Authority (if not within the NMHS), In-country department of emergency services or similar</td>
</tr>
</tbody>
</table>

Note: Text in italics is to assist the country, and can be modified.

Table 3. Justification for implementation of a CIF–EWS

The aim of the project is to strengthen the national forecasting and warning services on flooding and inundation in coastal zones, and in particular, to provide these tools for use by the NMHS and NHS (if not within the NMHS). A stakeholder workshop will be undertaken and agreement reached on the locations in-country or the region that will be affected by coastal inundation from hydrometeorological and marine events, exacerbated by sea-level rise. Historical events that have caused loss of life and/or infrastructure and led to social disruption include: _______________. A CIF–EWS will mitigate against such losses.

Other country information: To be supplied when developing a PDP.

Note: Text in italics is to assist the country, and can be modified.
## Table 4. CIF–EWS project summary

| Approach | The development of hydrological and marine model components for relevant flooding causes (rivers, waves and storm surges) and to purchase and install gauges and wave buoys necessary to collect and validate the marine data needed for the modelling. Further details of the proposed project: __________. |
| Outcome(s) | The focus of the CIF–EWS is to facilitate the development of efficient forecasting and warning systems for coastal inundation based on robust science and observations. In doing so, the CIF–EWS makes efforts to integrate cross-cutting scientific models into an open forecasting environment for improving / expanding / developing the forecasting and warning systems for storm surges, hydrological response to heavy rainfall and tropical cyclone landfall on coastal areas, and other phenomena causing coastal inundation. Other information related to the country: from the PDP (section 3.7 of the Guidelines). |
| Outputs | Open-source, end-to-end, integrated operational system for coastal inundation forecasting and warning, embedded to the national operational disaster management systems in country (at the end of the project):  
  - Develop/implement model components for relevant flooding causes (waves, storm surges, river flooding and wherever possible integrated causes of coastal inundation)  
  - Purchase and installation of relevant equipment such as wave buoys, river gauges for baseline data and IT infrastructure to support the modelling  
  - Specialized training programmes and manuals for coastal inundation forecasting/warning  
  - Capacity-building and availability of personnel for operation and maintenance of implemented systems and equipment  
  - Cross-institutional platform for national and international collaboration in technical development and operation  
  - Regular consultations with national stakeholders to review and update the requirements for coastal inundation forecasting and warning, and following the decision-making process including appropriate communication / awareness materials to understand the warnings  
  - Regular output of project performance indicators covering technical and financial aspects |
| Implementation period | Year 1–year 4 |
| Project budget | To be confirmed |
| Funding source | Sponsor(s); in-kind in-country agencies/government |

Note: Text in italics is to assist the country, and can be modified.
Table 5. CIF–EWS overview and activities

**Beneficiary country:** Country and/or region
Beneficiary groups of the proposed project are mainly coastal communities in-country in the immediate term, through the improved performance of national institutions responsible for coastal disaster forecasting, warning and climate adaptation planning. Every year, populations in coastal zones are affected by coastal inundation caused by waves, including long-period swell, storm surge and hydrological inundation, resulting in loss of life and damage to property. The results of this project will provide critical information to improve forecasting, warning and evacuation planning in coastal zones.

**Project location**
The technical development and associated activities will mostly take place at the headquarters of the NMHS and/ or NHS and the National Emergency Department where necessary. The general management and coordination of the project will be carried out by the NMHS following guidelines from WMO, and under the local government’s policy and procedures. The technical development of this proposed project will be conducted in close collaboration with international experts from government and private companies. WMO Regional Associations and Specialized Centres will also be engaged where necessary.

**Project implementing organization**
The Project Board will manage the project as described in section 3.7 of the Guidelines and in occasional consultation with WMO as required.

**Project activities**
The CIF–EWS project implementation is composed of four phases, following the 10 implementation steps in these Guidelines, as follows:

- **Phase 1:** Information gathering – project adaptation and establishing a Project Steering Group (Steps 1–6)
- **Phase 2:** System implementation following the PDP (Step 7 in section 3.7)
- **Phase 3:** Pre-operational testing and capacity development (Step 8 in section 3.8)
- **Phase 4:** Live running and evaluation (Step 10 in section 3.10)

Phase 1 is focused on development of the PDP and government, agency and donor/sponsor support.

