CLINT

CLIMATE INTELLIGENCE

D7.1 Local Climate Services

April 2022
With user updates: August 2023

This project is part of the H2020 Programme supported by the European Union, having received funding from it under Grant Agreement No 101003876

Programme Call:	Building a low-carbon, climate resilient future: climate action in support of the Paris Agreement (H2020-LC-CLA-2018-2019-2020)
Grant agreement ID:	101003876
Project Title:	CLINT
Partners:	POLIMI (Project Coordinator), CMCC, HEREON, CSIC, SMHI, HKV, E3M, TCDF, DKRZ, IHE, ECMWF, UAH, JLU, OGC, UCM
Work-Package:	WP7
Deliverable #:	D7.1
Deliverable Type:	Document
Contractual Date of Delivery:	30 April 2022
Actual Date of Delivery:	**30 April 2022**
Title of Document:	Local Climate Services
Responsible partner:	IHE
Author(s):	Claudia Bertini, Andrea Ficchì, Celia Ramos Sanchez, Lucia De Stefano, Matteo Giuliani, Dorien Lugt, Michiel Pezij, Andrea Castelletti, Schalk Jan van Andel

Content of this report:	This report describes the impacts of extreme events, current climate services used, user-inspired indicators of extreme events, and user requirements for enhanced climate services in the local-scale case studies
Availability:	This report is public.

Document revisions		
Author	*Revision content*	*Date*
Claudia Bertini, Andrea Ficchì, Celia Ramos Sanchez, Matteo Giuliani, Dorien Lugt, Schalk Jan van Andel	D7.1_v01 – First version of the report	2 April 2022
Alessia de Vita, Ursula Mc Knight	Internal revision	14 April 2022
Claudia Bertini, Andrea Ficchì, Celia Ramos Sanchez,Matteo Giuliani, Dorien Lugt, Elena Matta, Schalk Jan van Andel	D7.1_v02 - Revisions and additions throughout document after internal review	29 April 2022
Andrea Castelletti	Final check and report submission	29 April 2022

Table of Content

LIST OF ACRONYMS

Abbreviations

AI: Artificial Intelligence

CS: Climate Service

DSS: Decision Support System

EE: Extreme Event

EET: Extratropical Transition

GWL: Global Warming Level

RBD: River Basin District

S2S: Sub-seasonal to Seasonal

TC: Tropical Cyclone

WP: Work Package

WEF: Water-Energy-Food

ZW: Zambezi Watercourse

EXECUTIVE SUMMARY

This report provides a detailed overview of the local-scale case studies of the CLINT project in semi-arid, delta, and snow-dependent areas, called climate change hotspots. The case studies include the Zambezi Watercourse, Douro River basin, Rijnland, Aa en Maas, the main water system of the Netherlands, and Lake Como basin.

Each of these case studies faces one or more of the extreme events addressed in the CLINT project, such that the aim is to develop and test climate services on the basis of the AI-enhanced extreme event detection and prediction methods and evaluate the potential added value for the use cases across sectors and extreme events.

Through dedicated meetings, semi-structured interviews, and online surveys, several user organisations and stakeholders have been consulted, which resulted in a better understanding of their definition of the extreme event(s) concerned, their knowledge of early indicators for the extreme events, the impacts on the ground of the extreme events, and climate services they currently use for preparedness or adaptation.

A key result for the further steps of the CLINT project presented here concerns the user wish list and requirements for enhanced or new climate services. The AI-enhanced CLINT climate services to be developed will be benchmarked against climate services available at the start of the project.

This report concludes by describing how the potential impact of the CLINT climate services will be quantified for each case study. With the end-users engaged successfully and with clear user requirements expressed, the next phase of CLINT Work Package 7 of assessing existing services' benchmark performance and developing pilot AI-enhanced services is now strongly supported.

1 Introduction

The CLINT project is aimed at improving the detection, causation and attribution of Extreme Events (EE) using machine learning, ultimately developing innovative and sectorial AI-enhanced Climate Services (CS) to support adaptation, mitigation and disaster risk management strategies. The role of Work Package 7 (WP7) is to incorporate the AI-enhanced climate services that will be developed during the project in user-tailored pilot services for testing in selected local-scale case studies.

As a first step, existing climate services used by the stakeholders of the case studies in the different climate change hotspots have been identified. Through multiple interactions with the stakeholders, by (online) meetings, surveys (Annex 1), and semi-structured interviews (Annex 2), user requirements for enhancement of the existing CS or for new services were discussed. Local expertise is key to a deep understanding of how the different EE are recognized and defined in the area and what the impacts of these extremes are on the ground. This sometimes extends to knowledge on (early) indications (e.g. environmental variables) of EE, which may feed to WPs 2-5 as additional input, for example, for enhanced detection of extreme events.

This report provides user requirements for the CS to be further developed and evaluated in the following tasks of WP7 and provides information for the formulation of the impact indicators for quantifying the value of AI-enhanced CS to be developed by CLINT.

1.1 Climate change hotspots

The case studies in WP7 have been selected to cover a range of geographical settings that are particularly vulnerable to climate change: climate change hotspots. The hotspots addressed include semi-arid areas, deltas, and snow-dependent areas. Secondly, the case studies have been limited to local scale, ranging from river catchments down to land-reclamation areas, basically anything smaller than continental scale, as this is addressed in WP6 for case studies at the pan-European scale. Last but not least, the case studies had to cover together the extreme events addressed by the CLINT project: tropical cyclones and floods, heatwaves and warm nights, and droughts.
This has resulted in the following case studies:

Semi-arid areas

- Zambezi Watercourse - droughts, tropical cyclones and floods
- Douro basin - droughts

Deltas

- Rijnland - droughts
- Aa en Maas - droughts
- Main water system of the Netherlands - tropical cyclones

Snow-dependent areas

- Lake Como basin - droughts, floods, heatwaves, and warm nights

It shall be noted that, as per communication to the EC project officer, the initially proposed case study of Rijn and IJssel has been replaced by the case study of Aa en Maas, an adjacent local water authority in the Delta of the Netherlands. The case study focuses on the same extreme events: droughts.

1.2 Objectives of this deliverable

The objectives of this deliverable are to:

- Describe the local scale case studies in detail,
- Report on existing CS and user needs for enhanced or new services,
- Formulate any user-inspired EE variables and indices as input to WPs 2-5,
- Formulate the impact indicators for quantifying the value of AI-enhanced CS to be developed by CLINT.

1.3 Connection with Milestone MS2

This deliverable has been developed in conjunction with Milestone 2 - Data provision for local Climate Services, delivered February 2022, in which, on the basis of the case studies and user requirements, the benchmark hydrometeorological forecast and climate outlook datasets have been identified. These benchmark datasets represent the climate services available at the beginning of the CLINT project. The performance (skill and value) of AI-enhanced climate services that will be developed during CLINT will be measured against the performance of these benchmark datasets. These include sub-seasonal and seasonal hydrometeorological predictions, as well as European and Global climate change projections, depending on each of the case studies' specific needs. For the detailed list of benchmark datasets for all local-scale case studies, see MS2 - Data provision for local Climate Services.

1.4 Structure of the document

In the following chapters, grouped per climate change hotspot, each case study will be analysed in detail, following the same structure. First, a brief description of the catchment and area of interest will be provided (General case-study description). This includes a description of key user organisations (non-exhaustive), focussing on those having a prominent role in the case studies management of extreme events and being the main contact point for CLINT.

The second section (Detailed use-case description) provides more details on the intended use of the AI-enhanced climate services in extreme event management, including how the end-users define the EE considered; the impacts the EE have in the study area (local impact of extreme events); what the end-users are currently using as an early indicator for the EE, and how they make decisions based on the indicator; and suggestions, if any, for early indicators for the EE to use as input for WPs 3-5.

The third section (Existing climate services and need for enhancement) describes the state of the existing CS in the area, with a focus on what CS the end-users are currently employing and on what they would like to be improved.

The fourth and last section (Impact indicators for quantifying the value of AI-enhanced CS) provides information on the impact indicators adopted to quantify the potential added value of the AI-enhanced CS.

2 Semi-arid climate change hotspots

2.1 Zambezi Watercourse

2.1.1 General case study description

2.1.1.1 Catchment and hydroclimatology

The Zambezi Watercourse (ZW, Figure 2.1) is the fourth largest basin in Africa with an area of 1.32 million km^2 shared by eight countries (Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia, and Zimbabwe) with Zambia (42%), Zimbabwe (16%) and Mozambique (13%) encompassing about 70% of the entire basin (SADC, 2012). The basin is populated by almost 40 million inhabitants. The Zambezi River originates in the regions of eastern Angola and north-west Zambia at elevations around 1600 m.a.s.l. (Figure 2.1) and flows for 2,700 km through plains, gorges, and marshlands into the delta in Mozambique and finally into the Indian Ocean with a discharge of 2,600 m^3/s on average. The seasonality of both temperature and rainfall follows the periodic movement of the Intertropical Convergence Zone over southern Africa, with a rainy season from November to April and a dry season from May to October. The average annual rainfall in the basin is high, approx. 950 mm, though it is unevenly distributed across the basin, and the inter-annual variability is quite high. Up to 1,400 mm/y are observed in the northern and eastern parts of the basin, whereas 400 mm/y falls on average in the southern and western regions. Due to the high temperatures and potential evapotranspiration rates, a large amount of water is lost by evaporation (1600 mm-2300 mm). After the late 1970s, several dams constructed along the river to take advantage of its potential for hydropower energy production changed the natural flow pattern significantly, favouring the expansion of irrigated agriculture but affecting some of the valuable wetland ecosystems in the middle and lower course.

The ZW has a vital role in ensuring food security in the region due to its role in sustaining agriculture and fisheries. The existing irrigated areas cover about 182,000 ha; major cultivated crops are sugar cane, rice, wheat, and maize (Payet-Burin et al., 2019). The high runoff in the upper part of the ZRB combined with a fall of more than 1000 m along the river course to the ocean provides a good opportunity for hydropower production, which is currently exploited by an installed capacity of 5.5 GW that represents the main source of electricity within the basin. Around 70% of this installed capacity is concentrated in two mega-dams, namely Kariba and Cahora Bassa. Two other dams, Ithezi-thezi and Kafue Gorge, are instead located in Zambia on the tributary Kafue River and contribute an additional installed capacity of 1.1 GW. New dams in the basin are planned for the next decades to respond to both hydropower and agricultural capacity expansion (World Bank, 2010).

Climate change is expected to affect the basin's potential for hydropower and agriculture negatively (e.g., Hamududu and Killingtveit, 2016; Hughes and Farinosi, 2020) and lead to an increase in the frequency and severity of extreme events, both droughts and floods. According to most climate projections, air temperature and potential evaporation are expected to increase, while the total annual rainfall is projected to decrease (Hamududu and Killingtveit, 2016). Increased evaporation and reduced rainfall will lead to a decrease in river flows and increased reservoir evaporation, which will lead to a loss in water resources for agriculture and decreased hydropower production potential. According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2021), the observed and projected changes in the region of the ZW (East Southern Africa) are

- Observed decreases in mean precipitation;
- Observed and projected increases in heavy precipitation and pluvial flooding;
- Observed and projected increase in aridity, agricultural and ecological droughts;
- Observed increase in meteorological drought, projected increase in meteorological droughts from 1.5°C global warming level (GWL), higher confidence at higher GWLs;
- Projected increases in fire weather conditions; increases in mean wind speed; increase of average tropical cyclone wind speeds and associated heavy precipitation and of the proportion of category 4-5 tropical cyclones.

These changes are expected for the mid- 21st century for a global warming of at least 2°C, with least medium and high confidence.

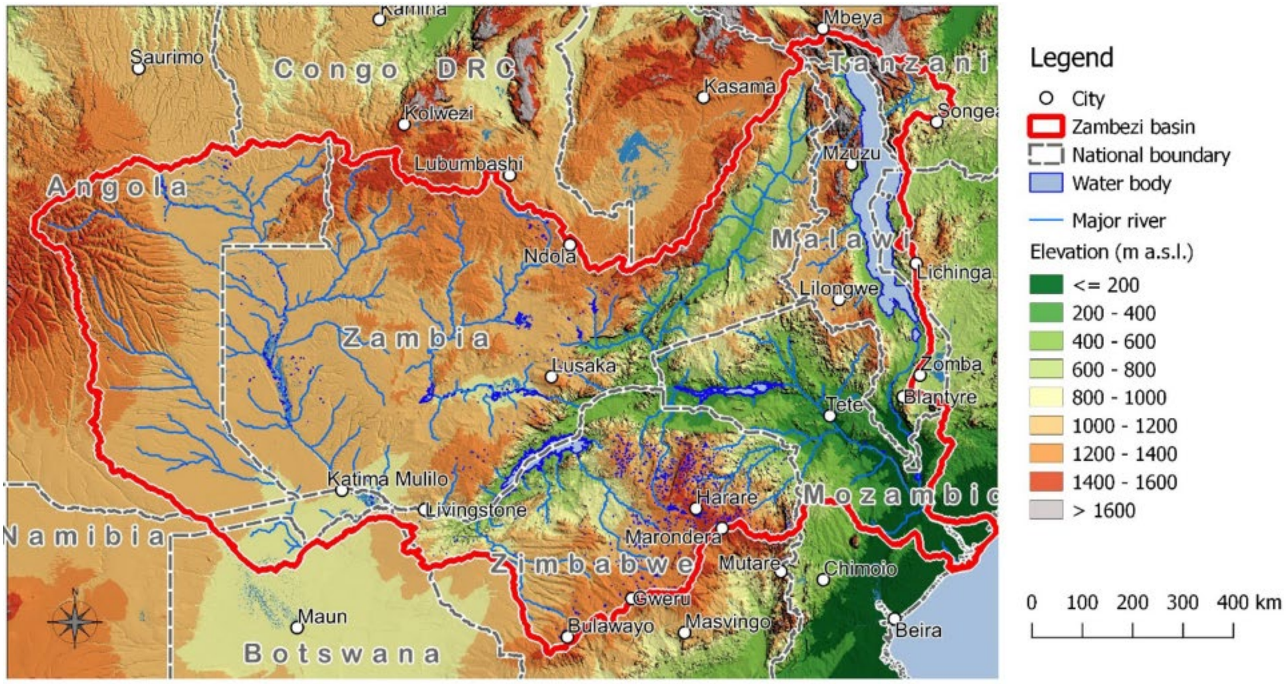


Figure 2.1. The Zambezi Watercourse in Southern Africa with its topography based on the DEM derived from SRTM data. The red outline indicates the catchment boundaries. [Source: EU H2020 DAFNE Project – Deliverable D2.1]

2.1.1.2 Users

The following groups of decision-makers and stakeholders were identified as key current or potential users of climate services for the ZW:

- The Zambezi Watercourse Commission (ZAMCOM) is a major river basin organisation in Africa. It was established in 2014 as an inter-governmental organisation bringing together 8 riparian countries of the Zambezi River Basin (Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia, and Zimbabwe), after signing an agreement in 2004 with the purpose of enhancing the cooperation over the shared water resource of the ZW to increase agricultural yields, hydropower production, and economic opportunities. ZAMCOM's objective is "to promote the equitable and reasonable utilisation of the Zambezi Watercourse's water resources and the efficient management and sustainable development thereof", coordinating both long-term planning and operational decisions across the basin. One of the key responsibilities of ZAMCOM is the design of allocation rules and policies for the allocation of water supplies across different users in the basin.
- Dam operators and hydropower companies, including ZRA, ZESCO and HCB:
    - The Zambezi River Authority (ZRA) was established as a body corporate in 1987 by parallel legislation in the Parliaments of Zambia and Zimbabwe following the reconstitution of the Central African Power Corporation (CAPCO). The ZRA is responsible for the operation and maintenance of the Kariba Dam Complex, investigating and developing new dam sites on the Zambezi River, and analysing and disseminating hydrological and environmental information on the Zambezi River and Lake Kariba.
    - The Zambia Electricity Supply Corporation Limited (ZESCO) is Zambia's largest power company (state-owned). It produces about 80% of the electricity consumed in Zambia and represents the country in the Southern African Power Pool. The company operates 9 hydropower stations with a combined capacity of 2,218 MW, including Itezhi-Tezhi, Kafue Gorge Upper, and the Victoria Falls plant (consisting of three run-of-the-river power plants).
    - The Hidroelectrica de Cahora Bassa (HCB) is Mozambique's main hydropower generation company (a private company with a majority state-owned capital participation). HCB operates the Cahora Bassa hydropower plant, which has an installed capacity of 2,060 MW.
- National Meteorological and/or Hydrological Services (NMHSs) of the eight riparian Countries, including for the three Countries covering most of the ZW basin: (i) Zambia's Meteorological Department (ZMD), i.e. the National authority for weather and climate services, and Water Resources Management Authority (WARMA); (ii) Zimbabwe's Meteorological Services Department and National Water Authority (ZINWA); (iii) Mozambique's National Meteorological Institute (INAM) and National Directorate of Water Resources Management (DNGRH). In Mozambique, the NMHSs delegate management and planning responsibilities at the regional and sub-basin level to regional agencies, i.e. ARA-Centro and ARA-Zambeze, for the Zambezi (Regional and basin Hydrological Agencies). These agencies deal with the development and dissemination of climate services and

hydrometeorological forecasts in the lower part of the ZW. These institutions are responsible for hydrometeorological forecasting and monitoring at the national and regional/local levels and maintain a network of ground gauges.

- The Southern Africa Development Community (SADC) is an inter-governmental organisation (headquartered in Botswana) that aims to develop further regional socio-economic cooperation and integration and political and security cooperation among 16 countries in southern Africa, including all the ZW's riparian countries. Through its Climate Services Centre (CSC), SADC regularly organises the Southern African Climate Outlook Forum (SARCOF), which is responsible for disseminating seasonal meteorological forecasts to member states. Also, ZAMCOM attends SARCOF dissemination events.
- National Environmental Regulatory Agencies, Ministries and Directorates responsible for planning and ensuring the implementation of environmental policies and regulations, including the Mozambique's Ministry of Land and Environment, Zambia Environmental Management Agency (ZEMA) and Zimbabwe's Environmental Management Agency (EMA). Zambia's ZEMA was established in 2011 to ensure the integration of environmental concerns in national plans. Zimbabwe's EMA is a statutory body established in 2002 responsible for ensuring the sustainable planning and management of natural resources and protection of the environment, the prevention of pollution and environmental degradation, and the implementation of conservation measures. All these Environmental Agencies are responsible for environmental plans where the ecological river flows in the ZW are key for the protection of environmentally sensitive areas and wetland ecosystems.
- Disaster Management Agencies, including the National Institute for Disaster Risk Management and Reduction of Mozambique (INGD), which is one of the main actors in the early warning chain for Tropical Cyclones, floods and droughts in the country.
- Humanitarian agencies, including the Red Cross – Mozambique (CVM), the United Nations Office for Coordination of Humanitarian Affairs (UN OCHA) and the World Food Programme (WFP), are involved in the early warning / early action chain and are key decision-makers for cyclone, flood and drought preparedness, contributing to enhancing the local adaptive capacity of National Agencies to face large-scale extreme weather events like tropical cyclones.
- Irrigation Schemes' Operators
- National Farmers Unions
- Water Supply companies

As part of CLINT, contacts were established via email and calls with the following users from the list above: the Zambezi Watercourse Commission (who also provided endorsement to CLINT), some dam operators and hydropower companies, some National and Regional Hydrometeorological Agencies and Environmental Regulatory Agencies, and two humanitarian agencies (the Red Cross and WFP). Seven different users responded to the invitation to fill in a survey (with 24 questions) with anonymous answers from different organisations, including ZAMCOM, a National Environmental Agency from one of the riparian countries, a national/regional hydrological service, WFP-Mozambique and the Mozambique Red Cross (humanitarians involved in drought, tropical cyclones and flood preparedness in Mozambique), and another stakeholder/user from a non-specified organisation. A call was conducted with ZAMCOM and a humanitarian manager to discuss in further detail their perspectives on EEs, their current use of climate services and their operational needs for further CS enhancements.

2.1.1.3 Extreme events

The ZW suffers from severe hydrometeorological hazards, including droughts, floods, and Tropical Cyclones (TC).

- Droughts: The ZW region is vulnerable to recurrent droughts that result in poor harvests and loss of livestock, food insecurity and loss of life, the spread of water-borne diseases and epidemics, damages to infrastructures and loss in hydropower production, leading to large economic losses. For example, during the severe 1991/92 drought, the loss in hydropower generation from the Kariba dam resulted in an estimated US$102 million reduction in Gross Domestic Product, US$36 million reductions in export earnings, and the loss of 3000 jobs in Zimbabwe (ZAMCOM, 2018). CLINT will provide AI-enhanced S2S hydroclimatic forecasts of extreme droughts for informing the multipurpose operation of the system (i.e. dams and irrigation diversions) that will contribute to improving the system performance in terms of hydropower production and irrigation supply, as well as in mitigating existing conflicts between these competing sectors.
- Floods and Tropical Cyclones: The downstream parts of the ZW are particularly exposed and vulnerable to tropical cyclones and related floods, as demonstrated by the recent devastating impacts of Cyclone Idai in 2019, which resulted in an estimated 1.85 million people in need of humanitarian assistance and protection, and in more than 1,000 fatalities over three countries (Mozambique, Malawi and Zimbabwe). CLINT will generate an AI-enhanced warning system for tropical cyclones to improve flood preparedness in Mozambique.

