D1.1- Report on Urban Flood and Water & Food security indicators

WP Leader:	**European Union Satellite Centre (SatCen)**
Task Leader:	e-geos (Task 1.1) and SatCen (Task 1.2)
Revision Date:	15/06/2023
Submission Date:	15/06/2023
Document Type:	Report
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Approved by:	Luisa Bettili (Project Coordinator, e-geos) and shared with the Consortium
Version	1.0
Dissemination Level:	Public (PU)

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This document is issued within the frame and for the purpose of the CENTAUR project. This project has received funding from the European Union's HORIZON-CL4-2021-SPACE-01 - Strategic Autonomy in Developing, Deploying and Using Global Space-based Infrastructures, Services, Application and Data *Framework Programme under Grant Agreement No. 101082720. The opinions expressed and arguments employed herein do not necessarily reflect the official views of the European Commission.*

HISTORY OF CHANGES

Date	Version	Author	Change Description
23/02/2023	0.1	Alexandre Arnal, Yannick Arnaud	Initial version with ToC
31/05/2023	1.0	ADE, CLS, DLR, ECM, EG, GMV, ITH, SAT, UNI, VIT	First version of the document

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1 EXECUTIVE SUMMARY

The present document represents the deliverable *D1.1 - Report on Urban Flood and Water&Food security indicators* of CENTAUR project and is produced under the Work Package *WP1 - Analysis of requirements and use cases definition*, in particular, under Tasks 1.1 and 1.2 that are in charge of an analysing the key reference data inputs needed to generate the indicators in both Flood and Food/Water Insecurity domains that will be performed.

The document analyses the underlying elements that should lay the groundwork for subsequent activities in CENTAUR by:

- Assessing how the current Copernicus CEMS and CSS-SEA service model with respect to Urban Flood risks and Water & Food Insecurity.
- Assess the user needs and define the user requirements for both Urban Flood risks and Water & Food Insecurity, based on users consultation activities.
- Identifying gaps in current response tools and determine ways to overcome them and enable appropriate responses to complex emergencies and crisis.
- Providing a preliminary inventory of basic indicators to be considered in the project, which will be completed during execution of *WP2 - Thematic product engineering*.

The information here included will be the basis for the *D1.2 - Report on CENTAUR Use Cases and Indexes definition* produced also under WP1 and with the aim to undertake a cross cutting analysis, to define the Use Cases according to EMS & SEA needs, and to design an advanced composite crisis indexes that will take advantage from the experience of already existing services.

2 INTRODUCTION

2.1 CENTAUR PROJECT DESCRIPTION

Climate change is a fact and its impact on human lives and security is continuously growing. The EU understood the importance and consequences of climate change a long time ago, adopting ambitious legislation in different policy areas. The Green Deal recognises that tackling climate change and striving for climate neutrality should be placed at the centre of societal and economic transformation. Over the last 50 years, more than 11.000 reported disasters related to extreme weather and climate conditions have caused over 2 million deaths and US$ 3,64 trillion in losses. The number of disasters has multiplied by a factor of five during that period, mainly driven by

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climate and more weather extremes[1]. In particular, the last twenty years have seen the number of major floods more than double, from 1.389 to 3.254, while the incidence of storms grew from 1.457 to 2.034[2]. Floods and storms were the most prevalent events and floods are the most common type of disaster worldwide, accounting for 44% of total events registered in the last twenty years. A global temperature increase of the global climate is estimated to increase the frequency of potentially high impact natural hazard events across the world. This could render current national and local strategies for disaster risk reduction and climate change adaptation obsolete in many countries. In total, between 2000 and 2019, there were 3,068 disaster events in Asia, 1,756 events in the Americas and 1,192 events in Africa.

Climate change is increasingly acknowledged within the EU's integrated approach to security. The related environmental degradation is recognized as a threat multiplier and an aggravating factor for political instability with serious implications for peace and security across the globe[3]. Nowadays, climate change is already causing people to migrate, and while migration should not be directly labelled as a security problem, implicitly the link with pressures on society and increased competition for resources are often made[4]. People living in places affected by violent conflict are particularly vulnerable to climate change and it is agreed that some of the factors that increase the risk of violent conflict are sensitive to climate change[5]. This way, it is estimated that 95 % of new displacements by conflicts in 2020 happened in countries that have high or very high vulnerability to climate change[6]. From 2008 to 2016, this represents over 20 million people per year that have been forced to migrate due to climate change effects[7].

Within Copernicus Security and Emergency Services evolution, the objective of CENTAUR is to respond to societal challenges deriving from Climate Change threats by developing and demonstrating new service components for the Copernicus Emergency Management Service (CEMS) and Copernicus Security Service - Support to EU External Action service (CSS-SEA), aiming to:

1. Improve situational awareness and preparedness around climate change and its impact on complex emergencies and multi-dimensional (security) crises;
2. Anticipate the occurrence and possible knock-on effects of crisis events, in particular those triggered by climatic extremes, thus contributing to resilience and effective adaptation.