Phases 2–4 of the project include:
- Progress review and stakeholder meeting (Step 2 in section 3.2)
- Adopt and implement model components for relevant flooding causes
- Purchase and installation of equipment (Phase 2)
- Training of forecasters on wave forecasting system (Phase 3)
- Adopt/develop and implement model components for storm surge modelling and river flood models (Phase 3)
- Consult with WMO on progress
- Training of forecasters on the storm surge forecast system (Phase 3) and river flood system (Phase 4)
- Training of forecasters on integrated coastal inundation forecasting (Phase 4)
- Training for the institutional (for example, disaster managers) end-user community on forecast products, interpretation and use
- Final stakeholder workshop, project completion and going live
- Enhancement and verification of the coastal inundation forecast products and communication of these ensuring the robustness of the system and widespread understanding by local stakeholders

**Roles and responsibilities**
Follow Step 6 in section 3.6 (PSG) and Step 7 in section 3.7 (PDP governance).

**Reporting and evaluation**
Fully detailed annual reports will be prepared for government/sponsors/donors to satisfy progress against the PDP and to allow project teams to provide input and takeaways of progress in all components of the project. WMO will also be informed through these annual reports on milestones.

Note: Text in italics is to assist the country, and can be modified.

### 3. Sustainability of project achievements

As part of the presentation to sponsors, an initial risk assessment should be undertaken based on sections 3.6 and 3.7 and Appendix 1 of these Guidelines, which provide guidance. Once funding has been allocated and the Project Board has been established, this risk assessment should be further refined as part of the PDP. Table 6 shows an example of a project’s work breakdown, budget and timing.
### Table 6. Example of work breakdown, budget and timing (for guidance only)

<table>
<thead>
<tr>
<th>Activity</th>
<th>Year 1 budget</th>
<th>Year 2 budget</th>
<th>Year 3 budget</th>
<th>Year 4 budget</th>
</tr>
</thead>
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<tr>
<td>Steps 1–4 Establish the requirements and capabilities</td>
<td>Risk assessment, hold stakeholder meetings including government agencies, establish national agreement, technical assessment of requirements, end-to-end linkages</td>
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<tr>
<td>Steps 5 and 6 Liaise with sponsors and donors and establish governance of the project</td>
<td>Engage with sponsors and donors (internal and external) and seek commitments</td>
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<tr>
<td>Step 7 Development and building of forecasting and warning system</td>
<td>Build or adapt wave and storm surge models</td>
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<td></td>
<td>Build or adapt riverine and flash flood models</td>
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<tr>
<td></td>
<td>Build or adapt other model components for relevant flooding causes as identified in system design</td>
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<td></td>
<td>Complete the CONOPS</td>
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<td></td>
<td>Build or adapt the coastal inundation forecasting system</td>
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<td>Develop composition and prototype of the model</td>
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<td>Develop a system combined with waves model, storm surge, river models</td>
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<td>Develop an integrated graphic display system</td>
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<td>Install servers and storages for the coastal inundation forecasting system</td>
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<td>Establish test equipment (wave gauges and so forth)</td>
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<td>Step 8 Test end-to-end system and CONOPS</td>
<td>Demonstrate the forecasting system</td>
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<td>Conduct comparative analysis and verification of the demonstration results</td>
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<td>Ensure compliance with PDP and CONOPS</td>
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<tr>
<td>Step 9 Ensure training and sustainability requirements</td>
<td>Training for forecasters and operators</td>
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<td>Project build completion with the PSG and stakeholder workshops, backup manual production, technical advice</td>
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<tr>
<td>Step 10 Go-live assessment</td>
<td>Go-live assessment with all stakeholders and focused on community response</td>
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<td>Feedback improvements as assessed</td>
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<td>Total for project activities (without administrative costs)</td>
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<td>Administrative costs</td>
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<td>Total costs</td>
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Note: The $ symbol indicates a budget estimate is required for this work component in the column year. No $ symbol indicates nil budget required for this work component in the given year. Adjustments may need to be made, but should be carefully documented.
APPENDIX 5. MODELS USED FOR COMPONENTS OF A COASTAL INUNDATION FORECASTING–EARLY WARNING SYSTEM