2.1.2 Detailed use-case description

The following use-case description is based on information collected mainly via a survey with 24 questions (see Annex 1). Anonymous responses were received from seven end-users related to the ZW case study. Here the answers are reported ensuring anonymity, referring only to the name of the organisations that were indicated and (or) their related sector of user activity or extreme events of interest (when the organisation was not specified). Additional details are reported about external sources when relevant and publicly available.

2.1.2.1 User-definition of extreme events

Droughts: ZAMCOM defines droughts as a natural hazard mainly caused by a lack of precipitation and increased evaporation. They state that droughts are due to cyclical weather patterns made worse by land use changes, increasing pressure on land and water resources, and climate variability and change. The key variables used by ZAMCOM to define extreme droughts are rainfall deficit impacting rainfed agriculture, low-water levels in rivers and lakes impacting irrigated agriculture and hydropower generation. An environmental regulatory agency of the ZW basin gave a similar definition of droughts to ZAMCOM's response, adding that they have adverse effects on the environment.

Floods: ZAMCOM defines floods as a frequent natural hazard with devastating effects, resulting in loss of lives and damages and destruction to properties and infrastructures across the member states sharing the basin. A national water authority and environmental regulatory agency defines flooding as the inundation of residential areas and assets due to heavy rainfall events and the bursting of rivers. A humanitarian organisation in Mozambique (Red Cross) defines floods based on river levels and the exceedance of the National Hydrological Agency's warning level thresholds (corresponding to return period levels).

Tropical cyclones: A humanitarian organisation in Mozambique defines tropical cyclones as storm systems with winds greater than a threshold (i.e., 120km/hour).

2.1.2.2 Local impact of extreme events

Each of the extreme events above mentioned has different local impacts on multiple sectors. A detailed description of how the local impacts are perceived and quantified by the different end-users is provided below for each of the extreme events considered for the case study.

Droughts: ZAMCOM reported that droughts cause high socioeconomic negative impacts, especially in the hydropower sector, as well as agriculture, both rainfed and irrigated, which are the two most affected sectors. The damage of droughts to agricultural activities leads to poor crop harvest, food insecurity and poverty. In addition to these impacts on agriculture, an environmental regulatory agency mentioned that other impacts include displacement of people, disease outbreaks, land use change, and environmental degradation. ZAMCOM stated that the impacts of droughts are quantified and assessed via socio-economic surveys and vulnerability reports.

Floods: ZAMCOM and an environmental regulatory agency reported that the impacts of floods include destruction of properties and infrastructure, disease outbreaks, displacement of people, poverty, and disruption of economic activities. ZAMCOM stated that the impacts of floods are quantified and assessed via socio-economic surveys, vulnerability reports and assessments of infrastructures. Similarly, the environmental agency assesses the impacts of floods via socio-economic surveys to estimate the number of households or people affected and assessments of infrastructures damaged or affected. A humanitarian organisation in Mozambique stated that the impacts of floods are death/injury, damage to vulnerable housing and other infrastructure, disease outbreaks, and loss of crops and livestock. They are often quantified by post-event analysis and field assessments.

Tropical cyclones: According to the Red Cross in Mozambique, the impacts of tropical cyclones include destruction of housing and infrastructure, displacement of people, death/injury, disease outbreaks, poverty, and disruption of economic activities. The impacts of tropical cyclones are assessed via field campaigns and surveys to estimate the number of households or people affected and the number of damaged houses and infrastructures.

2.1.2.3 Decision process for preparedness, adaptation, and event or risk management

Different climate and weather information and variables are used as an early indication of an upcoming EE. The choice depends on the type of event and the decision-making context, i.e. what users implement preparedness/adaptation measures.

- Droughts: ZAMCOM uses local real-time monitoring systems and seasonal forecasting systems (see Section "Climate services currently used" below) to inform both dam operators and irrigation schemes' operators to support their decisions aimed at optimising hydropower production and crop yields. To inform their farming and cropping practices, stakeholders of the agricultural sector look at Climate Outlook Bulletins from SADC, with interpretation of seasonal meteorological forecasts (especially seasonal rainfall totals). A humanitarian organisation in Mozambique (WFP) uses data on precipitation, Temperature/Evapotranspiration, soil moisture, and crop water stress for droughts assessment and early action planning.
- Floods: ZAMCOM uses meteorological forecasts and river flow forecasts for their planning and management decisions related to water allocations in the part of the basin upstream of Cahora Bassa. The environmental regulatory agency of Zambia uses weekly weather forecasts and updates. Actors related to flood preparedness and disaster management in Mozambique look at the DNGRH's flood bulletins based on observations, while the level of integration of complementary forecasts for the lower ZW (under testing) into the decision-making process is not known yet. In their Early Action Protocol (EAP) for floods, the Red Cross in Mozambique (CVM) use the information from the national bulletins in combination with global hydrological forecasts from the Copernicus Emergency Management Service (CEMS) – Global Flood Awareness System (GloFAS) run by ECMWF and the European Commission's Joint Research Centre.
- Tropical cyclones: Humanitarian organisations use hydrometeorological forecasts and observations from national mandated agencies, INAM and DNGRH, for early warning in Mozambique. This information is complemented by global forecasting systems information from large international centres (e.g. ECMWF).

The survey identified an even distribution across different types of datasets used by end-users to make long-term decisions (i.e. month and beyond). These datasets are:

- In-situ observations in real-time or near-real-time: hydrometeorological observations in the region are available from national hydrometeorological observatories and the Southern African Development Community's (SADC) Hydrological Cycle Observing System (HYCOS);
- Remote sensing data in real-time or near-real-time (e.g. satellite data);

- Model-based data (e.g. meteorological reanalysis) in real-time (or near-real-time);
- Climatology (defined as the incorporation of historical data over many years and their statistical/probabilistic analysis);
- Forecasts at short-term or at monthly/sub-seasonal scale: these include hydrological forecasts from ZAMCOM (ZAMWIS) and some national/regional local systems under development and testing (e.g. Mozambique's DNGRH);
- Seasonal forecasts: these include hydrological forecasts from ZAMCOM (ZAMWIS), Climate Outlook Bulletins, with interpretation of seasonal meteorological forecasts and agrometeorological updates from SADC.

On the other hand, decadal predictions and centennial climate projections are not currently used by any users who responded to the survey.

Regarding the question of how users make decisions based on these datasets and monitoring/forecasting systems, the survey's replies suggest that this information is not consistently used in a structured decision-making process for most sectors. The operator of Kariba dam is currently looking at the hydrological forecasts issued by ZAMCOM through ZAMWIS to support their decisions on dam's releases, but no detail on the actual decision-making process has been provided; this suggests that forecasts are not integrated formally into any Decision Support System (DSS) yet. ZAMCOM is working alongside National Hydrological Agencies to define and include streamflow/water level thresholds (different alert colour codings) to coordinate with the Member States in case of an extreme event. This will help users integrate forecasts into a structured decision-making process.

Some details about forecast-based decision making are publicly available for humanitarian actions and early warning systems for droughts in Mozambique (WFP), tropical cyclones and floods (Red Cross) in Mozambique and Zambia and are summarised here below. These systems and plans relate to Forecast-based Financing (FbF), which is a programme of humanitarian organisations that enables access to funding for early action based on hydro-meteorological forecast information and risk analysis (Coughlan de Perez et al., 2015).

- <u>WFP's FbF plan for droughts in Mozambique:</u> To enable the implementation of FbF projects, WFP has recently developed and implemented probabilistic seasonal forecasts of the Standardized Precipitation Index (SPI) covering Mozambique's rainfall season (October-April). Their system produces forecasts of the probability of the SPI to be less than -1, a threshold that identifies significant drought events at time scales of 2-3 months. These are derived from ECMWF ensemble seasonal daily precipitation forecasts and processed from August to February to forecast drought occurrence one to six months ahead of time (Bonifacio et al., 2021). Standard Operating Procedures (SOPs) are designed to outline the actions, actors, costs, thresholds, triggers, and predetermined funds to be mobilised in anticipation of an extreme drought event and are aligned with national disaster risk management plans.
- <u>Red Cross Early Action Protocol (EAP) for floods in Mozambique and Zambia</u>: The EAP for floods of Mozambique describes how CVM selected and will implement the FbF actions to protect vulnerable communities at risk. CVM activate anticipatory actions on the basis of

hydrometeorological warnings from INAM and DNGRH indicating that the trigger level, i.e., a threshold for river flow corresponding to a 5-year return period at each river reference station, will be reached or exceeded within 3 days, which is the lead time within which the CVM can act in advance before a flood event reaches the districts and communities potentially at risk. All actions currently included in Mozambique's EAP for floods are based on this 3-days preparation time window. A similar EAP for floods has also been implemented for Zambia, primarily by the Zambia Red Cross Society (ZRCS). The forecast information used in Zambia's EAP for activating early action comes from the Global Flood Awareness System (GloFAS), in combination with river water levels provided by WARMA. The trigger level in Zambia is fixed as the 10-year return period flood level at each river reference station, to be reached or exceeded within 7 days or 3 days. Different actions are implemented based on either the 7-days or 3-days preparation time window.

- Red Cross Early Action Protocol (EAP) for Tropical Cyclones in Mozambique: The EAP for tropical cyclones of CVM can in principle be used nationwide, but its activation is anticipated to be concentrated in coastal districts in northern and central Mozambique. Considering the physical context, logistics, and the local capacity, an activation will involve three districts at maximum and will target 1500 households (7500 people). The available lead time for cyclones in Mozambique is 72 hours, and the trigger is based on a threshold of wind speed for TC intensity (120 km/h or above at landfall). All actions presented in the EAP are to take place during these three days of preparation time. Meteorological forecasts are provided by the National Institute of Meteorology (INAM), based on forecasts collected from the Indian Ocean Regional Intervention Platform (PIROI), i.e. a French Red Cross tool. The actions included in CVM's EAP prioritise reinforcing individual vulnerable houses, reinforcing first-level primary schools built with local material, and preventing endemic diseases after storms.

2.1.2.4 User-inspired (early) indicators of extreme events for input to WPs 3-5

All users mentioned that rainfall is a variable at which they look to understand drought risk evolution. Observations and rainfall forecasts are used to characterise the meteorological drought risk quantitatively and the hydrological drought risk by all users qualitatively, but there is no integrated hydrological forecasting system at the basin scale to forecast river flows, especially in downstream parts of the catchments. WFP mentioned that it would be important to look at the Standardized Streamflow (or Runoff) Index, but local, national forecast models are not yet established for this.

In addition to rainfall, some users mentioned that other useful indicators could be used in addition as an early indication of extreme events (both droughts and floods) that could be based on Sea Surface Temperature (SST) indices, e.g. Nino-3.4 (ENSO), Indian Ocean Dipole (IOD), etc.

The humanitarian organisations in Mozambique reported the need for more advanced flood and drought forecasting models, taking into account the hydrological hazard and dynamic exposure and vulnerability rather than just water levels.

2.1.3 Existing climate services and the need for enhancement

2.1.3.1 Climate services currently used

Droughts and floods upstream of Kariba: ZAMCOM is currently using and developing a data and information system with a hydrological forecasting component called the ZAMWIS (Zambezi Water Resources Information System) (http://zamwis.zambezicommission.org/INFO). ZAMWIS has both a web-based version (with data access limitations) and a software interface (see Figure 2.2). This system provides access to historical and real-time hydrological data and forecasts to the users of the ZAMWIS database, which are the government institutions of the riparian countries, the dam operators, hydropower companies, irrigation schemes and other key stakeholders of the ZW, to support them in planning and managing the water resources in the basin. The ZAMWIS Flow Forecasting System (FFS) component is based on the MIKE River modelling software and produces river flow forecasts on the sub-seasonal to seasonal time scale (up to 3 months) in parts of the basin upstream of the largest dams. Within ZAMWIS, MIKE performs the hydrodynamic modelling along the river network and allows to forecast the river flow 90-days ahead using precipitation forecasts as inputs. The input data for ZAMWIS FFS include:

- forecasts of global gridded rainfall from the United States National Centre for Environmental Prediction (NCEP)'s Climate Forecast System (CFS) system (publicly available, https://cfs.ncep.noaa.gov/);
- rainfall gridded satellite observations from the NASA's Global Precipitation Measurement (GPM, https://www.nasa.gov/mission_pages/GPM/main/index.html);
- near-real-time observations of river flow from National Hydrological Agencies;
- near-real-time observations of water levels in reservoirs.

These forecasts and observations are combined with the expected reservoir releases and operation rules to provide forecasts of river flows. The system uses thresholds of streamflow level at river points mostly distributed in the main watercourse upstream of the Kariba dam. Currently, the main target of this system is to improve the reliability of seasonal forecasts, thereby providing dam operators and irrigation schemes' operators with information with enhanced confidence for flow releases and water management. For example, the operator of Kariba dam is currently looking at the forecasts issued by ZAMCOM through ZAMWIS to support their decisions on the dam's releases. A second target is to support disaster management by providing Disaster Management Agencies with reliable and targeted hydrological forecast information. In addition to the ZAMWIS transboundary system, hydrological forecasts are under development or testing phase in some of the NMHSs of the riparian countries. In Zambia, ZMD and WARMA do not run flood forecasting models yet. A national environmental regulatory agency from Zambia mentioned in the survey that information obtained from the meteorological department is currently used, however, this is likely to include only real-time observations or seasonal, regional meteorological forecast outlooks from SARCOF.

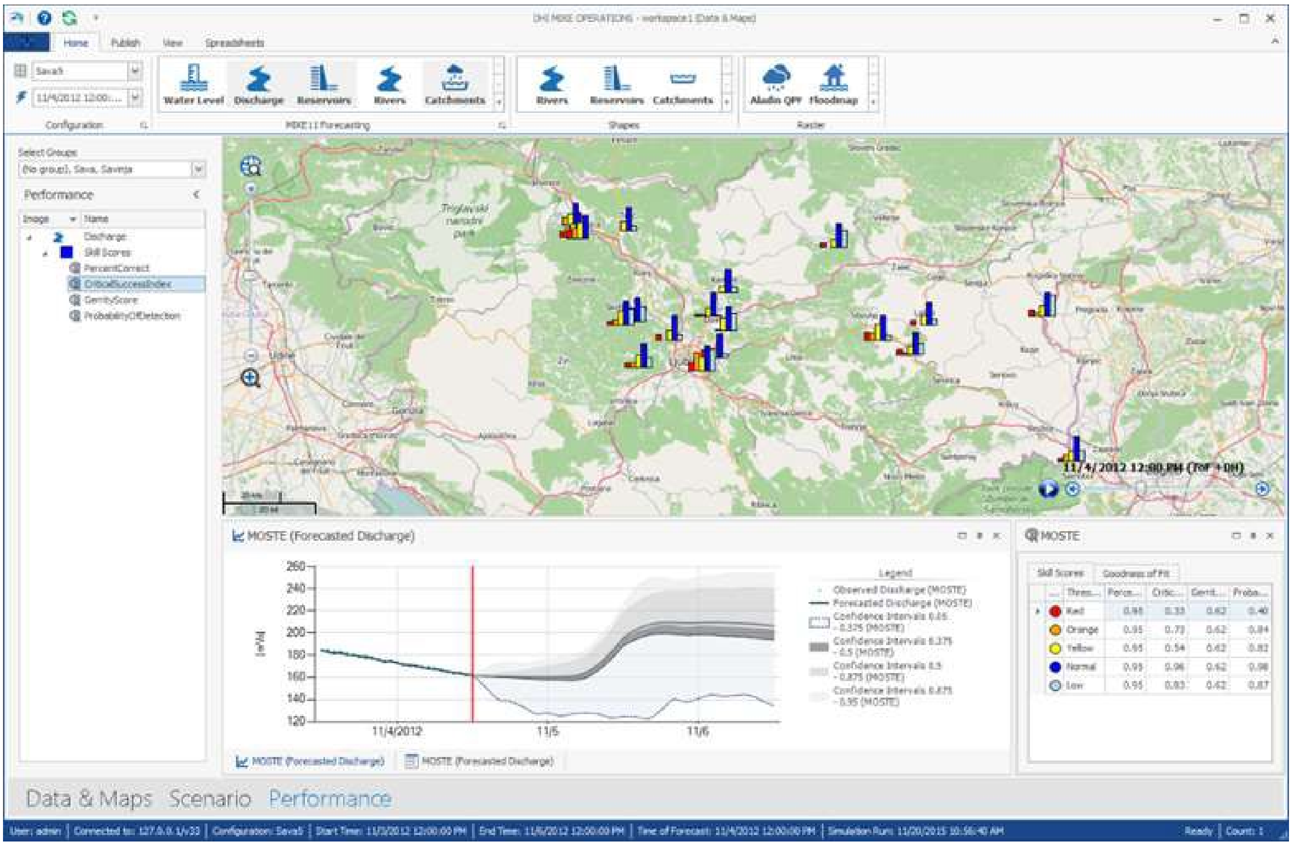
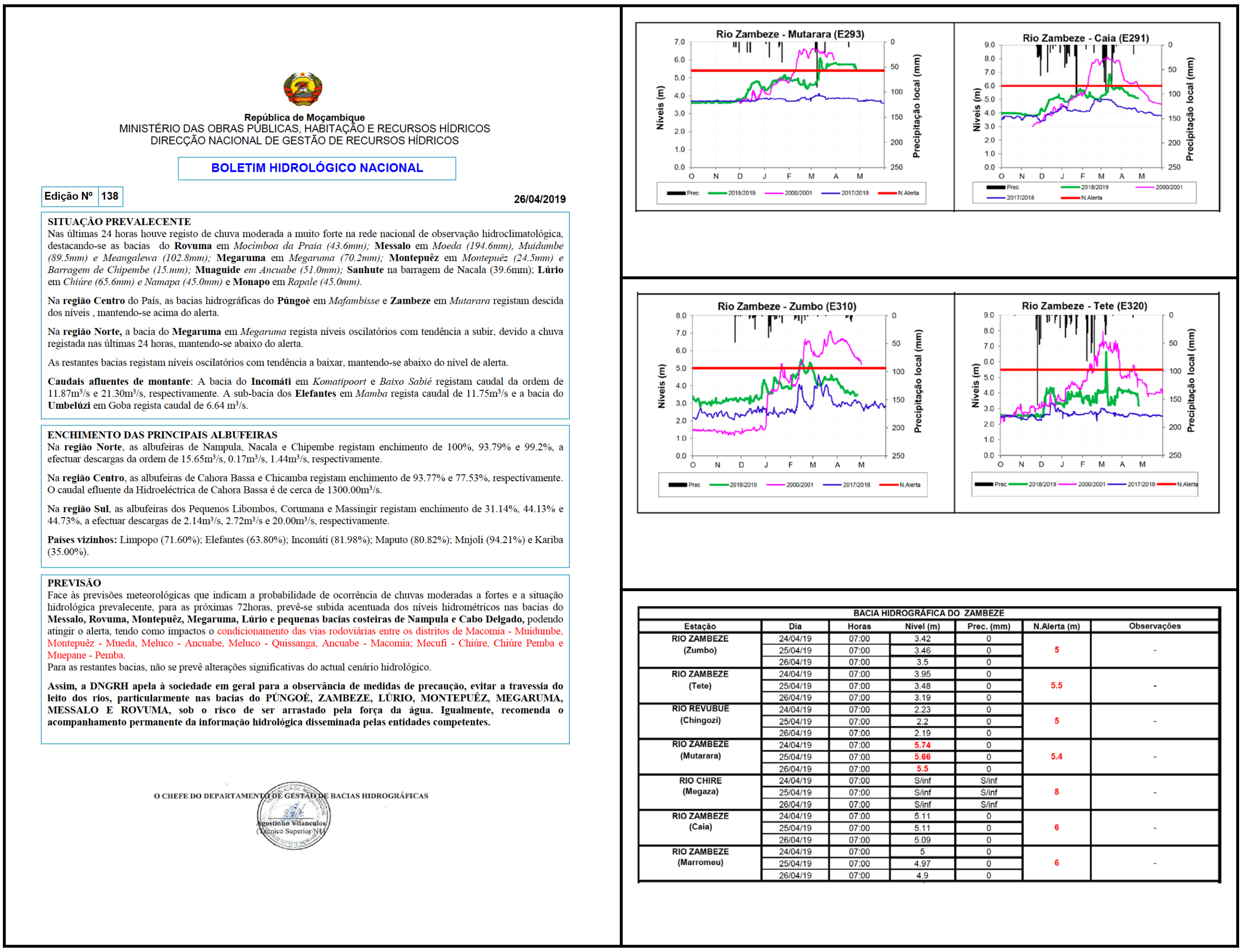


Figure 2.2. ZAMWIS software interface with an example of forecasted discharge in the Zambezi River Basin with confidence intervals (Source: ZAMCOM).