In the emergency domain, CENTAUR will address the flood-related threats to population, assets and infrastructures in urban areas. In the Security domain, CENTAUR will address water & food insecurity. The two work streams will be connected via a cross-cutting component focusing on exposure and vulnerability to climate change, as well as resilience and societal capacity for managing environmental risks and social conflict. Across work streams, indicators and models will be validated by different methods. CENTAUR will integrate data coming from multiple heterogeneous sources, with a specific focus on those generated by other Copernicus services, and, in particular, those of the Climate Change Service). It will combine these with meteorological data, socio-economic data, and data coming from new sensors (e.g. traditional and social media). Thus, it will enhance current capacities to produce composite risk indexes and to perform multi-criteria analyses in the emergency and security domains.

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[1] World Meteorological Organization (2021). WMO atlas of mortality and economic losses from weather, climate and water extremes (1970–2019).

[2] UNDRR report: The human cost of disasters: an overview of the last 20 years (2000-2019).

[3] Meyer, C., Vantaggiato, F. P., & Youngs, R. (2021). Preparing the CSDP for the new security environment created by climate change. European Union.

[4] Schaik, L., Bakker, T. (2017). Climate-migration-security: Policy Brief Making the most of a contested relationship. Planetary Security.

[5] W.N., J.M. Pulhin, J. Barnett, G.D. Dabelko, G.K. Hovelsrud, M. Levy, Ú. Oswald Spring, and C.H. Vogel (2014). Human security. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken,
P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 755-791.

[6] University of Notre Dame. (n.d.). Country index // Notre Dame Global Adaptation Initiative // University of Notre Dame. Notre Dame Global Adaptation Initiative. Retrieved January 23, 2022, from https://gain.nd.edu/our-work/country-index/.

[7] WEF (2020). *The Global Risks Report 2020*, Insight Report 15th Edition. World Economic Forum, Geneva Switzerland, p. 102. https://www.weforum.org/reports/the-global-risks-report-2020.

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2.2 SCOPE OF THE DOCUMENT

This document is produced under *WP1 - Analysis of requirements and use cases definition* that has the objective to provide user requirements and indications and to lay the groundwork for subsequent activities in CENTAUR.

Tasks 1.1 and 1.2 are in charge of an analysing the key reference data inputs needed to generate the indicators in both Flood and Food/Water Insecurity domains that will be performed. On one side, Task 1.1 is in charge of reviewing of EMS operations for Urban Flood detection and monitoring, gap analysis and definition of indicators. Taking advantage from the operational experience and events covered in EMS RM and RRM for flood events in urban contexts, including different types of urban morphology, the main limitation in terms of coverage, delivery times, production strategies and user feedback are reviewed. On the other side, Task 1.2 is in charge of reviewing of SEA operations for Water & Food Insecurity impacts, gap analysis and definition of indicators. The task starts with an end-user driven gap analysis between current Copernicus SEA operational Service Model and the desired service provision to respond to Climate Security impacts (in particular water & food insecurity). For this purpose, the review of the current service portfolio and past production is focused on: (a) reactive intelligence products that may be enriched by applying a new transversal approach that considers the climate change and its effects on the environment and population; (b) the SEA systems and platforms devoted to produce intelligence in a proactive way. It also includes proposals for new Copernicus SEA products and services in the water & food insecurity domain. In parallel, a complete state of the art review covering potentialities and limitations of the following long-term open data sources and indicators, in terms of spatial and temporal resolution, coverage, quality, suitability and accessibility are performed.

The main scope of this document is to report possible improvements and proposed evolutions at Copernicus CEMS and CSS-SEA level, by describing all existing data sources and indicators to be harvested, processed and integrated in the CENTAUR platform and identifying new indicators that should be generated within CENTAUR.

To cover the above objectives, the document has been structured into the following sections:

- Section 1. Summary of the document's contents.
- Section 2. Introduction, scope of the document, definitions, abbreviations, acronyms and reference documents.
- Section 3. Context of the project, both for urban flood detection and monitoring, and water and food insecurity impacts.
- Section 4. Gathering and analysis of user requirements.
- Section 5. Analysis of the gaps between current portfolio and the desired state of operations for CEMS.
- Section 6. Analysis of the gaps between current portfolio and the desired state of operations for CSS-SEA.
- Section 7. Identification and definition of datasets and indicators, both for CEMS and CSS-SEA.
- Section 8. Summary of the datasets and indicators.
- Section 9. Main conclusions.

2.3 DEFINITIONS, ABBREVIATIONS AND ACRONYMS

In this chapter, we delve into the fundamental concepts of datasets, indicators indexes and triggers exploring their unique characteristics and highlighting the key distinctions that set them apart.

There are numerous definitions of indicator:

- Broadly speaking, an indicator can be a sign, symptom, signal, tip, clue, grade, rank, object, organism, or warning of some sort — many things in everyday life (Meadows, 1998). In a more restricted sense, as is often used in the scientific literature, an indicator refers to a variable or an aggregate of multiple related variables

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whose values can provide information about the conditions or trajectories of a system or phenomenon of interest. In other words, an indicator is simply "an operational representation of an attribute (quality, quantity, characteristic, property) of a system" (Gallopin, 1997).