WMO Global Centres and Regional Specialized Meteorological Centres (RSMCs) produce products that can be used as the backbone for flood and marine forecasts, and hence coastal inundation for national forecast systems (JCOMM, 2012). This is termed a cascading system and is well established by WMO. The national coastal inundation systems are usually designed to utilize these global and regional products, as well as locally developed expertise and what can be designed by experts engaged in the system design (see section 3.7 above). The products from these centres for local models can include:

- Inputs from regional meteorological models (providing wind fields, pressures, air temperatures and precipitation)
- Inputs from global large-scale ocean circulation and wind wave models (providing information on large-scale sea surface height anomalies (SSHAs) and waves generated outside the region)
- Inputs to coastal marine inundation (using information from storm surge, wind wave and wind stress, tidal and large-scale anomalies)
- Inputs to hydrological models (riverine and rainfall run-off, covering flash floods) to handle inflow into the coastal domain from main rivers

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 provide accurate forecasts of coastal inundation from oceanographical and/or hydrological phenomena, resulting from severe hydrometeorological events, in different areas around the world, including: (a) storm surges produced by direct wind and wave forcing, (b) wave set-up from large swell events and (c) high river flows/streamflows, acting independently or in combination, interacting with sea-level variations, for example from tides and/or SSHAs, in coastal areas (JCOMM, 2012).

The implementation of a country’s or region’s Coastal Inundation Forecasting–Early Warning System (CIF–EWS) will be unique, depending on the primary causes of coastal inundation in the country, and the specific user requirements identified under the project development plan (PDP; see section 3.7 above). As a result, customized forecast and warning interpretive products will be identified and developed for each country separately in consultation with the local user community, coordinated by the Project Team.

1. Cyclone models

Most countries vulnerable to tropical cyclones/hurricanes/typhoons will have access to a wide range of relevant tropical cyclone information from numerical models from WMO Global Centres and RSMCs. For the purposes of storm surge forecasting, parametric tropical storm forcing is preferable to directly ingesting numerical weather prediction output. For parametric tropical storm forcing, only information such as central pressure, pressure drop and radius of maximum winds is required as input; the actual parameters vary according to the model selected. This also ensures that cyclone parameters are consistent with the official guidance on track and intensity. For countries that operate their own cyclone models, these variables may be automatically fed into the storm surge model (for example, Fiji).

2. Storm surge models

There are several readily available models that could be implemented for operational use, including Delft3D, JMA-MRI, SLOSH and IIT-Delhi. These models all have moderate computing requirements. It is also desirable for an operational storm surge forecast to use ensemble prediction techniques rather than simple deterministic approaches, which often incorrectly estimate the surge magnitude. Ensemble techniques entail multiple runs of the storm surge
model forcing varying initial conditions, which of course have implications for the computing power required, the staffing necessary and the forecast lead time. In the PDP, this can be accounted for in later stages if systems, computing and staff resources allow. For accurate storm surge modelling, it is critical to have accurate high-resolution bathymetric information for the coastal areas. Large-scale bathymetric products such as the General Bathymetric Chart of the Oceans and others are not typically sufficient.

3. **Tidal models**

Most developing countries do not have a tidal model, and have only a few tide gauges. However, in the initial stages of technical assessment, gaps in the tide gauge network can be identified, partly through the known evaluation of tidal dynamics at each area of a country. Tidal predictions are available from global tidal model forecasts as one example. These tidal predictions would need to be first evaluated using the tide gauges available.

4. **Sea surface height anomalies**

Information on SSHAs is routinely produced as a forecast product by RSMCs or major modelling centres (such as the Australian Bureau of Meteorology, the European Centre for Medium-Range Weather Forecasting or the National Oceanic and Atmospheric Administration). This information needs to be linked in real time to the coastal inundation model, for example through the Flood Early Warning System (FEWS) (see below). The timescales for SSHA information are much longer than the tidal variation, which simplifies the problem.