<u>Floods in Mozambique, downstream of Cahora Bassa:</u> The National Hydrological Service of Mozambique (DNGRH) produces regular daily national hydrological bulletins reporting the near-real-time evolution of river levels based on ground observations (see example in Figure 2.3). These bulletins include qualitative statements on the expected evolution up to three days ahead, based on observed river levels, state and releases of national reservoirs (including Cahora Bassa), and meteorological observations and forecasts. River level observations are reported numerically and graphically (see Figure 2.3), with data from the national monitoring network of river gauges, including seven stations in the ZW. These bulletins are shared with the national and regional end-users involved in flood preparedness in the country (e.g. INGC, ARAs, CVM - Red Cross, etc.). The near-real-time updated bulletins do not appear to be systematically publicly available, though some historical ones are available online. There is no systematic quantitative hydrological forecasting component in the bulletins, although in some cases, DNGRH can run local models to support the bulletin production. Local quantitative flood forecasts in the lower Zambezi were recently under testing in DNGRH and ARAs, after the model development through a World Bank Project ("Pilot program for climate resilience: Transforming hydrological and meteorological services project (P131049)"), running the HEC-RAS model using weather forecasts from INAM (Mozambique's

Meteorological Service), however, these forecasts have not been integrated systematically in the flood bulletins production yet.



República de Moçambique
MINISTÉRIO DAS OBRAS PÚBLICAS, HABITAÇÃO E RECURSOS HÍDRICOS
DIRECÇÃO NACIONAL DE GESTÃO DE RECURSOS HÍDRICOS

BOLETIM HIDROLÓGICO NACIONAL

Edição Nº 138 — 26/04/2019

SITUAÇÃO PREVALECENTE
Nas últimas 24 horas houve registo de chuva moderada a muito forte na rede nacional de observação hidroclimatológica, destacando-se as bacias do **Rovuma** em *Mocímboa da Praia (43.6mm);* **Messalo** em *Moeda (194.6mm), Muidumbe (89.5mm) e Meangalewa (102.8mm);* **Megaruma** em *Megaruma (70.2mm);* **Montepuêz** em *Montepuêz (24.5mm) e Barragem de Chipembe (15.mm);* **Muaguide** *em Ancuabe (51.0mm);* **Sanhute** na barragem de Nacala (39.6mm); **Lúrio** em *Chiúre (65.6mm) e Namapa (45.0mm)* e **Monapo** em *Rapale (45.0mm).*

Na **região Centro** do País, as bacias hidrográficas do **Púngoè** em *Mafambisse* e **Zambeze** em *Mutarara* registam descida dos níveis , mantendo-se acima do alerta.

Na **região Norte,** a bacia do **Megaruma** em *Megaruma* regista níveis oscilatórios com tendência a subir, devido a chuva registada nas últimas 24 horas, mantendo-se abaixo do alerta.

As restantes bacias registam níveis oscilatórios com tendência a baixar, mantendo-se abaixo do nível de alerta.

Caudais afluentes de montante: A bacia do **Incomáti** em *Komatipoort* e *Baixo Sabié* registam caudal da ordem de 11.87m³/s e 21.30m³/s, respectivamente. A sub-bacia dos **Elefantes** em *Mamba* regista caudal de 11.75m³/s e a bacia do **Umbelúzi** em Goba regista caudal de 6.64 m³/s.

ENCHIMENTO DAS PRINCIPAIS ALBUFEIRAS
Na **região Norte**, as albufeiras de Nampula, Nacala e Chipembe registam enchimento de 100%, 93.79% e 99.2%, a efectuar descargas da ordem de 15.65m³/s, 0.17m³/s, 1.44m³/s, respectivamente.

Na **região Centro**, as albufeiras de Cahora Bassa e Chicamba registam enchimento de 93.77% e 77.53%, respectivamente. O caudal efluente da Hidroeléctrica de Cahora Bassa é de cerca de 1300.00m³/s.

Na **região Sul**, as albufeiras dos Pequenos Libombos, Corumana e Massingir registam enchimento de 31.14%, 44.13% e 44.73%, a efectuar descargas de 2.14m³/s, 2.72m³/s e 20.00m³/s, respectivamente.

Países vizinhos: Limpopo (71.60%); Elefantes (63.80%); Incomáti (81.98%); Maputo (80.82%); Mnjoli (94.21%) e Kariba (35.00%).

PREVISÃO
Face às previsões meteorológicas que indicam a probabilidade de ocorrência de chuvas moderadas a fortes e a situação hidrológica prevalecente, para as próximas 72horas, prevê-se subida acentuada dos níveis hidrométricos nas bacias do **Messalo, Rovuma, Montepuêz, Megaruma, Lúrio e pequenas bacias costeiras de Nampula e Cabo Delgado,** podendo atingir o alerta, tendo como impactos o condicionamento das vias rodoviárias entre os distritos de Macomia - Muidumbe, Montepuêz - Mueda, Meluco - Ancuabe, Meluco - Quissanga, Ancuabe - Macomia; Mecufi - Chiúre, Chiúre Pemba e Muepane - Pemba.
Para as restantes bacias, não se prevê alterações significativas do actual cenário hidrológico.

Assim, a DNGRH apela à sociedade em geral para a observância de medidas de precaução, evitar a travessia do leito dos rios, particularmente nas bacias do PÚNGOÈ, ZAMBEZE, LÚRIO, MONTEPUÊZ, MEGARUMA, MESSALO E ROVUMA, sob o risco de ser arrastado pela força da água. Igualmente, recomenda o acompanhamento permanente da informação hidrológica disseminada pelas entidades competentes.

O CHEFE DO DEPARTAMENTO DE GESTÃO DE BACIAS HIDROGRÁFICAS
Agostinho Vilanculos
(Técnico Superior N1)

BACIA HIDROGRÁFICA DO ZAMBEZE

Estação	Dia	Horas	Nível (m)	Prec. (mm)	N.Alerta (m)	Observações
RIO ZAMBEZE (Zumbo)	24/04/19	07:00	3.42	0	5	-
	25/04/19	07:00	3.46	0		
	26/04/19	07:00	3.5	0		
RIO ZAMBEZE (Tete)	24/04/19	07:00	3.95	0	5.5	-
	25/04/19	07:00	3.48	0		
	26/04/19	07:00	3.19	0		
RIO REVUBUE (Chingozi)	24/04/19	07:00	2.23	0	5	-
	25/04/19	07:00	2.2	0		
	26/04/19	07:00	2.19	0		
RIO ZAMBEZE (Mutarara)	24/04/19	07:00	5.74	0	5.4	-
	25/04/19	07:00	5.66	0		
	26/04/19	07:00	5.5	0		
RIO CHIRE (Megaza)	24/04/19	07:00	S/inf	S/inf	8	-
	25/04/19	07:00	S/inf	S/inf		
	26/04/19	07:00	S/inf	S/inf		
RIO ZAMBEZE (Caia)	24/04/19	07:00	5.11	0	6	-
	25/04/19	07:00	5.11	0		
	26/04/19	07:00	5.09	0		
RIO ZAMBEZE (Marromeu)	24/04/19	07:00	5	0	6	-
	25/04/19	07:00	4.97	0		
	26/04/19	07:00	4.9	0		

Figure 2.3. Example of the National Hydrological Bulletins of Mozambique of 26 April 2019: first page of the bulletin (left), with text summarising the hydrological and reservoir situation in the country and a qualitative forecast for the main river level evolution, and a snapshot of the tables and hydrographs (right) with the last 3-days river levels at some reference stations in the Zambezi basin (Source: DNGRH).

Tropical cyclones and floods: For TC forecasting and warnings, INAM makes use of the TC forecasts provided by the Regional Specialised Meteorological Centre (RSMC). RSMCs have the WMO-mandated responsibility to monitor and name TCs in their region and provide forecasts to national hydrometeorological services. In the SWIO, the RSMC is Météo-France La Réunion (MF), which provides daily updates on the meteorological situation and potential for cyclogenesis. During a TC, MF issues technical bulletins and graphical warning products every 6 h. The technical bulletins provide detailed information on the key characteristics of the TC (location, size and intensity) in text format designed for the use of operational forecasters at the national authorities. Graphical warnings products are issued through the MF website (www.meteofrance.re/cyclone/) and show the location and evolution of the TC track in maps (see Figure 2.4). These maps show the predicted track of the tropical system's centre over the next 5 days, including a cone of uncertainty or 'potential track area' based on forecasts from a range of models, alongside an indication of the storm's expected intensity. The forecasts provided by the RMSC do not include information on rainfall or flooding, but INAM's operational forecasters use a variety of rainfall forecast products produced by global forecasting centres to prepare local rainfall forecasts based on their expert analysis (Emerton et al., 2020). The Red Cross in Mozambique mentioned their use of the meteorological forecasts from INAM and hydrological bulletins from DNGRH for their early action plans for TC and floods. In addition to these local forecasts and observations, global hydrological sub-seasonal forecasts from CEMS-GloFAS are used by the Red Cross as complementary information.

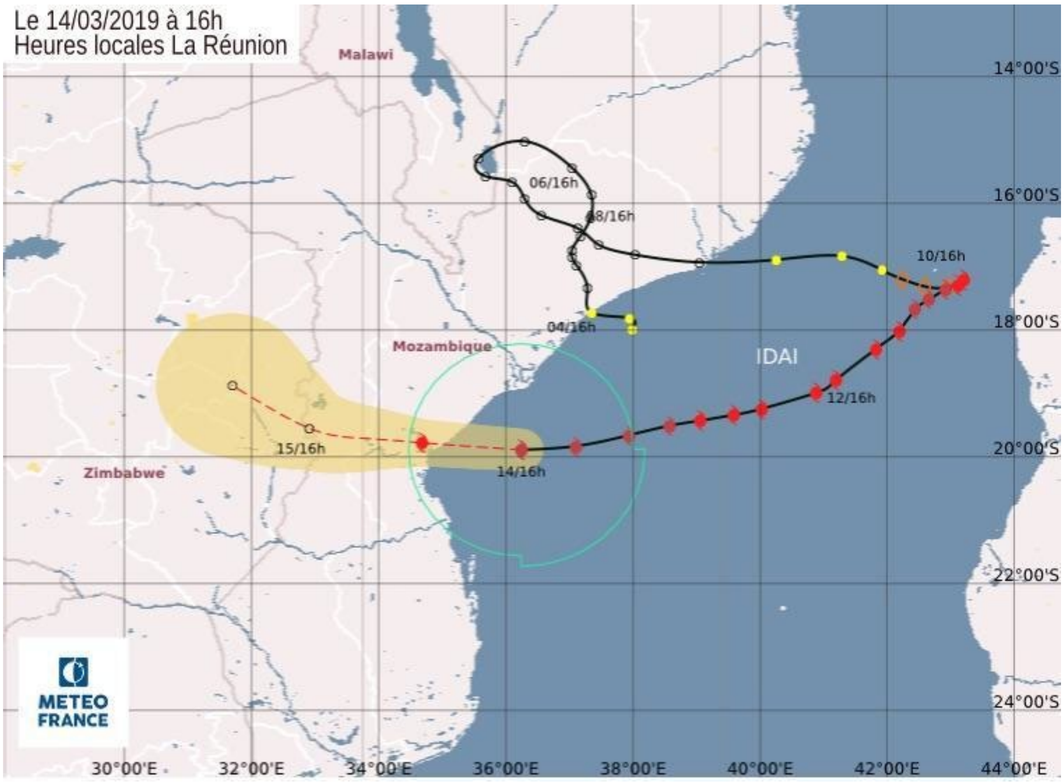


Figure 2.4. Example of the TC graphical warning issued by Meteo-France on 14 March 2019, one day before Cyclone Idai's landfall close to Beira, Mozambique (Source: Météo-France La Réunion).

<u>Characteristics of the Climate Services currently used</u>: The responses of the end-users to the survey suggest that the highest spatial and temporal resolutions of the services used so far by all users are 10 km and daily, with the lowest spatial resolutions being about 0.5°. At least three different prediction horizons (lead times) are important for the essential variables that seem mostly used in current climate services, i.e. precipitation, temperature, streamflow and wind. The top-three most

frequent combinations of variables and lead times used are (i) streamflow with a lead time of some days (all users look at this variable/horizon); (ii) precipitation with a lead time of some weeks (almost all users look at this variable/horizon); (iii) wind with a lead time of some days (almost all users). The ways the forecasts are used and their update frequency are summarised below:

- Quantitatively as input to an impact model (hydrology, energy, agriculture, etc.): at least once per month or once per season or once per year (depending on the user/objectives)
- Quantitatively as input to a decision support system: either at least once per season or at least once per year (depending on the user/objectives)
- Quantitatively to trigger emergency operations: either at least once per season or at least once per year (depending on the user/objectives)
- Qualitatively as additional knowledge to make decisions: either at least once per season or at least once per year (depending on the user/objectives)
- Visually (qualitatively) to see what the future situation might be: either at least once per week, or once per month or once per season (depending on the user/objectives)

2.1.3.2 User wishes and requirements for enhanced climate services

ZAMCOM has planned to further enhance ZAMWIS to include a Decision Support System (DSS). The DSS will allow further integration of flow forecasting and monitoring tools, multi-objective optimisation, multi-criteria decision analysis, environmental and socio-economic analysis and determination of environmental flows. For flood forecasting, the lack of near real-time information and control points downstream of Kariba is a current limitation of ZAMWIS for this application, but ZAMCOM wishes to improve this in collaboration with national institutions of Mozambique.

The following general wishes and requirements for enhanced services emerged from the survey (by single or multiple end-users):

- ZAMCOM mentioned that daily and monthly forecasts are needed to prepare and plan for disaster mitigation, flood and drought, respectively: more advanced forecasts and their integration into DSSs are needed.
- ZAMCOM also mentioned the need for the continuous availability of products for decision making with user-friendly characteristics/interfaces.
- Users from the Environmental Regulatory sector mentioned that historical data are “scanty and poorly stored” and sometimes difficult to access, thus denser networks and more accessible repositories in real-time are needed. Higher number of gauge stations with good quality instruments are needed to assess forecast skills.
- Multiple users mentioned the need for increased precision, quality and reliability of data and forecasts.
- The humanitarian users mentioned the need for better drought and flood triggers, taking into account vulnerability and exposure layers.
- Two users (humanitarian and river basin commission) mentioned the need for capacity building, equipment and software.

The ideal spatial resolution of climate services/hydrometeorological predictions indicated by the end-users who took the survey is about 10km. On the other hand, the ideal temporal resolution indicated by the users is more variable across sectors: while monthly data and forecasts could be sufficient for ZAMCOM and dam operators, a finer temporal resolution is needed by other users, with a weekly time step required in the environmental regulatory sector, and a daily (or sub-daily, in the case of impending extreme floods) required in the disaster management and humanitarian sectors.
The ideal lead time (prediction horizon) of climate services/hydrometeorological predictions varies among the end-users and extreme events: while 3 months/seasonal horizons are required by ZAMCOM and the Environmental Regulatory Agency, as well as by WFP for drought preparedness, shorter lead times (of 5-10 days) are sufficient for humanitarian organisations and actors involved in flood and cyclone preparedness and response (e.g. Red Cross). In current early-action protocols, 72 hours is sufficient for tropical cyclones, also given the current level of forecast accuracy.
The ideal update frequency of climate services/hydrometeorological predictions varies across sectors, with the highest frequency required by users of 3 to 6 hours (due to stability of forecasts and decisions) to daily.

The following improvements in CS and forecast information have been ranked as top-five priorities by the end-users in the survey, providing a score (for low to high interest) for eleven options (the list of all possible options is reported in Annex 1):

1. better drought predictions and better flood extent predictions (ex aequo);
2. better prediction of weather extremes;
3. better prediction of streamflows, e.g. inflows to dams;
4. higher spatial resolution of the forecasts;
5. better (more reliable / sharper) probabilistic seasonal forecasts.

Other less voted options that were still frequently indicated include producing more scenarios of hydrological predictions and weather/hydrological forecasts for longer lead times and higher temporal resolutions.

The responses of end-users to the survey question on what are the criteria to measure the success of (enhanced) Climate Services in supporting their operational activities highlighted that they require the highest accuracy and reliability of the hydrometeorological forecasts with respect to observations. In particular, the humanitarian organisations involved in both drought and flood preparedness require the best possible ratio between success (hit rates) and failures (false alarms and misses) of predictions.

2.1.4 Impact indicators for quantifying the value of AI-enhanced CS

Three key groups of impact indicators were identified following the exchanges reported above with all the ZW's end-users:

1. Hydropower production indicators to be maximised; their formulation will stem from the requirements and objectives of the dam operators and hydropower companies. Enhanced sub-seasonal and seasonal drought predictions will be used to improve dam management operations and optimise hydropower production.
2. Crop yield indicators to be maximised; their formulation will follow the requirements and objectives of irrigation schemes' operators and agricultural stakeholders in the basin. Enhanced sub-seasonal and seasonal hydrometeorological forecasts will be used to improve dam management operations and optimise food production.
3. Flood and Tropical Cyclones triggers' success indicators, expressed as maximisation of hit rates (or other forms of the critical success index of the warnings), and minimisation of false alarms; their formulation will follow the needs and current plans of the humanitarian organisations involved in flood early warning systems in the lower Zambezi (e.g. Red Cross and WFP in Mozambique). Enhanced sub-seasonal (and possibly, seasonal) flood and TC forecasts will be used to improve current EAP triggers.

2.2 Douro

2.2.1 General case study description

2.2.1.1 Catchment and hydroclimatology

The Douro River Basin is the largest river basin in the Iberia Peninsula (Figure 2.5). It stretches over 98,103 km^2 and is shared by Spain (80% of its territory) and Portugal (20%). The total river basin discharge amounts on average to 11,999 hm^3/year. From a water resources management perspective, the Spanish part of the Douro River Basin (from herein called "Douro river basin district" or "Douro RBD") is divided into 13 water exploitation systems. CLINT will focus on the Orbigo exploitation system, which is located in the northwest part of the Douro RBD (Figure 2.5), covers approximately 4986 km^2, and encompasses the Orbigo river basin, being Orbigo being a right tributary of the Douro river (DRBA, 2021).

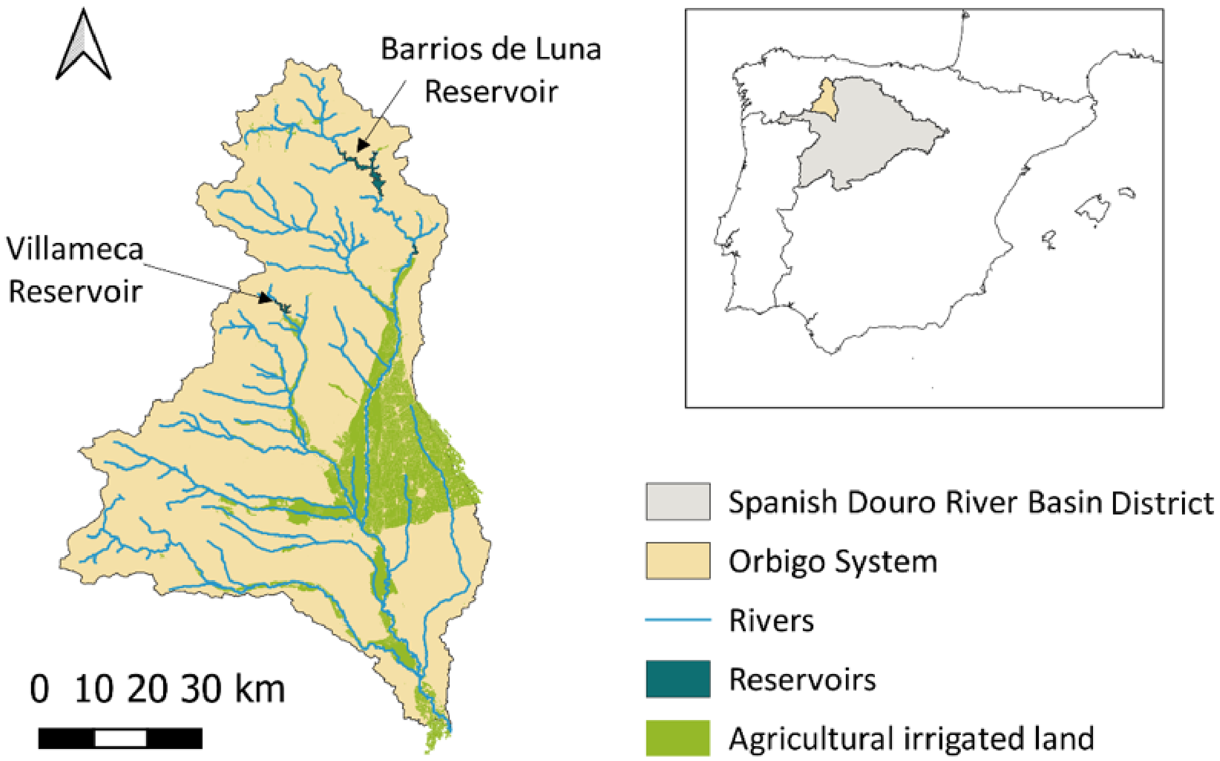


Figure 2.5. Orbigo exploitation system

The mean annual rainfall of the sub-catchment is about 680 mm/year and most of the precipitation occurs between October and May. Average actual evapotranspiration, which accounts for 417 mm/year, is unevenly distributed throughout the year and reaches its peak in May. These climatological features derive in a marked seasonality in the natural flow regimes, which are characterised by high flows during January, February, and March due to winter rainfall and snowmelt, and low flows during summer. The mean annual discharge of the Orbigo River is 290 mm/year (1,260 hm^3) (Figure 2.6) (DRBA, 2021).