5. **Wave models**

To account for wave contributions to operational coastal inundation forecasting, it is necessary to implement a wave model, particularly for the nearshore areas. Where waves occur in conjunction with storm surges, a coupled model may be required to produce the total water-level forecasts, or wave contributions may be added parametrically based on the wave height forecast.

**Wave model examples:** There are readily available models that can be implemented for operational use, most notably SWAN. The SWAN model has moderate to high computing requirements, depending on the grid domain and spacing. Unlike storm surge, deterministic techniques are acceptable for wave forecasts, although ensemble approaches are also possible. SWAN is implemented as a limited area, nearshore model, which uses forecast wave information from larger scale wave forecasts, such as those run operationally by, for example, the Australian Bureau of Meteorology, the European Centre for Medium-Range Weather Forecasting or the National Oceanic and Atmospheric Administration, as boundary conditions.

**Wave set-up and run-up (distant swell):** In many small island developing States (SIDS) and along other coasts, this is often associated with distant extra-tropical storms, or in some cases, distant tropical cyclones. As a result, the local wind forcing is not as critical, although local winds should be input to any nearshore wave model. Unlike for storm surge, these winds can be taken directly from numerical model output. It is not a simple matter to take even the nearshore wave forecasts onto the coast as inundation. This may require a wave set-up model or in some cases, as in Fiji, an infragravity wave model (such as XBeach) to model the inundation extent.

6. **Rainfall run-off models**

Run-off generation in upper parts of river catchments needs to be modelled to further track it in a downstream coastal direction. For this purpose, so-called rainfall run-off models are widely used, which are based on accounting for water balance of the watershed in simplified form. Air temperature, precipitation and sometimes other variables (observations and forecasts) are used to force such models. Before running models, parameters should be calibrated either using automated parameter optimization procedures (if historical data are available), or with the help
of their a priori estimation based on hydrometeorological and land-surface information. Further model validation is an important step before implementing them in operational practice. The Manual on Flood Forecasting and Warning (WMO, 2011b) describes calibration and validation procedures, including basic steps, data requirements and verification criteria. There are several freely available rainfall run-off models, used in operational hydrological practices of many National Hydrological Services, such as HBV, SACSMA, HEC-HMS, HYPE, GR4H and others.

Another possible and freely available solution is the Dynamic Water Assessment Tool (DWAT), which has proved its ability to model floods of different origins in all parts of the world. It incorporates different modelling options, including rainfall run-off modelling (Kim et al., 2019).

Rainfall run-off models are also used in the flash flood forecast and warning process. For example, the Flash Flood Guidance System (Georgakakos, 2018) utilizes the SACSMA model to estimate catchment characteristics, which are relevant for flash flood guidance computation.

The output of a rainfall run-off model is streamflow at the outlet of the river catchment, which should then be routed in a seaward direction with the help of river routing models.

7. **River routing models**

Some models can route the upstream streamflow generated by rainfall run-off models to the coastal area as input to coastal inundation. There are several levels of complexity of the possible solutions, including hydraulic models of river streams and valleys (one-dimensional models are more applicable for operational purposes as they require much fewer resources – computation is done on a desktop computer in 3-5 minutes). When coupling with an ocean model, it is important to ensure the hydraulic model has an option to simulate the backwater effect.

8. **Hydrological platforms**

Modelling can be done partly within the framework of platforms, which integrates different flows of data and products, and provides initial conditions of hydrological models. Platforms relate here to software systems that can provide interoperability of modelling systems, which do not possess this capability. They can also allow input of data with different formats and can provide output in multiple ways. An example of an interoperable platform that can be applied is DEWETRA (Italian Civil Protection Department and CIMA Research Foundation, 2014; Italian Civil Protection Department, n.d.), which is a multitask platform capable of collecting and processing hydrometeorological measurements, initiating hydrological models, and visualizing modelling and forecasting results as well as vulnerability layers (demographics, infrastructure and so forth). The platform has proved to be operationally effective in some National Meteorological and Hydrological Services (for example, Albania, Bolivia (Plurinational State of), Caribbean SIDS, Italy, Lebanon and many others), where it is used as a component of a national Early Warning System.

9. **Other expert systems for hydrology and coastal inundation**

The above-mentioned systems for hydrological modelling require extensive initial data. Sometimes, the requirements can be higher than the capability of a country where a CIF–EWS is planned to be implemented, including historical data for model validation. For such cases, less-sophisticated options requiring less complex data are applicable, including decision tree, or expert, warning systems that are calibrated based on upstream river water levels, precipitation amounts and sea level (tidal level) near river mouths. A good example of such an expert system is the Coastal Inundation Alert Support System, implemented in Fiji for the Nadi River basin area in the framework of the Coastal Inundation Forecasting Demonstration Project for Fiji (G. Smart, personal communication, 2019; JCOMM, 2019c).
10. **Inundation models**

One of the major technical and sophisticated aspects while addressing coastal flooding is coupling of a sea/ocean model with a river model in the river estuary transition zone. There are several options possible, including coupling a one-dimensional hydraulic model with an ocean model. Figure 2 in Chapter 2 above shows the connections between the above component models in arriving at coastal inundation.

Few countries have inundation models. The importance and feasibility of explicit inundation modelling will have to be assessed during the project through surge simulation and topographic information. An integrating model such as FEWS will allow various relevant inputs to be combined to produce inundation forecast products. A critical aspect for inundation modelling is the availability of high-resolution topographic information.
APPENDIX 6. EXAMPLES OF SERVICE PRODUCTS FOR COASTAL INUNDATION FORECASTS AND WARNINGS

The box below gives an extract of a WMO news item on the outcomes of a Coastal Inundation Forecasting–Early Warning System (CIF–EWS) fully operational in Fiji in 2020. Note the value of the system for an extreme event (Tropical Cyclone Harold) in April 2020, with a major storm surge, and good forecasts leading to successful evacuations.

**Fiji, April 2020**

Harold hit the islands Vitu Levu and the islands to the east as a Category 4 in the night from 7 to 8 April 2020 causing power outages, blocked roads due to fallen trees, and widespread flooding. As of 14 April, more than 1,541 people were sheltering in 52 evacuation centres in Central, Western and Eastern divisions.

Fiji Government’s Divisional Commissioners have identified all evacuation centres (EC) that can be used and have estimated their capacity under COVID-19 rules. Social gathering restrictions and other COVID-19 protocols remained in force.

The Coastal Inundation Forecasting Demonstration Project for Fiji that was completed in November 2019, saw the Fiji Meteorological Service (FMS) operationalize a coastal flooding early warning system which allows for forecasting flooding sources from ocean and river sources. Last week, it was used to determine the storm surge heights, recorded at approximately 6.5 metres [post analysis indicates about 2 m], and estimations indicated that it was probably up to 8.5 meters [post analysis about 6.5 to 8.5 m] in less sheltered areas.

FMS Director Misaeli Funaki said the coastal inundation forecasting system enabled the accurate recording of wave size and formed the basis of successful evacuation warnings to vulnerable communities. Unfortunately, some of the FMS outer island stations were severely damaged by storm surge, including Matuku, which was completely destroyed.

“Every instrument was destroyed. This includes communication equipment, observational instruments and the building,” said Mr Funaki.

*Source: WMO (2020d)*

The figure below shows that the CIFDP Pacific Community (SPC) model predicted a distant swell wave field off Maui Bay, Coral Coast, Fiji, on 27 May 2018. Subsequent on-ground observations confirmed the predictions. This system has been operational as part of the Fiji CIF–EWS since November 2019.
The Maps below show the significant swell height for every 12 hours for the following week.

**CIFDP SPC model prediction of a distant swell wave field off Maui Bay, Coral Coast, Fiji, 27 May 2018**

Source: H. Damlamian, personal communication, SPC (2022)
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