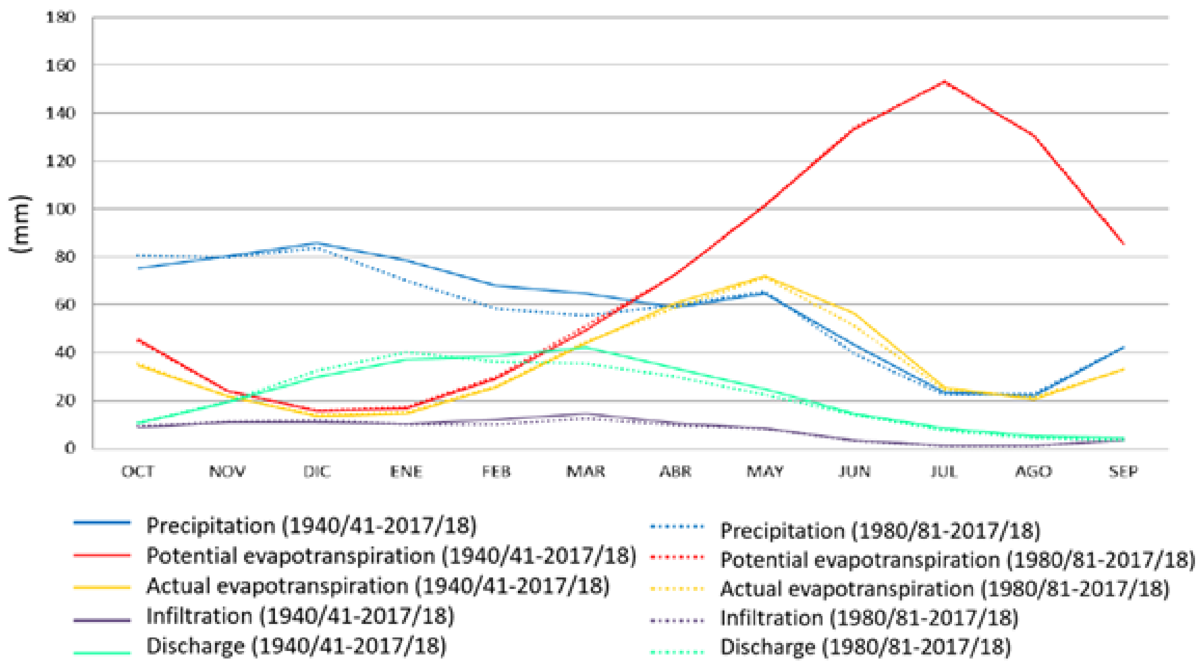


Figure 2.6. Mean monthly evolution of the main hydroclimatological variables in the Orbigo system for two reference periods (1940/41-2017/18 and 1980/81-2017/18) (DRBA, 2021)

The Orbigo system is an agrarian area with prevailing intensively irrigated agriculture where the major cultivated crop is maize. Mean annual water demand for irrigation accounts for 370 hm^3/year, which represents 90% of the total water demand in the system. Other water uses within the Orbigo system are: domestic (16.97 hm^3/year), cattle industry (5.64 hm^3), industrial (2 hm^3/year), recreational (0.7 hm^3/year), and others (21.96 hm^3/year) (DRBA, 2021).

Water demands are mostly satisfied with surface water resources regulated by reservoirs. The main reservoir in the region is Barrios de Luna, located in the Luna River at the headwaters of the system (Figure 2.5). With a storage capacity of 308 hm^3, it represents 90% of the total storage capacity in the system. Barrios de Luna reservoir supplies water for half of the population of Leon city and other small communities and industrial areas, and the irrigation of more than 50,000 ha (73% of the total irrigated area in the system). Besides, the reservoir discharge should meet the environmental flow requirements aimed at protecting aquatic ecosystems, which account for 23.6 hm^3/year. There are also other non-consumptive uses, namely hydropower generation, flood control, and recreation. It is a within-year reservoir that reaches low levels every year after the irrigation campaign at the end of summer (DRBA, 2021). During wintertime, the operation of the reservoir must guarantee flood control while aiming at maximising water storage to satisfy irrigation water demands in spring and summer. Additionally, there is the Villameca reservoir, which has a capacity of 20 hm^3. It contributes to the satisfaction of domestic water (Astorga town among others), irrigation and environmental water needs.

Under normal conditions, the reservoir is at the maximum levels at the beginning of the irrigation campaign and usually able to provide water for the multiple annual water needs. However, as the maximum water storage is similar to the amount of annual water demands when there is a drought, and the reservoir volume does not reach maximum levels, water shortages occur, affecting mainly irrigation demands and making the system vulnerable to drought events. Difficulties to meet the irrigation water demand occur during droughts and dry spells. Tensions arise among users and decision-makers. Besides, there are other effects during dry spells, namely the reduction of minimum environmental flows and temporary tolerance of aquatic ecosystems degradation.

These tensions are likely to increase, as Climate Change is expected to intensify drought characteristics in the Douro RBD. More specifically, the 2- and 5-years duration droughts are projected to occur more frequently, both for RCP 4.5 and RCP8.5 (CEDEX, 2017). Additionally, water resources availability in the Orbigo System for the 2039 horizon is expected to decline by 7%, from 1,263 hm^3/yr to 1,174 hm3/yr (CEDEX 2020).

2.2.1.2 Users

- Douro River Basin Authority (Douro RBA)**:** it is the main administrative body responsible for water management. Within this institution, the Hydrological Planning Office and the Technical Office were interviewed for CLINT. The Hydrological Planning Office is in charge of developing 6-year River Basin Management Plans, in accordance with the National Article 39.2 of the Water Law. They ensure and report on the compatibility of the actions proposed by the users with the Hydrological Plan of the basin and elaborate the Drought Management Plan. The Technical Office is responsible for carrying out the studies, projects, direction and exploitation of water infrastructure, including dams.
- AEMET**:** it is the Spanish National Meteorological Agency, which is in charge of the provision of climatological, weather and seasonal forecast information.
- Barrios de Luna Reservoir Union: it is an organisation that gathers all the water user associations using water released from Barrios de Luna Reservoir. It is in charge of monitoring water use among water user associations and the irrigation system. It also acts as a liaison between the Douro RBA and the water user associations and farmers.

2.2.1.3 Extreme events

Droughts are one of the most recurrent and high-impact extreme events affecting the region, and it is predicted an increase in their frequency due to Climate Change as the 21^{st} century progresses. AI-enhanced S2S and seasonal forecast provided by CLINT will allow exploring other approaches to manage water resources and Barrios de Luna reservoir in Orbigo system, contributing to optimizing the water allocation process and the drought indicator system while maintaining the security level of the current drought risk management system. Overall, CLINT will contribute to improved drought both in the short and long-term.

2.2.2 Detailed use-case description

2.2.2.1 User-definition of extreme events

The Douro RBA defines droughts as an unpredictable natural event that is mainly caused by a lack of precipitation, resulting in a significant temporary descent of available water resources. They understand droughts as part of the normal climatic variability, and, therefore, one of the hydroclimatological characteristics of a region that shapes its ecosystems and habitats.

From a more practical point of view, the Douro RBA distinguishes between two types of droughts: prolonged drought and temporary water scarcity. While the prolonged drought is related to hydroclimatic variables, temporal scarcity is associated with a temporary unbalance between water resources availability and socioeconomic water demands (operational drought).
Based on this distinction, and for management purposes, Douro RBA establishes two types of indicator systems:

- Prolonged Drought Indicator System**.** Its aim is the identification of hydro climatological droughts, regardless of the type of water resources management. It combines the following variables: (i) last 6-month cumulative reservoir inflows; (ii) last 6-month cumulative discharge in gauge stations in natural flow regime; (iii) last 9-month cumulative in selected rainmeters. A single threshold is defined to determine the occurrence of prolonged drought. These variables are rescaled and aggregated in a weighted way, producing a single indicator (or index), which ranges from 0 to 1. Prolonged droughts occur when the indicator reaches values below 0.3 (Figure 2.7).

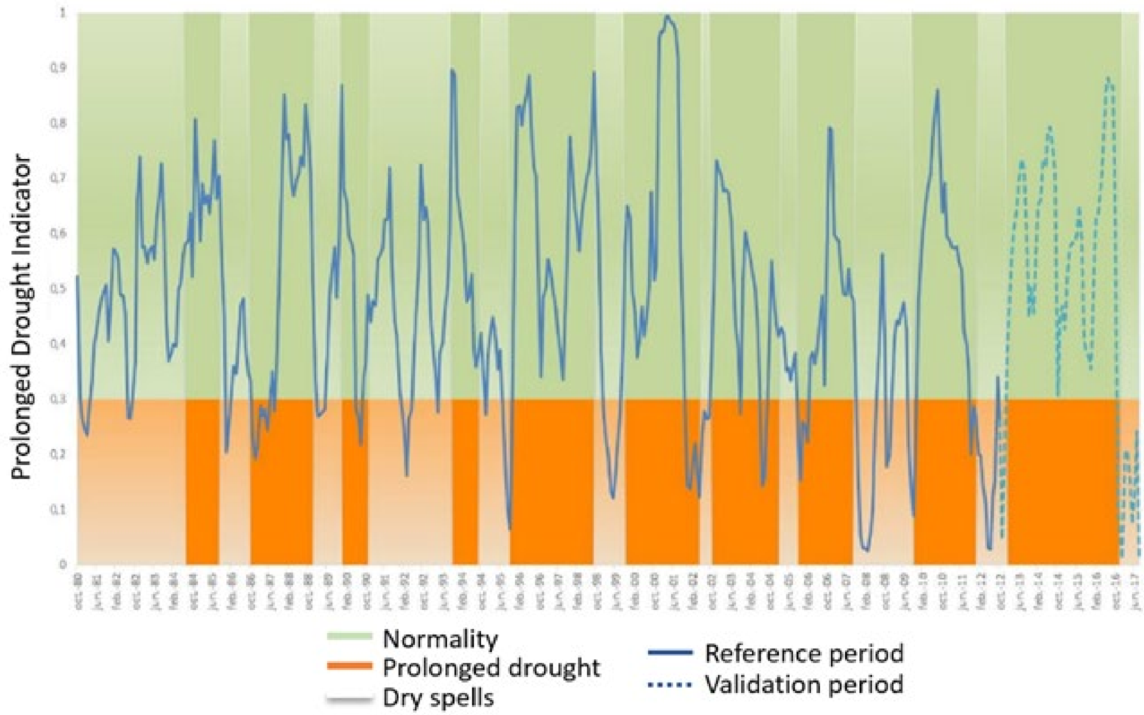


Figure 2.7. Prolonged drought indicator evolution in Orbigo system (1980-2016) (DRBA, 2018). Prolonged drought occurs when the index is lower than 0.3 (orange zone), while normality happens when the index is above 0.3 (green zone).

- Scarcity Indicator System. It aims at reflecting a temporary problem in meeting water demands, not caused necessarily by hydroclimatological droughts. It considers only the reservoir water storage. Three thresholds are defined for the scarcity indicator, corresponding to different limits of water scarcity stages (pre-alert, alert, and emergency). These variables are rescaled and aggregated in a weighted way, producing a single indicator (or index) (Figure 2.8).

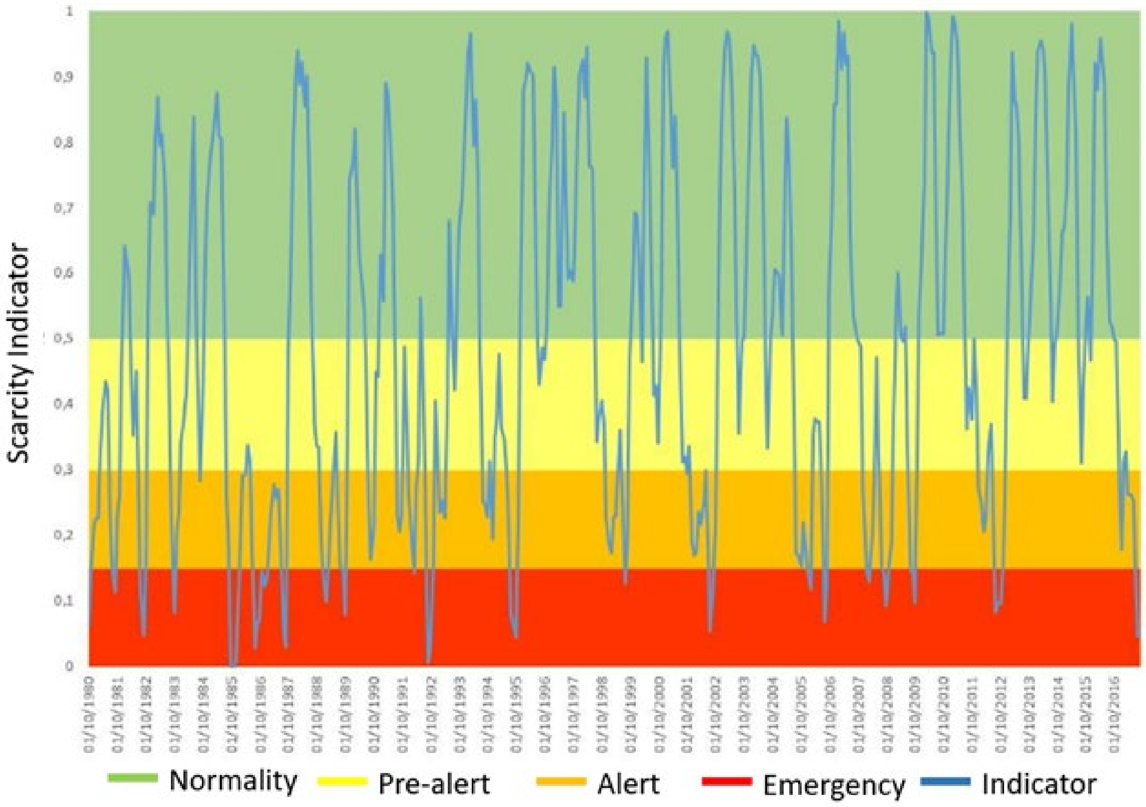


Figure 2.8. Scarcity indicator evolution in Orbigo system (1980-2016) (DRBA, 2018)

2.2.2.2 Local impact of extreme events

Drought-related impacts are formally documented in the post-drought reports that Douro RBA issues after drought episodes. Impacts are categorised as environmental and socioeconomic impacts. Most environmental drought impacts reported in the post-drought reports are related to water quality. The significant streamflow reduction due to drought causes an increase in pollutant concentrations in water, as the water dilution capacity decreases. Changes in water quality and quantity have an impact on biodiversity. Even though Iberian species are naturally adapted to droughts and dry spells, fish mortality is also reported during these events. For instance, during the drought in 2004 and 2005, hundreds of dead fish were found. Droughts are also related to a decline in bird breeding. Finally, from the scarcity of data related to water quality during drought periods, it can be inferred that regular measurements for the monitoring of water quality during droughts are less intensive (DRBA, 2018).

Regarding socioeconomic impacts, rainfed and irrigated agriculture is the most affected socioeconomic sector. In the Orbigo system, the area with rainfed agriculture is small compared to the one with irrigated agriculture, and thus the highest impacts are registered for irrigated agriculture. Some of the measures that are implemented to manage water scarcity associated with drought are water curtailments and irrigation shifts. For instance, the 2017 drought damaged rainfed crops and resulted in a decline in the cultivation of irrigated crops. Consequently, 70% of the cereal crop yield was lost. Besides agriculture, other sectors are also impacted. Hydropower generation declines during droughts; for instance, during the drought of 2004 and 2005, the hydropower generation of hydroelectricity halved the one of the previous five years. From the farmer's point of view, meteorological droughts in winter lead to higher water demands at the very beginning of the irrigation season, as the soil moisture is not enough for germination. Some other social impacts of droughts reported in the Orbigo system are tensions between farmers and Barrios de Luna Reservoir Union and Douro RBA on reservoir levels, as farmers put pressure to decrease reservoir levels extraordinarily to satisfy irrigation water demands. For instance, during the drought in 1998/99, Barrios de Luna reservoir minimum level extraordinarily decreased from 50 to 30 hm^3 (DRBA, 2018).

Social tensions can arise during droughts, as farmers that have water-saving technologies are sometimes exempt from water curtailments or irrigation shifts. Finally, there are also recreation and aesthetic impacts derived from measures such as the prohibition of private swimming pool filling and green areas irrigation (DRBA, 2018).

2.2.2.3 Decision process for preparedness, adaptation, and event or risk management

The Douro RBD has a Drought Management Plan (last release in 2018) that aims at ensuring domestic water demand, avoiding degradation of aquatic ecosystems, and minimising socioeconomic (negative) impacts of droughts. It describes the development and application of the two aforementioned drought indicator systems in the Douro RBD.

<u>Scenario of prolonged droughts</u>

When the threshold of prolonged drought is crossed, temporary degradation of the ecological status of water bodies is tolerated and minimum environmental flows can be decreased (referred to as drought environmental flows).

<u>Scenarios of water scarcity</u>

Different actions related to water demand, water offer, administrative organisation, and environment derive from the three different scenarios of drought intensity level.

- <u>Pre-alert:</u> general awareness measures. Communication of the situation to ensure preparedness, encouragement for voluntary water-saving among the society, attention to aquatic ecosystems and their protection, and maintaining drought monitoring.
- <u>Alert:</u> concerning water demand: (i) non-essential domestic water uses may be partially limited (e.g. irrigation of parks and gardens and use of swimming pools); (ii) implementation of up to 50% of agricultural irrigation water curtailments. Concerning water offer: (i) activation of the emergency plan for domestic water supply; (ii) activation of the emergency plan for extraordinary water transfers within and among exploitation systems. Concerning the administrative organisation of water management: (i) Preparation for the approval of a Drought Decree, in case extraordinary measures need to be implemented; (ii) Setting up of

the Permanent Drought Committee; (iii) more stringent fines for illegal wastewater discharges are applied; (iv) monthly meetings for reservoir operations; (v) general reinforcement of cooperation and coordination among users and institutions. Concerning the environment: (i) implementation of a control programme to identify environmental impacts.

- Emergency: concerning water demand: (i) essential domestic water use may be partially limited, and non-essential domestic water uses are prohibited; (ii) implementation of up to 100% of agricultural irrigation water curtailments. Concerning water offer: (i) potential extraordinary water transfers within and among exploitation systems. Concerning the administrative organisation: (i) intensification of all the measures activated in the Alert scenario; (ii) Approval of a Drought Decree to allow for extraordinary measures. Concerning the environment: (i) intensification of the measures activated in the Alert scenario.

In addition to these two types of scenarios, a scenario of "extraordinary drought" is declared in two circumstances. First, if a prolonged drought and a scarcity emergency scenario overlap in time. Secondly, when there is an emergency scarcity scenario. The declaration of extraordinary drought allows the RBA to implement extra measures that are not included in the Drought Management Plan.

2.2.2.4 User-inspired (early) indicators of extreme events for input to WPs 3-5

All users mentioned that snow melt is a variable at which they look to foresee water availability in the upcoming irrigation season, but it is not formally integrated into their decision support system nor in their drought indicator systems. Therefore, discharge forecast due to the expected snow melt evolution is an early indicator of drought that users currently use but do not quantify

2.2.3 Existing climate services and the need for enhancement

2.2.3.1 Climate services currently used

Agricultural water users and the River Basin Authority in the Orbigo system do not use any specific Climate Service to support decision-making.

Agricultural water users use weather forecasts, with up to 48 hours lead time, as climate information mainly for reservoir operation. During the irrigation campaign, agricultural water users and reservoir operators (Douro RBA) consult daily rainfall weather forecasts provided by AEMET to avoid dam water releases for irrigation if rain is expected. During the winter, the reservoir operators receive reports every other day from the numeric prediction model HARMONIE-AROME managed by AEMET with information about the next 48 hours of snowpack evolution, which supports flood control.

On the national level, there exists a Climate Service for reservoir management called S-ClimWare (Sánchez-García et al., 2022), which is provided by AEMET and offers seasonal forecasts for temperature rainfall, accumulated snowfall, and water reservoir inflow. This CS provides information for a list of reservoirs, including Barrios de Luna Reservoir, through an open-access website. Additionally, AEMET and Directorate General for Water from the Ministry for Ecological

Transition and Demographic Challenge (MITECO) organise once a year (in autumn) a workshop where information about the seasonal forecast is provided to the Spanish RBAs, including the Douro RBA. Among other types of information, data about the predicted dry or wet nature of the winter and spring seasons is transmitted. Interviewed stakeholders from the Douro RBA referred to be aware of this information but declared that they do not use it.

2.2.3.2 User wishes and requirements for enhanced climate services

Agricultural water users and the RBA expressed interest in using short-range, AI-enhanced S2S and seasonal forecast information, especially during drought. Table 1 shows forecast characteristics in the wished Climate Services according to the users' needs identified in the first round of interviews.

Table 1. User wishes and requirements for forecast and projections characteristics of the AI-enhanced CS

Required by	Type	Time horizon	Impact variables	Spatial res	Temporal res
Reservoir operators (Douro RBA), Barrios de Luna Reservoir Union	Forecast	1-10 days	Reservoir inflow	0.1°	Hourly
Hydrological Planning Office (Douro RBA), Technical Office (Douro RBA), Barrios de Luna Reservoir Union	Forecast	S2S	Temperature, potential evapotranspiration, rainfall, reservoir inflow	0.1°	Daily
Hydrological Planning Office (Douro RBA), Technical Office (Douro RBA), Barrios de Luna Reservoir Union	Forecast	seasonal		0.1°	Daily
Hydrological Planning Office (Douro RBA)	Projection	2100	Frequency, duration and intensity of droughts. Impacts on water resources availability	0.1°	NA

Other requirements and criteria for the successful use of the AI-enhanced CS are:

- The AI-enhanced information provided by the Climate Services developed by CLINT should be made available for decision-making on a continuous basis (sporadic or irregular information cannot be integrated into the decision-making process).
- The AI-enhanced forecast should be integrated into their local decision-support systems and transformed into variables that are easily interpreted, such as reservoir inflows. This way, it can complement the information based on the climatology that is currently being used to support decisions.
- It is important to combine different types of forecast time horizons, such as from weather forecast (early warning) to S2S and seasonal.

- Forecast probabilities should be higher than 60% to be suitable to support decision making.

2.2.4 Impact indicators for quantifying the value of AI-enhanced CS

Impact indicators will be developed based on the current official drought indicator system. The drought anticipation capacity will be used to quantify the value of the drought indicator system after integrating the AI-enhanced forecast provided by CLINT. In addition, other variables (and indicators) related to the consequences of integrating forecasts in the drought indicator system will also be used. For instance, potential impact indicators may be avoidance of unnecessary water curtailments during the irrigation campaign, avoidance of the unnecessary implementation of reduced drought environmental flows, etc.

3 Delta climate change hotspots

3.1 Rijnland

3.1.1 General case study description

3.1.1.1 Catchment and hydroclimatology

The local case study of Rijnland is a small sub-catchment of 1000 km^2 at the very end of the Rhine delta in the Netherlands (Figure 3.1). Due to a history of peat excavations, land reclamation, and continuous soil subsidence, the area lies 72% below sea level, and it has become a highly controlled drainage and irrigation system from which excess water is discharged by means of pumping stations to the adjacent river Rhine, main shipping canals, or directly to the North Sea. In case of water demand, freshwater is taken in from a small tributary of the Rhine at the city of Gouda. At its western boundary with the North Sea, Rijnland has a strip of land above sea level because of the dunes, from which the water is freely drained and discharged through gravitational flow (controlled with weirs) to the collector canal system of the drainage and irrigation area (main drainage canal).

The land use consists mostly of agricultural crops, including high-cash crops of flower bulbs and grassland for dairy farming, and at the same time, the area is highly urbanised with historic cities and important economic infrastructure, such as Amsterdam's Schiphol international airport. The area has 1.3 million inhabitants.

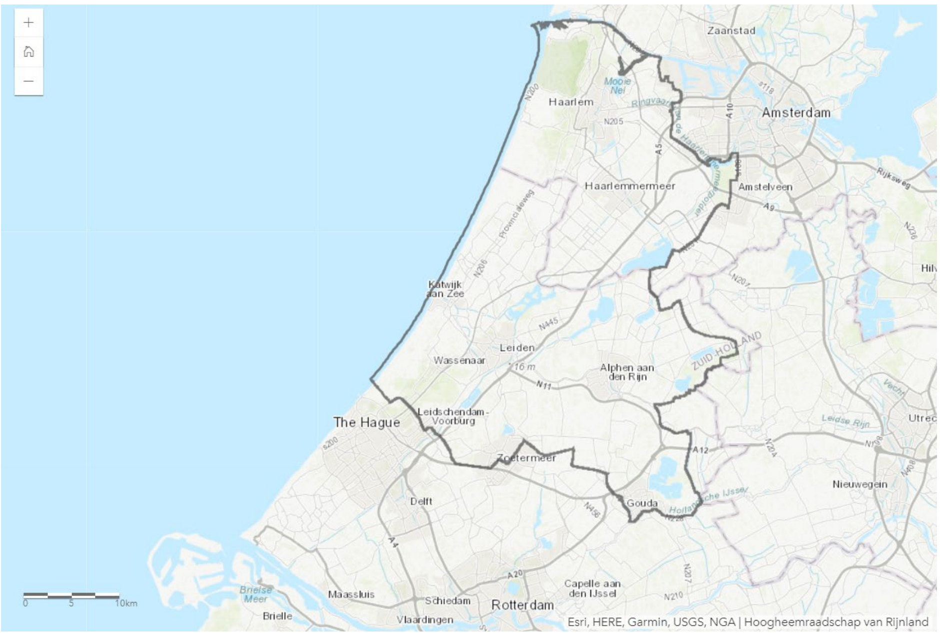


Figure 3.1 Command area of the Rijnland water board, the Netherlands. The outline indicates the water system boundary (Source: Rijnland, 2022).

Rijnland's climate is Temperate-Oceanic (Köppen classification: Cfb), with rain throughout the year with an average amount of 842 mm (Schiphol station). Temperature is much lower in winter (December-February) than in summer (June-August), such that evapotranspiration is pronounced seasonal and exceeds rainfall in summer (see Figure 3.2), with a yearly average of 602 mm (Makkink reference evapotranspiration).

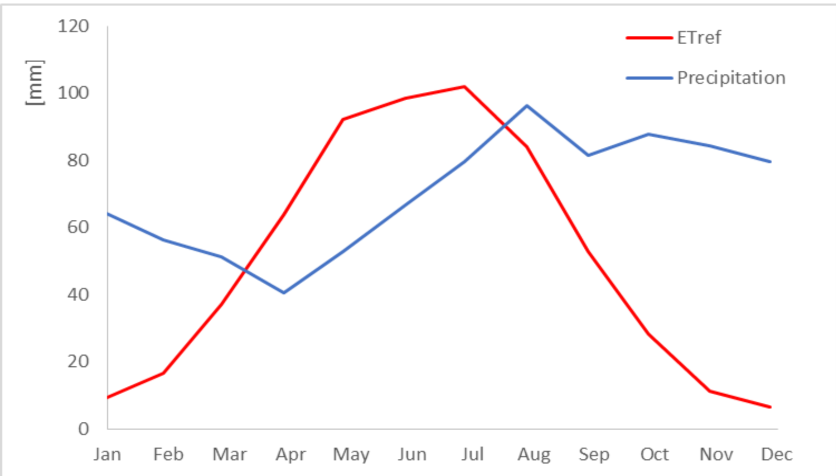


Figure 3.2 Average monthly precipitation and potential Makkink reference evapotranspiration, Schiphol station, 1989-2021, the Netherlands (Source data: KNMI, 2022).

3.1.1.2 Users

The Rijnland water system is managed by the Rijnland Water Board. The water board is responsible for surface water quantity and quality, including operation of wastewater treatment plants, maintenance of embankments and regulating structures (e.g. pumping stations, weirs, and inlets), and operational management and real-time control of the interconnected system of discharge canals that together serve as a reservoir, both for storing and conveying excess rainfall-runoff from the catchment and for irrigation supply to agricultural lands. The same storage basin with interconnected canals and lakes is also used for commercial and recreational shipping. The water board is responsible for the operation of the Spaarndam shipping sluice.

As water authority, the water board's actions interrelate with many stakeholders in the area, including the agricultural sector, nature conservation, (water) tourism, (water) transport, industry (flood control, cooling water, wastewater management, permitting), and individual citizens. For its operational water management, the water board relies on the provision of meteorological forecasts and extreme event alerts from the national meteorological service of the Netherlands, the KNMI, and commercial weather forecast provider DTN, and on the provision of storm surge, stage, and streamflow predictions at its boundary water systems from the national hydrological service of the Netherlands, Rijkswaterstaat. In its operational water management task, the water board works together with municipalities that operate the sewer systems and with neighbouring water boards and Rijkswaterstaat for coordinated operation of the surface water systems, e.g. during droughts (Rijkswaterstaat, 2021a; Rijkswaterstaat, 2021b).

The Rijnland Water Board is the CLINT user organisation for this case study. Through multiple online meetings, the water board expert representatives have elaborated on the challenges of the water board during droughts and how the water board manages drought events. The findings of these meetings and from supporting documentation received are elaborated in the sections below.

3.1.1.3 Extreme events

The Rijnland area suffers from both floods and droughts. The CLINT project focuses on drought events.

3.1.2 Detailed use-case description

3.1.2.1 User-definition of extreme events

The water board of Rijnland adopts a specific threshold-based user definition of drought. Threshold values vary with time of the season and for increasing alert level.
Rijnland is considering a drought to be present if both of the following thresholds are crossed:

- Net precipitation deficit in the Rijnland area (Precipitation - potential Makkink reference evapotranspiration): >125 mm deficit (first alert level)
- Low discharge threshold at Lobith, where the Rhine enters the Netherlands: <1000 m^3/s from September to April (varying in summer months up to <1400 m^3/s for May)

3.1.2.2 Local impact of extreme events

In Rijnland, prolonged dry spells in combination with low flows of the river Rhine lead to a shortage of fresh surface water to counter salinity problems and potential dike instability along the storage basin (leading to floods). Extensive manual dike inspections then may need to be planned, and the intake of surface water via alternative supply routes may need to be organised in coordination with neighbouring water authorities (Rijkswaterstaat, 2021b).

3.1.2.3 Decision process for preparedness, adaptation, and event or risk management

In case of drought, Rijnland follows a detailed operational handbook (Rijnland, 2019), which includes guidelines for:

- Increase of alert level
- Inspection of embankments
- Alternative fresh surface water inlet

At low discharge of the Rhine, salt intrusion from the North Sea causes salinity at the intake point at Gouda to become too high to use. To counter salinity problems in the Rijnland surface water, alternative surface water from the eastern neighbouring water board can be let in. This is called KWA (Dutch abbreviation for small-scale water supply, Rijkswaterstaat, 2017). This alternative freshwater supply enters Rijnland in Bodegraven and is partly discharged further to southern boundary waterboard Delfland if they are also in a drought situation (Figure 3.3). The water board operates targeting spatially distributed salinity levels.

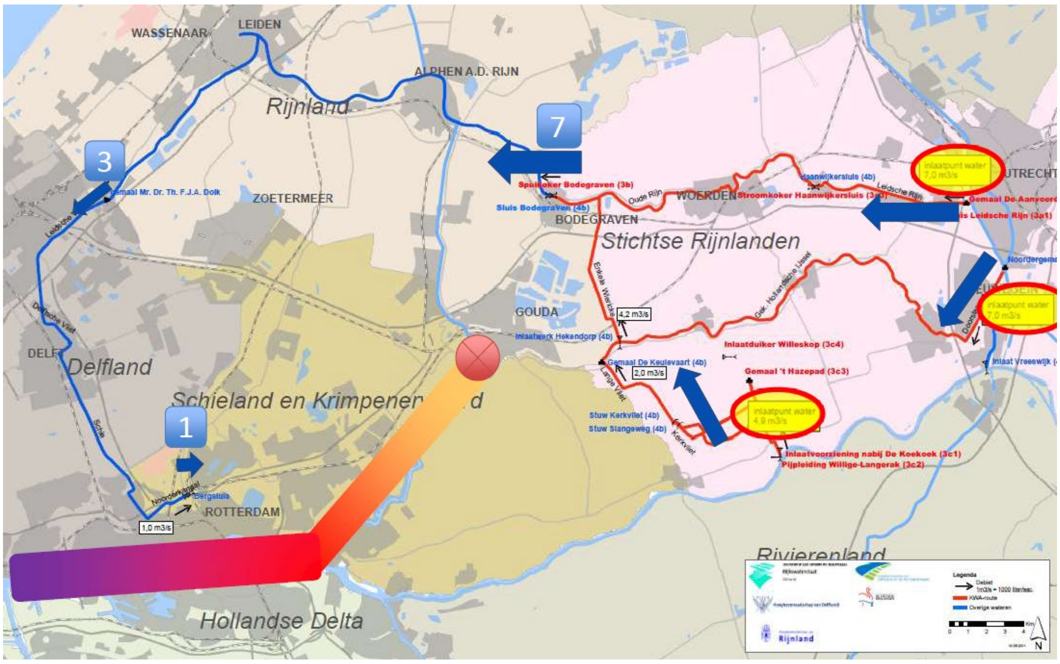


Figure 3.3. Additional freshwater supply from the east entering Rijnland in Bodegraven, and partly being discharged further to southern boundary water board Delfland. Values represent discharge in m3/s. The purple to red bar indicates salt intrusion from the North Sea during low flows of the Rhine, such that the regular inlet of Gouda cannot be used. (Source: Van der Zwan, 2022).

3.1.2.4 User-inspired (early) indicators of extreme events for input to WPs 3-5

Drought indicators identified by the Rijnland users include next to low-discharge criterium for hydrological drought, the running precipitation deficit or excess evaporation (precipitation - evaporation), which is a request to WPs3-5 to include. A third indicator concerns salinity levels of the surface water, which is considered to remain a locally determined state, such that it is not directly relevant for WPs 3-5. However, it may be used to refine the list of historic droughts in the Rijnland case study, which may be used as targets for AI-enhanced detection.

3.1.3 Existing climate services and the need for enhancement

3.1.3.1 Climate services currently used

Rijnland's drought event management operates on the basis of monthly to weekly drought monitor reports. The drought report includes climatological, present-state observations, and forecasts up to two weeks in advance. Present-state observations concern precipitation, reference evaporation, discharge of the river Rhine, and salinity, over the running summer half year starting from April (e.g. establishing the trend and developing sums over the past months as the season progresses, Figure 3.4).

Forecasts are based on the ECMWF 2-week ensemble predictions of precipitation and temperature, and 2-week discharge predictions of the river Rhine at location Lobith, where the Rhine enters the Netherlands. In addition, meteorological observations at selected locations upstream in the Rhine basin are taken into account.

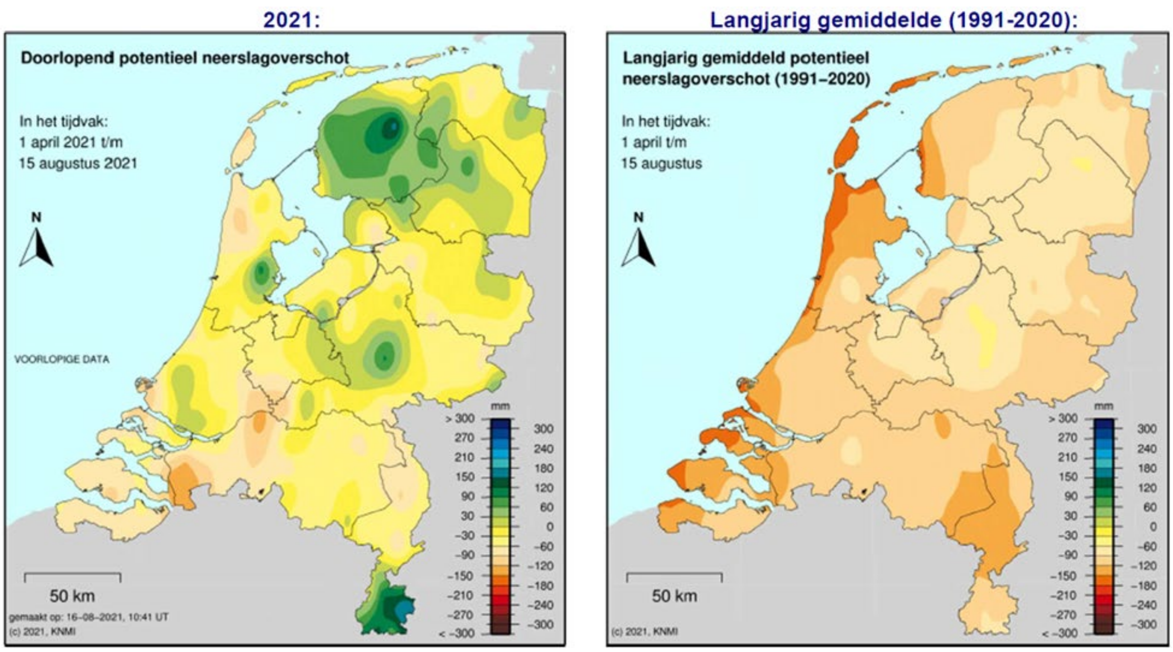


Figure 3.4. Running difference between observed precipitation and potential Makkink reference evapotranspiration from 1 April to 15 August 2021 on the left, as compared to the 30-year average (1991-2020) over the same period. Negative values indicate potentially more evapotranspiration than precipitation. It can be seen that in 2021 this precipitation deficit was less than normal, such that no drought alerts were indicated (Source: KNMI as presented in Rijnland, 2021).

In 2021, for the first time, Standardised Precipitation Index (SPI) maps were included in the Rijnland drought monitor system. These maps are produced by the Royal Netherlands Meteorological Institute (KNMI), and they concern the 1-month SPI over the past month. Combined with the 2-week ECMWF meteorological forecasts, an SPI ensemble prediction is provided for the coming 2-weeks (Figure 3.5).

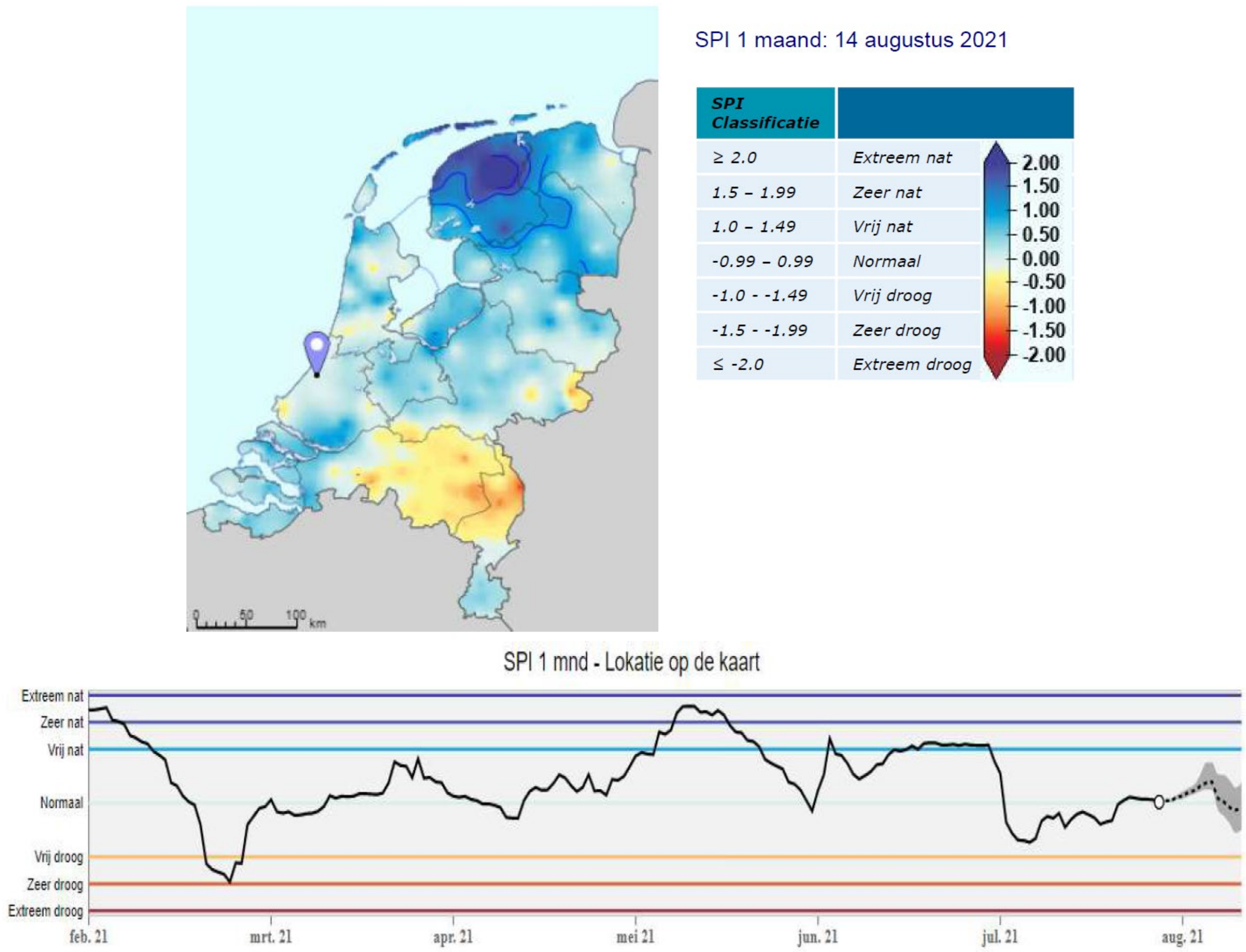


Figure 3.5. SPI-1 month map of the Netherlands of 14 August 2021 (top), with extracted SPI time series (bottom) for the location of interest for Rijnland as indicated on the map. The legend, in Dutch, refers to standard SPI classification differentiating extreme, very, and moderately dry conditions (red to yellow). (Source: KNMI as presented in Rijnland, 2021)

3.1.3.2 User wishes and requirements for enhanced climate services

The Rijnland water board would like to explore if it is possible to extend its forecast horizon for droughts from 2-weeks to a month. This would increase the drought preparedness of the water board, enabling it to more effectively plan its dike inspections and alternative freshwater supply in consultation with regional and local stakeholders.

3.1.4 Impact indicators for quantifying the value of AI-enhanced CS

The impact indicator for the Rijnland case study is drought preparedness. With the AI-enhanced CS of CLINT, the aim is to be able to provide earlier alerts for droughts. With this increased lead time, the Rijnland water board can increase its alert level earlier, plan better for dike inspections and additional freshwater supply, thus enhancing its drought preparedness. The quantification of this impact will, therefore, have as key variable pre-alert time. Starting from the present alert levels on the basis of a maximum 2-week outlook, CLINT will analyse first until what forecast horizon, the presently available sub-seasonal predictions have drought forecast skill for Rijnland, and what is the forecast skill for 1, 2, 3, and 4-week horizons.

To establish this benchmark of presently available forecasts, the following products and variables will be evaluated: E-HYPE sub-seasonal hydrometeorological service (precipitation, evaporation, soil moisture, discharge); ECMWF ER (Extended Range) forecasts (precipitation, evaporation).

The CLINT AI-enhanced predictions for Rijnland droughts will subsequently be assessed on forecast skill against lead time, in the same way: maximum lead time of positive skill, and forecast skill from 1 to 4 weeks.

3.2 Aa en Maas

3.2.1 General case study description

3.2.1.1 Catchment and hydroclimatology

This local case study focuses on a sub-catchment of the river Meuse, which is part of the Dutch Rhine-Meuse delta. This sub-catchment covers the river Aa and its tributaries and has a size of approximately 1600 km^2. The area has 745.000 inhabitants, which are distributed along larger cities and smaller hamlets. The climate of the sub-catchment is temperate oceanic and experiences precipitation throughout the year with an average amount of 767 mm (KNMI station at Volkel). Temperatures typically vary between 3.3 C° in January and 18.3 C° in July. Therefore, evapotranspiration is strongly seasonal and generally exceeds rainfall rates in summer periods. Climate change projections show that extreme events will become more pronounced in the area, leading to both drier periods and to more extreme precipitation events.

The subsurface of the catchment mainly consists of unconsolidated Pleistocene sandy and fluvial gravel sediments. Remnants of peat and fine sands can be found in the southern parts of the catchment. The continuous addition of straw-mixed cattle droppings resulted in an approximately 1 m thick layer of brown earth with high organic matter content (plaggen soils) in some parts of the catchments. The land use consists mostly of agricultural fields used for animal and crop farming. Farmers irrigate from deep groundwater reservoirs during dry periods. The regional water authority operates a system of weirs and pumping stations to minimise situations of drought and excess water. In addition, the water authority continuously uses surface water in the southern part of the catchment to increase groundwater recharge.

3.2.1.2 Users

The sub-catchment is managed by the regional water authority Aa en Maas, which is the CLINT user organisation for this case study. Figure 3.6 shows the location of the management area in the Netherlands. This authority is responsible for surface water quantity and quality. Their daily operations consist of operational management and real-time control of the surface water system, operation of wastewater treatment plants and the maintenance of embankments. They use various information sources for their operational water management. Examples are up-to-date measurements of various hydrological variables and meteorological forecasts in combination with hydrological models. The water authority cooperates with several stakeholders in the area, such as the agricultural sector, nature conservation, transport, industry, and citizens. In addition, the regional water authority cooperates with the national water authority Rijkswaterstaat to align the management of the regional water system and the management of the river Meuse.

Figure 3.6: Location of the management area of regional water authority Aa en Maas in the Netherlands (indicated by the green shape).

3.2.1.3 Extreme events

Groundwater levels drop significantly during dry summers in the sandy soils of the Dutch delta. The management area of regional water authority Aa en Maas also experiences these negative effects of drought events. The drop in groundwater levels affects the supply of water in two ways: (1) reduced availability of crop water availability and (2) reduced availability of groundwater available for irrigation. CLINT project will, therefore, focus on drought events.

3.2.2 Detailed use-case description

3.2.2.1 User-definition of extreme events

Regional water authority Aa en Maas mainly assesses drought using two variables:

- Thresholds for groundwater levels (location-specific);
- Low discharge threshold in the river Meuse and other local surface waters (location-specific).

3.2.2.2 Local impact of extreme events

Meteorological drought leads to shortages in both the surface water and groundwater systems. Both systems are used by the agricultural, drinking water and industry sectors for abstractions. Water shortages thus lead to decreased productivity and potential financial losses for these functions. Also, nature conservation areas are impacted by water shortages, as droughts are potentially devastating for their ecosystems.

3.2.2.3 Decision process for preparedness, adaptation, and event or risk management

During droughts, the water authority is monitoring its management area. Among others, the thresholds as discussed in Section 3.2.2.1 are used to decide whether restrictions should be imposed on water abstractions for irrigation. Both surface water and groundwater are used for these abstractions. The water authority is also managing a system of weirs to optimally locate surface water in the management area. They also have the possibility to pump water from the river Meuse in their surface water system. On a more strategic level, regional water authority Aa en Maas signed a groundwater covenant in 2021 together with neighbouring water authorities. This covenant forms the basis for more intensive cooperation for drought impact mitigation.

3.2.2.4 User-inspired (early) indicators of extreme events for input to WPs 3-5

The water authority is especially interested in indicators focusing on the water availability for the various functions. Specifically, we can make a distinction between indicators for the availability of surface water (e.g. discharge) and soil water (e.g. soil moisture, groundwater levels).

3.2.3 Existing climate services and the need for enhancement

3.2.3.1 Climate services currently used

Water authority Aa en Maas now uses a combination of meteorological forecasts (up to 2 weeks ahead) and observations of various hydrological variables. The observations include discharge data from the river Meuse and other local surface watercourses and groundwater level measurements which are spread over the entire management area.

3.2.3.2 User wishes and requirements for enhanced climate services

The regional water authority Aa en Maas would like to investigate the effectiveness of ECMWF Extended Range forecasts, more specifically with 46-day lead times. They have two specific questions:

1. Which information do seasonal forecasts of various hydrological variables such as precipitation, evapotranspiration, soil moisture and groundwater levels provide?

2. How does this information help them in their decision-making process?

3.2.4 Impact indicators for quantifying the value of AI-enhanced CS

The most interesting impact indicator for the regional water authority is drought hazard. The ECMWF Extended Range meteorological forecasts will be used as benchmark data to assess the added value of seasonal forecasts to gain knowledge on drought hazards on seasonal time horizons. CLINT will investigate what the most optimal forecast horizon is and what the forecast skill is of the ECMWF Extended Range data on forecasts of soil moisture, groundwater levels, and discharges. Also, CLINT will investigate the impact of various measures (e.g. weir management) to mitigate the drought hazard. The CLINT AI-enhanced forecasts will subsequently be used to generate new drought hazard information and assessed in the same manner as the ECMWF Extended Range forecasts. A comparison of the results based on AI-enhanced forecasts with results based on ECMWF Extended Range meteorological forecasts will be made.

3.3 Main water system of the Netherlands

3.3.1 General case study description

3.3.1.1 Catchment and hydroclimatology

The main water system of the Netherlands differs from the other case studies of CLINT for two main reasons: first, the area of interest is at a national level rather than at a catchment scale, since it involves the entire country; second, the main focus is not in forecasts at the sub-seasonal or seasonal scale, but in climate change projections.

Figure 3.7 presents an overview of the main water system in the Netherlands, including safety standards and different regions.

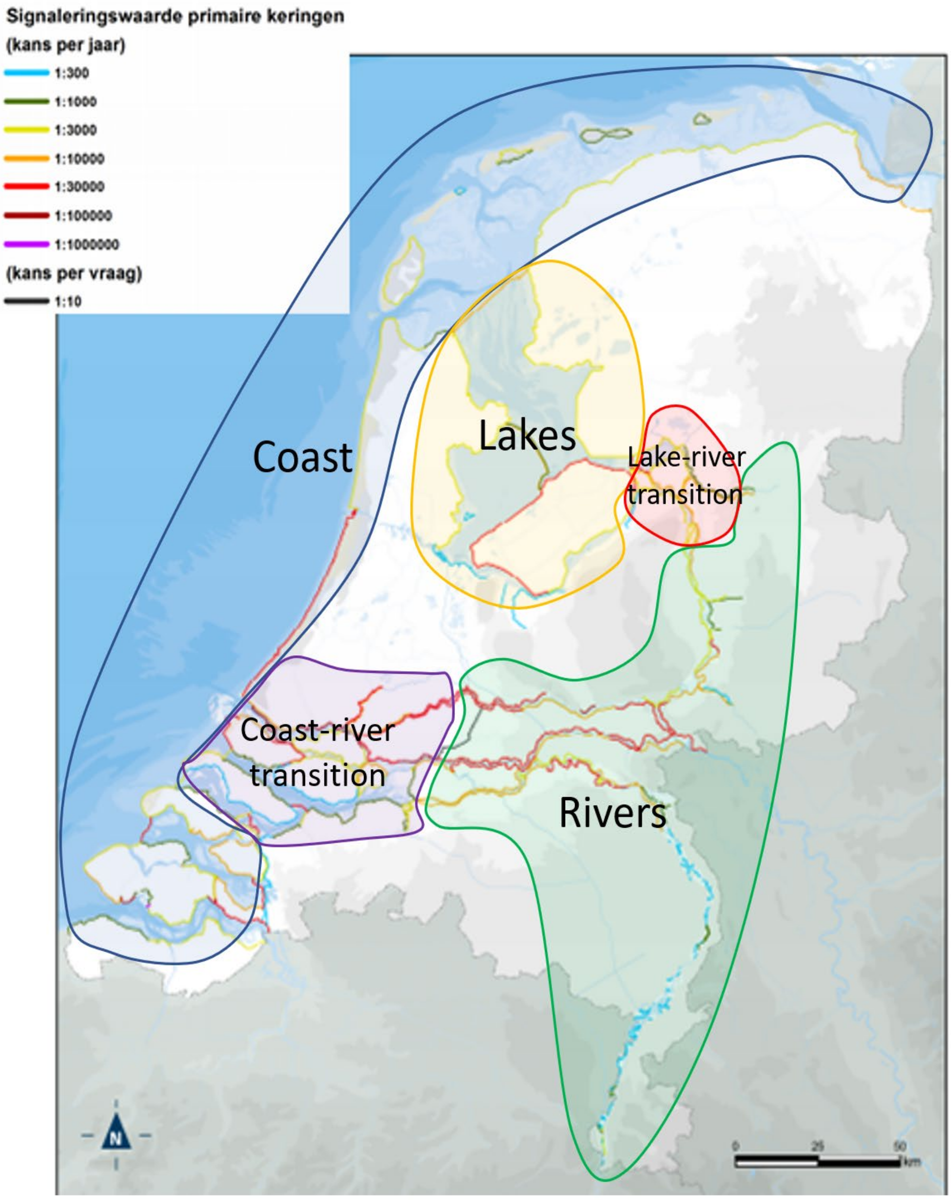


Figure 3.7. Design norms for levee reinforcement for the primary defence structures. When the indicated flood hazards per year are exceeded, reinforcement should start. A second norm exists, which may never be exceeded at any location. The coloured areas indicate the regions in the main water system.

As in this case study we consider the impact of extratropical transitions (EET) on flood risk in the Netherlands, we classify the main water system as all open waters that have primary flood defences to protect the adjacent land from flooding. When considering the cause of a flood risk event, we can roughly divide the main water system into three distinct regions and two transition regions, as indicated in Figure 3.7. Each region is susceptible to flood events in a different way. Table 2 describes the three regions and how ETTs can pose a flood risk for the adjacent flood defences.

Table 2. Characteristics of the three main water systems of the Netherlands and effects that extratropical cyclones have in those systems.

System	Characteristics	Effect of ETT
Coast	The coastal water system consists of the Wadden Sea, Dutch Coast, Western Scheldt and Eastern Scheldt. For the coast, flood events will most likely be caused by storm surges: on the relatively shallow North Sea, wind storms can cause set-up (surge) of the water, meaning that these factors are correlated.	ETT can cause large storms. If these also have an NW orientation, they lead to large surges that can form a threat to the dunes and dikes.
Lakes	The Lakes are a water system that used to be the “Southern Sea” before it was enclosed by the “Afsluitdijk”. It consists of the IJsselmeer, Markermeer, and some minor adjacent lakes. High lake water levels can be caused by high river discharges (river IJssel), rainfall, and high sea water level (preventing the discharge of water). As the lakes are relatively shallow, wind can cause a significant set-up.	Due to the general SW orientation of the lakes, ETT can cause a large set-up. In combination with high wind (waves) this can threaten the dikes.
River reaches without tidal influence	The river Rhine (splits up into Waal, Lek and IJssel) and Meuse are the main rivers of the Netherlands. The water levels are determined by the discharge, except for the last 10’s of kilometres, where the sea or lake can cause high water as well (backwater effect). Wind has a relatively small effect on this water system: it will only cause local waves and no set-up.	Large wind speeds cause local waves, which will be a threat to the dikes in case of coinciding high water. This is an unlikely situation, unless the ETT causes heavy rainfall in the Meuse and Rhine catchment as well.

The transition areas of these three parts subsystems are mostly a combination of river and sea, or river and lake. What makes them special is that moveable storm surge barriers in these regions are designed to keep high sea or lake levels out. However, these barriers might fail, making them an important part of the risk analysis as well.

The design standards are displayed in Figure 3.7 as well. They vary between flooding on average once per 300 years and once per 1.000.000 years. The strictness of the safety standard depends on the potential impact of a flood. This impact is determined based on three factors:

- The individual risk. No person may be exposed to a higher risk of dying due to a flood, than 1/100.000 in a year.
- The group risk. Large groups of people dying due to a flood will cause extra societal impact. Therefore, this is subject to an extra strict standard.
- The economic cost of a flood. Not only loss of life, but also economic damage is considered in determining the safety standard.

A required safety standard follows from each of these three criteria. The strictest of the three is the one that will be used. Note that safety standards become on average stricter closer to sea. This is because a dike breach along the low-lying coastal areas will cause a much more severe flood (larger area, larger flood depths, fewer possibilities for evacuation, longer recovery times) than an upstream river flood. This emphasises the importance of insight into possible causes of storm surge, and with this, ETTs as well.

3.3.1.2 Users

The user organisation for this case study is the technical directive for water management of the Ministry of Infrastructure and Water, Rijkswaterstaat (RWS). Online meetings have been conducted with RWS experts concerned with potential future changes in flood risk of the main water systems of the Netherlands.

3.3.1.3 Extreme events

In this case study, we consider the impact of extratropical transitions on flood risk in the Netherlands. The flood risk situation in the Netherlands is highly influenced by storm surges. Currently, storm surges are mainly caused by storm depressions, whereas extratropical induced storm events may become relevant for flood risk management if the occurrence of extratropical transitions increases in future climate. Not only may statistics of wind speed change, but also dominant wind directions or the season at which storm surges occur. In other words, we study the contribution of extratropical-induced storm surges to wind statistics in the Netherlands in future climate. Currently, these events do not have a significant impact on wind statistics in the Netherlands. In this case study, the potential impact of a change in occurrence of extratropical transitions will be related to changes in flood risk in the Netherlands as well as impacts on flood risk management. These changes in flood risk management could include the need for change in the design of flood defence measures or changes in maintenance policy as the storm surge season changes.

Note that the effects of ETTs on the Dutch Coast might be similar to other Western European coasts, with the differences that:

- The North Sea is relatively shallow and, therefore, more susceptible to storm surges.
- More southern (Atlantic Ocean) coasts might be more frequently hit by ETTs.

The balance between these two determines the impact of ETTs on a specific European region.

3.3.2 Detailed use-case description

3.3.2.1 User-definition of extreme events

An extreme event is an event that poses a significant flood risk for primary flood defences. Each defence has its own safety standard, depending on the area it is protecting. For every flood defence, the probability of flooding increases with the extremity of the event. For some flood defences, this might be a storm, while for others it might be a high river discharge. This makes it difficult to pinpoint a certain threshold as 'extreme'. There are, however, alarm levels that are used for crisis management. For example:

1. A River Rhine discharge at Lobith (the largest river in the Netherlands) of 11800 m^3/s is considered code red. This happens approximately once per 100 years.
2. A sea water level of 3.65 m+NAP at Hoek van Holland is considered code red. Also this is estimated to happen once per 100 years.

Both definitions are derived from the national guidelines for flood risk 2021 (*Landelijk Draaiboek Hoogwater en Overstromingsdreiging*).

3.3.2.2 Local impact of extreme events

Extreme events might cause flooding. The impact of a flood obviously depends on the flooded area and the type of event that caused the flood. For primary flood defences the impact is in general very large, with potentially large loss of life and economic damage. To give an indication, the "maximum floodable area" is given in Figure 3.8 (exported from: https://basisinformatie-overstromingen.nl, which also contains detailed information on individual floods and consequences). Note that this is an aggregation of the most extreme floods at every breach location, so this will never happen all together.

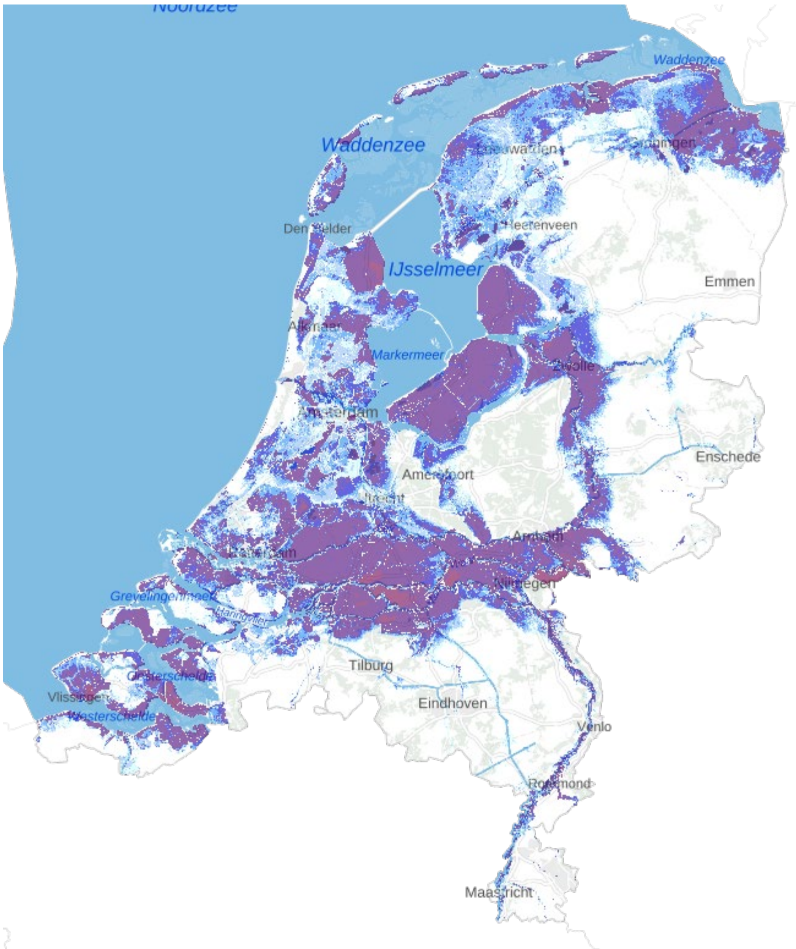


Figure 3.8. Maximum floodable area (worst-case scenario) for the Netherlands.

3.3.2.3 Decision process for preparedness, adaptation, and event or risk management

The Dutch approach to flood risk adaptation is a so-called "multi-layer safety" approach, in which three layers are distinguished (Figure 3.9):

1. Reducing the probability of a flood, for example by building flood defences.
2. Consequence reduction. This has more to do with spatial planning. For example, do not build in (highly) vulnerable areas, try to influence flood patterns, or protect critical infrastructure.
3. Measures to improve the crisis/disaster management. For example, by informing inhabitants of certain areas, building shelters, or improving the crisis management organisation.

The cornerstone of a multiple layer safety system is the acceptable risk to an area, including the risk of loss of life. Different measures can be taken to reach and maintain an acceptable risk. Investments in evacuation (e.g., the preparation of personnel, or equipment and traffic infrastructure) can reduce the consequences and the risk of a flood because of the reduction in loss of life and damage to movable goods. The following question arises: which measures are the most effective and efficient to accomplish and maintain an acceptable risk, especially when budgets are limited? Investments in evacuation have to compete with other measures in a multi-layer safety system, such as reinforcement of flood defences or the adaptive development of urban areas.

A cost-benefit analysis assesses the optimal investment strategy of flood risk management for society, taking into account all of the costs and benefits. Based on a cost-benefit approach, the need to invest in multiple layers can be defined related to the reduction of the risk or the contribution to evacuation as well as the costs of the measures. In addition, these measures can also contribute to other objectives of a society. For example, just as a dike can be used for multiple forms of land use, a fireman can also be used for other purposes besides flood risk management.

Figure 3.9. Schematic overview of multi-layer safety approach, layer 1 prevention (bottom), layer 2 spatial planning (middle) and layer 3 disaster management (top).

3.3.2.4 User-inspired (early) indicators of extreme events for input to WPs 3-5

In addition to the "code red" events such as described in the previous sections, there is a larger spectrum of less and more extreme events as well presented in the national guidelines for flood risk 2021 (*Landelijk Draaiboek Hoogwater en Overstromingsdreigin*g). Water level simulations are continuously being made based on weather forecasts to give an early warning in case one of these indicators might be exceeded. If this research concludes that tropical cyclone-induced storm surges are relevant for flood safety, the existence of tropical cyclones or their extratropical transition become relevant early indicators for decision-makers and should be considered in the future.

3.3.3 Existing climate services and the need for enhancement

3.3.3.1 Climate services currently used

Climate services that are currently used for research on extreme events are the ECMWF seasonal forecasts. This dataset provided about 8,000 years of synthetic weather simulations (if the ensemble realisations and overlapping periods are assessed individually). These are translated into water levels by the Royal Dutch Meteorological Institute, which can then be used for coastal flood assessments.

3.3.3.2 User wishes and requirements for enhanced climate services

The problem with the mentioned ECMWF data, is that the temporal resolution is limited to 6 hours. Especially for wind analyses, a finer temporal resolution would improve the analysis.

3.3.4 Impact indicators for quantifying the value of AI-enhanced CS

When considering flood risk research in the Netherlands, climate services are primarily used for extreme value analysis of causal factors for floods. An indicator for the value of AI-enhanced CS is, therefore, a better insight into causal factors of these extreme events. The problem with extreme value statistics is that it is difficult to determine whether your estimate is right. That is why insight into the causal factors (perhaps learning about a new type of event) is the most valuable result to obtain. This insight will enhance flood risk management from storm surges in two ways. Firstly, because these insights will be taken into account in the design of flood defence measures. Secondly, because these insights will be used in crisis/disaster management as new (early) indicators will be taken into account in forecasting and early warning.

4 Snow climate change hotspots

4.1 Lake Como basin

4.1.1 General case study description

4.1.1.1 Catchment and hydroclimatology

Located in the Italian Alps, the Lake Como basin (Figure 4.1) is part of the Adda River Basin and is a highly controlled water system in the Lombardia region (northern Italy). The catchment has an area of 4500 km^2 and includes a large regulated lake (active capacity 247 Mm^3), 16 Alpine hydropower plants (total storage capacity sums: 545 Mm^3; 13% of national hydropower) and a wide irrigation-fed cultivated area (1320 km^2). The hydrometeorological regime is typical of sub-alpine regions, characterised by dry periods in winter and summer, and flow peaks in late spring and autumn fed by snowmelt and rainfall, respectively. Snowmelt during May-July is the most important contribution to the accumulation of the seasonal storage, which is then used for irrigation supply in the summer during the peak demand period (Denaro et al., 2017; Figure 4.2). The latter often exceeds the natural water availability and makes the role of the lake operation paramount for the system. The regulation of the lake is driven by two primary competing objectives (Giuliani et al.

2016): water supply, mainly for irrigation, and flood control along the lake shores. The agricultural districts downstream prefer to store snowmelt in the lake to satisfy the peak summer water demands, when the natural inflow is insufficient to meet irrigation requirements. Yet, storing such water increases the lake level and, consequently, the flood risk. Additional interests are related to hydropower, navigation, fishing, tourism, and ecosystems, which further challenge the existing water management strategies and motivate the search for more efficient solutions relying on hydroclimatic services. Extreme heat is another factor of risk for agriculture in the area, since early or in-season heatwaves and summer persistent anomalously warm nights may jeopardize the yield. Finally, the co-occurrence of droughts and warm extremes in the region produces high risks related to compound events. Forecasts can potentially inform farmers' agricultural practices (Li et al., 2017) and contribute to improving the reliability of the irrigation supply (Giuliani et al., 2020), particularly in facing severe dry conditions, as well as to mitigating existing conflicts between competing sectors.

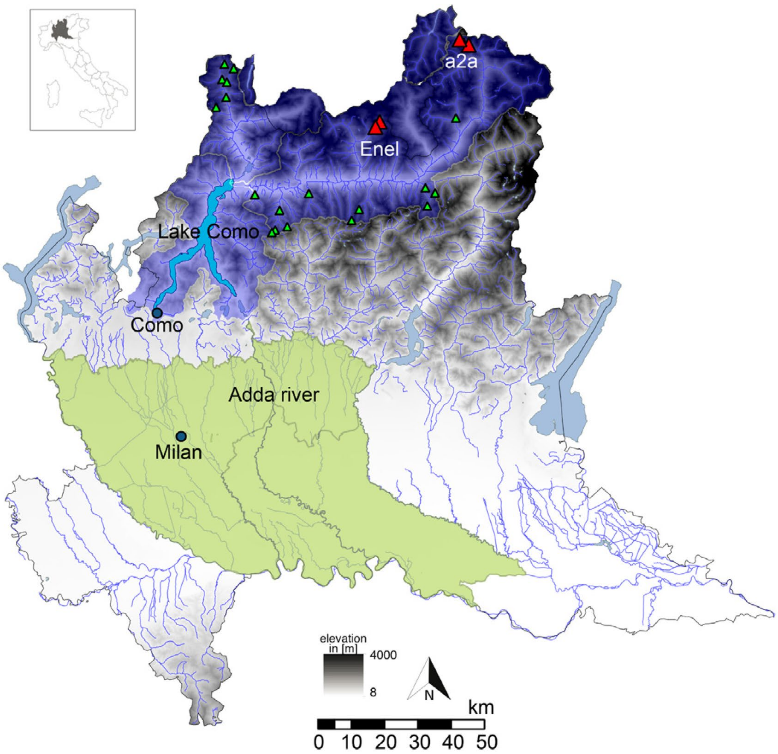


Figure 4.1. Map of the Lake Como basin (Denaro et al., 2017): Lake Como, the catchment area (violet), and downstream agricultural districts (green). The triangles denote hydropower reservoirs with the red ones being the four main ones considered in Denaro et al. (2017).

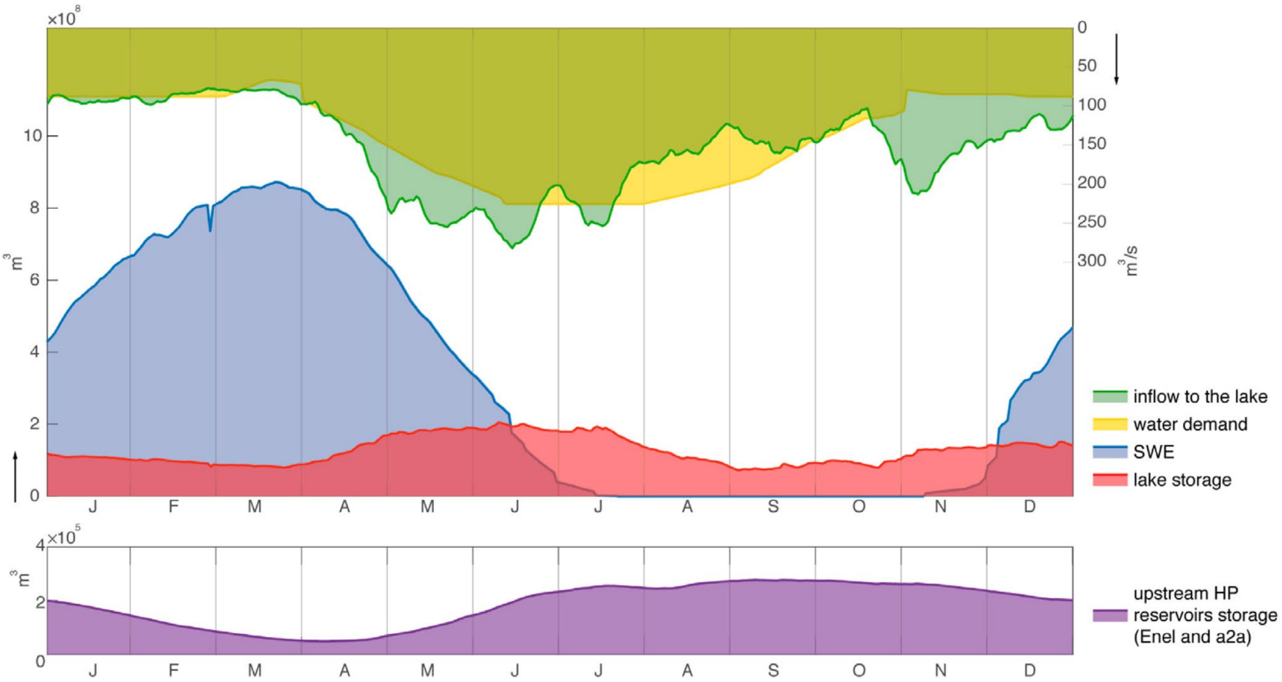


Figure 4.2. Main components of the hydrological cycle in the study area. The patterns represent moving averages computed from observed data over the period 2006–2013 (Denaro et al., 2017).

4.1.1.2 Users

The following groups of decision-makers and stakeholders were identified as key current or potential users of climate services for Lake Como:

- Lake operator: Consorzio dell'Adda (Consortium for the Adda River, www.addaconsorzio.it) is the institutional operator of Lake Como, controlling its regulation since 1946. The Consortium, following its statute, "provides for the construction, maintenance and operation of the Regulatory Work of Lake Como, as well as regulating the use of the water available in the general interest".
- Irrigation users: several large irrigation districts are served with water supply through a dense network of irrigation canals fed by the lake releases. There are four districts with a total surface of 1,400 km^2, mostly cultivated with maize, rice and soy. The irrigation governance in the districts is managed by twelve Consorzi di Bonifica e Irrigazione (Consortia for reclamation and irrigation) that are part of a regional office called ANBI (Associazione Nazionale delle Bonifiche, delle Irrigazioni e dei Miglioramenti Fondiari per la Lombardia). These Consortia are public economic entities of the regional system of Lombardia, which have a consolidated organisational and professional structure to address multiple purposes: (i) they govern the artificial waters of the irrigated plain, (ii) they contribute to protecting large densely populated areas by floods and natural disasters, (iii) they ensure the irrigation of countryside and the development of agriculture, (iv) they protect the environment and the landscape, ensuring the existence of biotopes and natural reserves.

- Hydropower companies: different companies manage the large storage and hydropower production capacity of the Lake Como (and Adda) basin. This storage capacity is divided into 16 alpine hydropower reservoirs (globally storing 545 Mm^3) located in the upper catchment, upstream of the lake, and 11 smaller run-of-the-river power plants located downstream of the lake along the Adda river that depend on the lake releases. Three of the largest hydropower companies are A2A, Enel Green Power and Edison.

4.1.1.3 Extreme events

The Lake Como Basin suffers from severe hydrometeorological hazards including droughts, floods, heatwaves and warm nights:

- Droughts: extreme drought events have increased in recent decades, challenging the reliability of the irrigation supply from spring to autumn. For example, two droughts in 2003 and in 2005 led to severe crop failures and exacerbated the conflicts between agriculture and other sectors (Anghileri et al., 2012). CLINT will provide AI-enhanced S2S and seasonal hydroclimatic forecasts of extreme drought indices for informing the operation of the lake that will contribute to improving the reliability of the irrigation supply and mitigating existing conflicts between competing sectors.
- Floods: the occurrence of floods along the lake shores is a recurrent problem, especially in autumn, when floods are driven by intense rainfall events, but some flooding events may occur in late spring due to intense snow-melt peaks (Denaro et al., 2017). An increase in the flood risk associated with high water levels is expected due to climate change, given the projected anticipation of the snow melt coupled with the projected decrease of water availability in the summer period, which would require storing additional water in the lake for longer periods (Forzieri et al., 2014). The AI-enhanced S2S hydroclimatic forecasts provided by CLINT will be used to inform the operation of the lake, contributing to improving the management of flood risk.
- Heatwaves, warm nights and compound events: heatwaves and warm nights are an additional factor of risk for agriculture in the basin, and may impact the crop yield with direct and indirect effects (e.g. crop heat stress, proliferation of algae in irrigation canals, etc.). The co-occurrence of droughts and warm extremes in the region produces high risks related to compound events. CLINT will generate AI-enhanced S2S forecasts of heatwaves and warm nights, also including compound events, to inform farmers agricultural practices.

4.1.2 Detailed use-case description

The following use-case description is based on information collected via a survey with 24 questions (see Annex 1). Anonymous responses were received from four end-users related to the Lake Como case study, and via interviews conducted with some representatives of the twelve Consorzi di Bonifica e Irrigazione (the governance entities of the irrigation districts, see section "Users") led in collaboration with the MODFABE project (https://modfabe.deib.polimi.it/). The users who responded to the survey come from different sectors (lake regulation and hydropower) and have 10 to 30 years of experience. Here the answers are reported ensuring anonymity, referring only to the related sector of user activity or to the extreme events of interest. Additional details are reported with reference to external sources and users when relevant and publicly available.

4.1.2.1 User-definition of extreme events

Droughts and heatwaves/warm nights: The lake operator defines droughts as a natural hazard that is mainly caused by a lack of precipitation and consequently decreased inflows to the lake. For this, they look at monthly inflows and if these are lower than the ten lowest historical monthly values recorded so far, then a drought is occurring. Similarly, hydropower companies define a drought event as a period when inflows and reservoir levels are lower than predetermined thresholds; for one of the users from a hydropower company (who took the survey), an extreme drought event corresponds to levels that have not been experienced at least in the last 50-100 years. The irrigation consortia define droughts as a lack of water available from rainfall and from the lake storage, that can be released and derived through irrigation canals; for the irrigation supply, a key aspect of the drought is the temporal distribution of rainfall over the cropping season and not only the total amount of seasonal rainfall. The irrigation Consortia are also concerned with high temperatures, heatwaves and warm night risk, as these alter the crop cycle and the consequent irrigation demand patterns.

Floods: The lake operator defines a flood event based on the lake levels at a specific point in Como city (piazza Cavour): if the levels are higher than a threshold (now equal to 1.1 m), a flood is occurring. Similarly, hydropower companies look at inflows and reservoir levels to define flood events based on the exceedance of predetermined thresholds; an extreme flood is defined when water levels reach thresholds that have not been experienced at least in the last 50-100 years.

4.1.2.2 Local impact of extreme events

Each of the extreme events above mentioned has different local impacts on multiple sectors. A detailed description of how the local impacts are perceived and quantified by the different end-users is provided below for each of the extreme events considered for the case study.

Droughts and heatwaves: The lake operator stated that droughts cause high socioeconomic negative impacts, especially for agriculture, as the Consorzio dell'Adda is not able to supply the necessary agricultural water demand for downstream irrigation districts. The lake operator stated that the impacts are quantified only by recording the events from a hydrographic point of view, no measure of socio-economic impacts is collected or recorded by them. For hydropower companies, the negative impacts of droughts are losses in energy production and consequent decrease in revenues that can be measured and recorded. For the irrigation consortia the negative impact of droughts and heatwaves are the disturbances to the crop cycle, given by lack of water, high temperatures and more irregular rainfall patterns that require adaptation of the cropping practices and irrigation methods; this jeopardises the irrigation supply and generates crop losses. A secondary and indirect effect of high temperatures is the proliferation of algae in irrigation canals, which reduces the maximum flow rate for irrigation by partially filling the canal sections.

Floods: According to the lake operator, flooding of lake shores and valley areas are the key impacts of floods in the basin. They record these impacts only from a hydrographic point of view (e.g. water level in Como). For hydropower companies, flood impacts include direct damages to their infrastructures but also indirect effects, as floods undermine various aspects of the territory, including people, accesses, infrastructures, etc. These impacts include energy overflow, accidental maintenance costs, person-hours needs/availability, people at risk, restoration costs, and production losses. To assess the impact, the risk of human loss, rebuilding costs and prolonged operating losses are considered.

4.1.2.3 Decision process for preparedness, adaptation, and event or risk management

Different climate and weather information and variables are used as an early indication of an upcoming EE, and the choice depends on the type of event and on the decision-making context:

- Droughts: According to the lake operator, there is no perfectly reliable precursor, but seasonal forecasts can be used, while monitoring their reliability. For the hydropower companies, meteorological forecast information from multiple sources can be used, but their reliability needs to be assessed. For some of the irrigation consortia, a precursor of water supply availability is the lake storage before the start of the irrigation season, and for others seasonal and medium-range rainfall forecasts can be useful complements in some situations (e.g. before the sowing/planting phase).
- Floods: For the lake operator, a precursor is a forecast of heavy rainfall. Similarly, hydropower companies also look at meteorological forecasts from multiple sources.

The survey identified that different types of datasets are used by end-users to make long-term decisions (i.e. month and beyond):

- In-situ observations in real-time or near-real-time;
- Model-based data (e.g. meteorological reanalysis) in real-time (or near-real-time);
- Climatology (defined as the incorporation of historical data over many years and their statistical/probabilistic analysis);
- Forecasts at short-term or at monthly/sub-seasonal scale;
- Seasonal forecasts.

On the other hand, decadal predictions and centennial climate projections are not currently used.

Regarding the question of how users make decisions based on this data, little specific information was collected from the survey.

The lake operator mentioned that for floods, the ideal decisions of the lake releases are aimed at increasing the storage volume available for lamination, but this represents a challenge. To support their decisions on dam's releases for flood preparedness, the operator of Lake Como is currently looking at the short-term (3-days) hydrological forecasts issued by PROGEA (through the EFFORTS system), but these forecasts are not integrated formally into any DSS yet.

A possible decision for droughts that was mentioned by the lake operator and some of the irrigation Consortia is the partial conversion (adaptation) of the irrigation methods, but this conversion is a slow process that requires years for adapting practices and investments. A short-term decision that

can be made by farmers is the shift of the planting season in case of heavy rainfall events within a season, and this alters the crop cycle and affects the irrigation consortia.
One of the users from a hydropower company mentioned that for their plants, they follow the guidelines of the Swiss Federal Office of Energy (UFE) for extreme events. Hydropower companies need to evaluate the magnitude and timing of the extreme events, to plan and adapt the plant's operation to minimise the risks, e.g. by preventive diversion of water inflows, reservoir control, etc.
Additional information on possible actions in case of droughts was collected from local newspapers and official bulletins of the Lombardia Region (Regione Lombardia, 2022) and highlights that in case of an expected or ongoing extreme drought in the region of Lake Como, the Regional Council can call a panel called «Tavolo regionale per l'utilizzo della risorsa idrica in agricoltura» ("Regional panel for the use of water resources in agriculture"). This panel aims to identify the actions to be taken to deal with the drought and the expected consequent irrigation problems before they hit the agricultural sector in the late spring and summer months. The panel is made up of the president of the region, regional councillors for "Local Authorities, Mountain and Energy Resources'', "Agriculture, Food and Green Systems", "Environment and Climate", the Secretary General of the Po River District Authority and representatives of farmers' associations, land reclamation consortia, large lakes regulatory bodies (including Lake Como operator) and major hydroelectric energy producers. The Lombardia Region, in agreement with all the subjects who take part in the panel, can evaluate the opportunity to make exceptions to the release of the minimum environmental flow, within the framework of the provisions of the current 'Water Protection and Use Program', with the primary purpose of storing water into the lakes, including Lake Como; this action can be accompanied by a simultaneous shift in times for the start of the irrigation season. Another possible action that can be taken is to ask industrial users, such as hydropower plants, to make water available for agricultural use, which by law immediately follows drinking water use. The meeting is based on an analysis and a continuous monitoring of data on water scarcity, carried out with the significant contribution of ARPA Lombardia (the Regional Environmental Protection Agency), to support the identification of shared compromise solutions, where the requests of all the participants are heard to face the water crisis, with evidence-based planning that is aimed at an optimal use and management of the water resources.

4.1.2.4 User-inspired (early) indicators of extreme events for input to WPs 3-5

Related to the question of what information users think could be used in addition as an early indication of upcoming EE, the lake operator suggested that daily inflows should be used and compared with climatology-based thresholds to predict if a flood is going to occur, for example, by checking if inflows are greater than the top 10%-highest historical values recorded so far. Some users (lake operator and hydropower companies) stressed the need for reliable meteorological forecasts and catchment knowledge (see Section on "User wishes and requirements for enhanced climate services"), and one of them mentioned the influence of large-scale synoptic circulation on the local meteorology.

4.1.3 Existing climate services and need for enhancement

4.1.3.1 Climate services currently used

Droughts: The lake operator uses seasonal forecasts from Meteoswiss to understand possible drought occurrence and evolution. The hydropower companies look at seasonal forecasts too, as well as historical averages and extremes, in addition to common weather forecast websites for medium-term predictions, aimed at adapting their plant management, e.g. reservoir level control and preventive diversion of water inflows. While a few representatives of irrigation consortia in the Lake Como Basin stated that they do not use any specific Climate Services to support decision-making, others reported that they look at seasonal forecasts to understand future water availability and at the monthly or weekly bulletins of ARPA Lombardia in high-flow conditions. Moreover, farmers (their users) look at short-term weather forecasts for rainfall and temperature, with lead times up to some days, to support their short-term decisions (e.g. to schedule the sowing time).

Floods: The lake operator, Consorzio dell'Adda, uses short-term forecasts to support their decision-making, especially for floods. The EFFORTS (European Flood Forecasting Operational Real-Time System) is a decision support system with a user-friendly GIS interface for real-time flood forecasting and hydrological monitoring, developed by the Italian company PROGEA s.r.l. (www.progea.net/chi-siamo.php). Since 2009, the EFFORTS system has been operationally run and maintained as a real-time forecasting system for the Adda River Basin, upstream and downstream of Lake Como. EFFORTS provides hydrological forecasts with a lead time of up to 48-60 hours, using meteorological forecasts from COSMO-I2 (COnsortium for Small-scale MOdelling, www.cosmo-model.org). The short-term meteorological forecasts from COSMO-I2 used as inputs in EFFORTS have a spatial resolution of approximately 2.8 km, an hourly time step and are updated with a daily frequency. The hydropower companies look at common weather forecast websites for short-term predictions (see paragraph above on droughts).

Characteristics of the Climate Services currently used: The responses of the end-users to the survey suggest that the highest spatial and temporal resolutions of the services used so far by all users are 2-7km and hourly (lake operator and hydropower companies). These high resolutions are used ahead of (or during) flood events, while the lowest resolutions of interest (about 50km and weekly / monthly) are used during the dry season. The highest spatial resolutions are those of public weather services, i.e. Meteoswiss model (7 km) and soon Cosmo Lami model (2 km).
At least four different prediction horizons (lead times), from some hours to some months, are important for the essential variables that are mostly used in current climate services, i.e. precipitation, temperature, streamflow and wind. The top-five most frequent combinations of variables and lead times used are (i) precipitation with a lead time of some hours, days, weeks or months; (ii) streamflow with a lead time of some hours, days, weeks or months; (iii) temperature with a lead time of some days, weeks or months; (iv) snow with a lead time of some days, weeks or months; (v) energy demand with a lead time of some hours, days, weeks, or months.

The ways the forecasts are used and their update frequency are summarised below:

- Quantitatively as input to an impact model (hydrology, energy, agriculture, etc.): at least once per day or once per week (depending on the user/objectives)
- Quantitatively as input to a decision support system: either at least once per day or at least once per week (depending on the user/objectives)
- Quantitatively to trigger emergency operations: either at least once per day or once per week (depending on the user/objectives)
- Qualitatively as additional knowledge to make decisions: either at least once per day or once per week, or once per month (depending on the user/objectives)
- Visually (qualitatively) to see what the future situation might be: either at least once per day or once per week, or once per month (depending on the user/objectives)

4.1.3.2 User wishes and requirements for enhanced climate services

In terms of general wishes and requirements for enhanced climate services, the survey highlighted the need for:

- an improvement of the spatio-temporal resolution of forecasts;
- higher reliability of the prediction, especially in terms of the effects of the EEs;
- an extension of the skilful lead time of available forecasts, before EEs, especially at the sub-seasonal to seasonal scale;
- more detailed catchment knowledge to improve hydrological predictions.

The ideal spatial resolution of climate services/hydrometeorological predictions indicated by the end-users who took the survey is about 5km to 10km (lake operator and hydropower companies), but for some key specific locations of interest higher resolution would be beneficial (hydropower). The ideal temporal resolutions indicated by the users are daily for the lake operator, and up to hourly / sub-hourly during high-flow conditions for the hydropower companies.

The ideal lead time of climate services/hydrometeorological predictions indicated by the end-users are seasonal for the lake operator and irrigation consortia, and weekly for hydropower companies. The ideal update frequency of climate services/hydrometeorological predictions is every 12 hours for the lake operator and up to every hour (or even up to 10 minutes) during high-flow events for hydropower companies, while every 12/24 hours is sufficient during normal conditions.

The following improvements in CS and forecast information have been ranked as top-five priorities by the end-users in the survey, providing a score (for low to high interest) for eleven options (the list of all possible options is reported in Annex 1):

1. better prediction of weather extremes;
2. better prediction of inflows;
3. higher spatial resolution;
4. higher temporal resolution;

5. more scenarios of hydrological predictions; more scenarios of climate projections; better, more reliable/sharper, probabilistic seasonal forecasts; weather forecasts for longer lead times, e.g. sub-seasonal to seasonal (ex aequo, same score across options).

The responses of end-users to the survey question on what are the criteria to measure the success of (enhanced) Climate Services in supporting their operational activities, highlighted that they require the highest accuracy of the forecast hydrometeorological variables with respect to observations. In particular, it was mentioned that a good accuracy of the forecasts would be required for these variables:

1. Rainfall: estimated/observed accumulations (mm) and locations where these were predicted;
2. Inflows: magnitude and timing of inflows at selected locations (assessed comparing the forecasts with the observed inflows).
3. Temperature: estimated high-temperature peaks and locations where these were predicted.

4.1.4 Impact indicators for quantifying the value of AI-enhanced CS

Three key groups of impact indicators were identified following the exchanges reported above with all the Lake Como Basin's end-users:

1. Hydropower production indicators to be maximised; their formulation will stem from the requirements and objectives of the hydropower companies. Enhanced sub-seasonal and seasonal drought predictions will be used to optimise hydropower production.
2. Irrigation supply deficit to be minimised / crop yield indicators to be maximised; their formulation will follow the requirements (water demand) and objectives of the irrigation districts (Consortia for irrigation) in the basin. Enhanced sub-seasonal and seasonal hydrometeorological forecasts (of inflows, precipitation, snow and temperature) will be used to improve dam management operations and optimise agricultural production.
3. Heatwaves, warm nights and compound event indicators; these indicators could be expressed as hit rates and false alarms or other types of success indexes. Enhanced sub-seasonal and seasonal hydrometeorological forecasts from CLINT will aim to improve the warnings for these extremes and compound events.

5 Conclusions and outlook

This report provides a detailed overview of the local scale case studies of the CLINT project. It represents the progress made in understanding the impacts of extreme events on the ground, and the operational practices for preparedness and planning or design for climate change adaptation. An overview has been acquired for each of the case studies on what climate services are currently being used, and what users envisage as a valuable enhancement of existing services or development of new services.

From the case studies described, it can be seen that all extreme events addressed in the CLINT project are represented, as well as all time scales of the envisaged climate services, ranging from sub-seasonal to seasonal predictions up to decadal and long-term climate change projections. Droughts are addressed in more case studies than the other extreme events, as are the S2S forecasts as compared to climate change projections.

With respect to input to other WPs in the CLINT project, most interesting are the user definitions of extreme events as these sometimes refer to a combination of criteria or threshold values that differ from criteria commonly used in climate sciences.

With the end-users in each case study engaged successfully and with clear user requirements expressed, the next phase of CLINT WP7 of assessing benchmark performance of existing services and starting the development of pilot AI-enhanced services we believe now to be strongly supported.

References

Anghileri, D., Castelletti, A., Pianosi, F., Soncini-Sessa, R., Weber, E., 2012. Optimizing watershed management by coordinated operation of storing facilities. J. Water Resour. Plann. Manage. 139 (5), 492–500.

Bertoni, F., Giuliani, M., Castelletti, A., & Reed, P. M., 2021. Designing with information feedbacks: Forecast informed reservoir sizing and operation. Water Resources Research, 57, e2020WR028112. https://doi.org/10.1029/2020WR028112

Bonifacio, R., Guimaraes Nobre, G., and Cuellar, D., 2021. Drought Forecasting, Thresholds and Triggers: Implementing Forecast-based Financing in Mozambique, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-10434, https://doi.org/10.5194/egusphere-egu21-10434.

CEDEX, 2017. Evaluación del impacto del cambio climático en los recursos hídricos y sequías en España. Publicado en: https://www.adaptecca.es/recursos/buscador/evaluacion-delimpacto-del-cambio-climatico-en-los-recursos-hidricos-y-sequias-en

CEDEX, 2020. Incorporación del cambio climático en los planes hidrológicos del tercer ciclo, Nota del 26 octubre de 2020.

Coughlan de Perez, E., van den Hurk, B., van Aalst, M. K., Jongman, B., Klose, T., and Suarez, P., 2015. Forecast-based financing: an approach for catalyzing humanitarian action based on extreme weather and climate forecasts, Nat. Hazards Earth Syst. Sci., 15, 895–904, https://doi.org/10.5194/nhess-15-895-2015.

Denaro, S., D. Anghileri, M. Giuliani, and A. Castelletti, 2017. Informing the operations of water reservoirs over multiple temporal scales by direct use of hydrometeorological data, Advances in Water Resources, 103, 51–63

DRBA, 2018. Plan especial de sequía. Duero River Basin District. Valladolid (Spain)

DRBA, 2021. Plan Hidrológico de la parte española de la Demarcación Hidrográfica del Duero Revisión de tercer ciclo (2022-2027). Anejo2. Inventario de recursos hídricos naturales. Duero River Basin Authority, Valladolid (Spain) (Draft version)

Emerton, R., Cloke, H., Ficchi, A., Hawker, L., de Wit, S., Speight, L., et al., 2020. Emergency Flood Bulletins for Cyclones Idai and Kenneth: A Critical Evaluation of the Use of Global Flood Forecasts for International Humanitarian Preparedness and Response. Int. J. Disaster Risk Reduction 50, 101811. doi:10.1016/j.ijdrr.2020.101811

Forzieri, G. , Feyen, L. , Rojas, R. , Floerke, M. , Wimmer, F. , Bianchi, A. , 2014. Ensemble projections of future streamflow droughts in Europe. Hydrol. Earth Syst. Sci. 18 (1), 85–108.

Giuliani, M., Y. Li, A. Castelletti, and C. Gandolfi, 2016. A coupled human-natural systems analysis of irrigated agriculture under changing climate, Water Resources Research, 52, 6928–6947

Giuliani, M., L. Crochemore, I. Pechlivanidis, and A. Castelletti, 2020. From skill to value: isolating the influence of end user behavior on seasonal forecast assessment, Hydrology and Earth System Sciences, 24

Hamududu B, Killingtveit A., 2012. Assessing Climate Change Impacts on Global Hydropower. Energies; 5(2):305-322. https://doi.org/10.3390/en5020305

Hughes, D.A., Farinosi, F., 2020. Assessing development and climate variability impacts on water resources in the Zambezi River basin. Simulating future scenarios of climate and development. J. Hydrol. Reg. Stud. 32 (2020), 100763. https://doi.org/10.1016/j.ejrh.2020.100763.

IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press.

KNMI, 2022. Royal Netherlands Meteorological Institute (KNMI), https://climexp.knmi.nl, March 2022

Li, Y., M. Giuliani, and A. Castelletti, 2017. A coupled human–natural system to assess the operational value of weather and climate services for agriculture, Hydrology and Earth System Sciences, 21, 4693-4709

Payet-Burin R., Kromann M., Pereira-Cardenal S., Strzepek K., Bauer-Gottwein P., 2019. WHAT-IF: an open-source decision support tool for water infrastructure investment planning within the water–energy–food–climate nexus. Hydrol. Earth Syst. Sci. 23, 4129–4152

Regione Lombardia, 2022. Bollettino Ufficiale, Serie Ordinaria, N. 16. 19 April 2022

Rijkswaterstaat, 2017. KWA-Waterakkoord KWA Midden-Holland, Document number 2017-17.012372 (in Dutch)

Rijkswaterstaat, 2021a. Landelijk draaiboek waterverdeling en droogte, version 2.8, 30 March 2021 (in Dutch)

Rijkswaterstaat, 2021b. Draaiboek RDO West-Midden 2021, Rijkswaterstaat Midden-Nederland District Zuid, version 0.1, 1 January 2021, Utrecht, the Netherlands (in Dutch)

Rijnland, 2019. Calamiteitenplannen Hoogheemraadschap van Rijnland, Version July 2019, Leiden, the Netherlands (in Dutch).

Rijnland, 2021. Zomermonitor 2021, rapport nr. 04, 16-08-2021 (week 33), Document nr. Document nr. 21.058799, Dossier DIG-3774/013, Hoogheemraadschap van Rijnland (in Dutch).

Rijnland, 2022. https://rijnland.maps.arcgis.com/apps/MapSeries/index.html?appid=230be61a2b7446439d1c40138c98f7ec.

SADC, 2012. Regional infrastructure master development plan – Energy sector plan.

Sánchez-García, E., Abia, I., Domínguez, M., Voces, J., Sánchez, J. C., Navascués, B., ... & Del Portal, C. R., 2022. Upgrade of a climate service tailored to water reservoirs management. *Climate Services*, *25*, 100281.

Van der Zwan, 2022. Presentation Rijnland water board, 26 January 2022.

World Bank, 2010. The Zambezi River Basin. A Multi-Sector Investment Opportunities Analysis. Volume 3: State of the Basin (p. 202). Washington, DC: World Bank.

ZAMCOM, 2018. Zambezi River Basin Policy Brief 1. Floods and Droughts in the Zambezi River Basin. Harare, Zimbabwe: Zambezi Watercourse Commission and Southern African Research and Documentation Centre.

Annex 1: End-users survey

This annex provides the list of questions asked to the end-users of the Zambezi Watercourse and Lake Como basin, in the format of an anonymous survey, provided via a web-based text form to fill.

<u>Basic Data</u>

- In which organisation/sector are you working?
- What is your position in your organisation?
- How many years of experience do you have?

<u>Formulating user-inspired EE variables and indices (specify the EE)</u>

- What do you consider as an Extreme Event (EE) in general in your local area? How do you define it?
- What information is used as an early indication of an upcoming EE?
- What information do you think could be used in addition as an early indication? Why is it not used yet?
- What are the (negative) impacts of these EE on the ground?
- How do you quantify those impacts (any quantitative information you use for it)?
- What are the main current and future challenges for EE preparedness?

<u>Specifications of local existing services and data and on the decision-making process</u>

According to European Commission's Roadmap for Climate Services (2015), climate services cover "the transformation of climate-related data - together with other relevant information - into customised products such as projections, forecasts, information, trends, economic analysis, assessments (including technology assessment), counselling on best practices development and evaluation of solutions and any other services in relation to climate that may be use for the society at large."

- If you are using climate services (e.g. hydrometeorological forecasts) in your work, which climate services are you using and for what decision(s)? (Please describe in ~3 sentences, including links if applicable; indicate 'NA' if not used/applicable)
- On what basis do you make long-term (i.e. month and beyond) decisions?
    a. Present state (real time) or near-real time
        i. In-situ observations in real time or near-real time
        ii. Remote sensing data in real time or near-real time
        iii. Model-based (i.e. re-analysis, hydrological model etc.) in real time or near-real time
    b. Climatology (*defined as the incorporation of historical data accumulated over many years, such as records of rainfall, temperature, streamflow, etc., and their statistical*

(probabilistic) analysis. This sets an understanding of the past and allows prediction under the assumption that the future will be within the historical records.)

c. Forecasting
   i. Short-term or monthly/sub-seasonal
   ii. Seasonal
d. Decadal predictions
e. Centennial climate projections
f. Other - please state

- What are the highest spatial and temporal resolutions of the service(s) that you use? (Example of answer: <10 km & daily)

- How are the predictions used, and how often?

	At least once per day	At least once per week	At least once per month	At least once per season	At least once per year	Not used in this way
1. Quantitatively as input to an impact (hydrology, energy, agriculture, etc.) model						
2. Quantitatively as input to a decision support system						
3. Quantitatively to trigger emergency operations						
4. Qualitatively as additional knowledge to make decisions						
5. Visually (qualitatively) to see what the future situation might be						

- What is the importance of the prediction horizon (lead-time) for each of the essential variables that you use? Please, rank-order (from 1 to 5, with 1 = least important, to 5 = most important) each variable per prediction horizon.

	Not used	**Some hours in advance**	**Some days in advance**	**Some months in advance**	**Some seasons in advance**	**Some years in advance**	**Some decades in advance**	**N/A**
Variable		(1-5)	(1-5)	(1-5)	(1-5)	(1-5)	(1-5)	
1. Precipitation								
2. Temperature								
3. Streamflow								
4. Soil moisture								
5. Wind								
6. Solar radiation								
7. Energy demand								
8. Snow								
9. Evapo-transpiration								
10. Water demand								
11. Crop development stages								
12. Others, please specify: ____________								

- If you use sub-seasonal to seasonal (S2S) forecasts, what are the main limitations to interpret and use forecast information? E.g. forecast skill, horizon, resolution, probabilistic nature of the forecast?
- If available and possible, could you please share any references to and/or detailed description of the EE monitoring, prediction/outlook, preparedness, and management procedures?

Needs for local climate services

- What is your ideal spatial resolution of climate services/hydrometeorological predictions? (Example: “about 10 by 10 km”)
- What is your ideal temporal resolution of climate services/hydrometeorological predictions? (Example: “daily”)
- What is your ideal lead time (predicted horizon) of climate services/hydrometeorological predictions?
  (Example: “a couple of days”)
- What is your ideal update frequency of climate services/hydrometeorological predictions? (Example: “every 6 hours”)
- What would you envisage to get out of this project (in terms of climate services improvement)?
- Please state your interest for the following options of improved climate services/prediction information using a score from 1 (low interest) to 5 (high interest):

	Not important	Not very important	Important	Very important	Extremely important
1. Better prediction of weather extremes					
2. Better (more reliable / sharper) probabilistic seasonal forecasts					
3. More scenarios of climate projections					
4. Weather forecasts for longer lead times (e.g. sub-seasonal to seasonal)					
5. Higher spatial resolution of the predictions					
6. Higher temporal resolution of the predictions					
7. Better inflow / streamflow predictions					
8. Better flood extent predictions					

9. Better drought predictions					
10. Better lake level predictions					
11. More scenarios of hydrological predictions					

Quantifying the value of AI-enhanced climate services

- What are your criteria to measure success of Climate Services (in supporting your operational activities)?
- Is there any quantitative formulation of these criteria available? If yes, could you provide a description (or any relevant web link)?

Annex 2: End-users semi-structured interviews

This annex provides a list of the questions that were asked during semi-structured interviews to the end-users. The questions here are presented in general terms, referring to extreme events. However, during the semi-structured interviews, questions were tailor-made for the extreme events faced in the specific case study. So, for instance, in the case of Douro river basin, all the questions were specifically referring to drought events.

Basic Data

- What would you envisage to get out of this project?
- Additional competent authorities and/or users
- Who are the main actors in the system that actively participate in the decision making?

Formulating user-inspired EE variables and indices (specify the EE)

- What do you consider as an extreme event (e.g. drought): general, problematic extreme event for the case study?
- What do you consider as relevant information that is used as (early) indication of an upcoming extreme event?
- What information do you think could be used in addition to what you already use as an early indication for the extreme event?
- What are the (negative) consequences of the extreme event?
- What could be relevant measures for prevention, mitigation, response and recovery of the extreme event impact?
- Do you perceive that climatology is losing reliability as a benchmark for forecasting what will happen in the future in terms of the extreme event? If so, do you plan to make any modifications in your current indicator systems and DSSs to solve this?
- Do you consider Climate Change as a cause of current extreme events or as something that will affect in the future?
- Do you plan to incorporate the Climate Change projections into daily planning, e.g. by modifying the indicator system?

Specifications of local existing services and data and on the decision-making process

- What are the key dates for decision making and in which management body are the decisions made?
- How does the extreme event affect the decision-making process?
- Kind request for references to and/or detailed description of the extreme event monitoring, prediction/outlook, preparedness, and event management procedures.

- Kind request for historic observational data, forecasts/predictions, list of past extreme events, overview/information on past event management (what was done before, during, and after the events, what was done in other years).
- What are the models, Climate Services, Decision Support Systems (DDS) currently in use?

Needs for local climate services

- Which are the main present and future challenges in managing EE? Which are the main sources of conflicts and negotiations?
- Do you consult/integrate any sort of forecast into decision-making? If so, what are the main limitations to interpret and use forecast information? E.g. forecast skill, resolution, probabilistic nature of the forecast.
- What are the characteristics of the desired forecast temporal and spatial resolution, form of data, provision way, variables?
- Are you satisfied with the Climate Change projections provided by the National Weather Agency? What kind of improvement would be useful?
- What are the climate change impact variables of interest?

Quantifying the value of AI-enhanced climate services

- What are the criteria you use to measure the success in managing the extreme event?

CLINT

CLIMATE INTELLIGENCE