- An indicator is a quantitative metric that provides a signal or sign of the presence, state, or rate of change of a situation or condition. It is derived from raw/input data through a process of analysis and interpretation and is used to provide insight into specific phenomena or trends. Indicators are often used as benchmarks to make decisions and are based on variables that supply information on other variables that are more difficult to access. They can be used for comparison or difference and are typically designed to be easily understood.

An index, instead, is an aggregate of two or more indicators.

- An index is a combination of indicators into a single value/score is called an index. An index is thus a compound measure (a compound-indicator) aggregating multiple indicators (and depends on this set of indicators). An index typically measures multi-dimensional concepts which cannot be captured by a single indicator. Indices in this sense are similar to mathematical, computational or statistical models. Similar to indicators, indices are standardized measures that allow for comparisons over time, over different geographic areas and/or across tasks (trends).

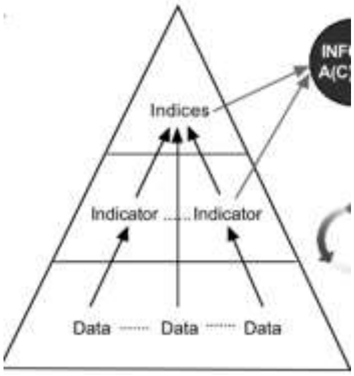

Figure 1. Data, Indicator and Index.

Finally, triggers, warnings and alarms may be based on indicators or indices. If certain specific conditions are met, an associated action is carried out. In case values on key risk-indicators or crises-indices exceed a defined threshold, an action will be triggered. This action may entail the re-calculation of other indicators or indices, modifications of data-collection schedules, additional enrichment or (re-) processing of data elements, email or social media notification of persons or updating of visualization/dashboards etc. The severity of the detected change can be taken into account for the kind of action(s) taken (e.g. immediate notification vs casual email). Relevant stakeholders can be notified rapidly and provided with relevant information.

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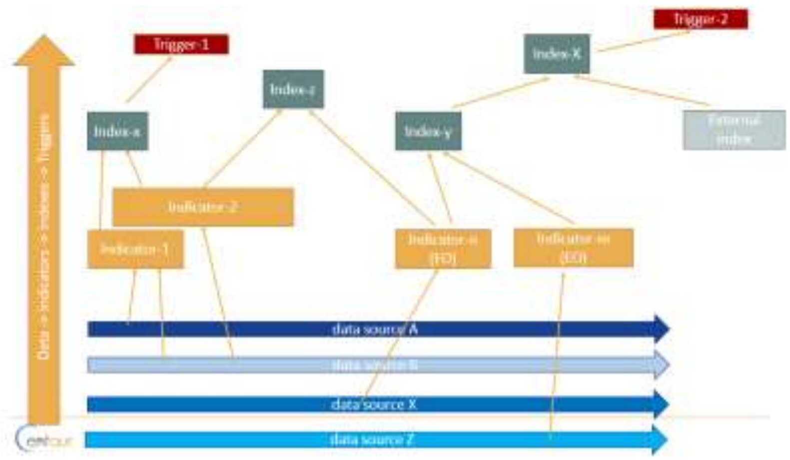

Table 1. Table with abbreviations and acronyms.

Acronym	Description
AOI	Area of Interest
BN	Briefing Note
CEMS	Copernicus Emergency Management Service
CMC	Country Map Coverage
CPCC	Civilian Planning and Conduct Capability
CSDP	Common Security and Defence Policy
CSS-SEA	Copernicus Security Service in Support to EU External Action
DG GROW	Directorate-General Internal Market, Industry, Entrepreneurship and SMEs
DGI	Digital Geographic Information
DRC	Danish Refugee Council
EC	European Commission
ECOWAS	Economic Community of West African States
EEAS	European External Action Service
EO	Earth Observation
EU INTCEN	European Union Intelligence and Situation Centre
EU	European Union
EUMS	European Union Military Staff
FAO	Food and Agriculture Organisation of the United Nations
FIR	First Impression Report
GIS	Geographic Information System

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Acronym	Description
HR/VP	High Representative of the Union for Foreign Affairs and Security Policy/Vice-President of the European Commission
IDP	Internally Displaced Persons
IHL	International Humanitarian Law
IPC	Integrated Food Security Phase Classification
ISP	Integrated approach for Security and Peace Directorate).
JRC	Joint Research Centre
MB	Mapbook
MINUSMA	Multidimensional Integrated Stabilization Mission in Mali
MPCC	Military Planning and Conduct Capability
OSINT	Open-Source Intelligence
PSC	Political and Security Committee EU
QR	Quick Report
REST	Representational State Transfer
SAR	Synthetic-Aperture Radar
SitRoom	EEAS Situation Room
UNEP	UN Environment Programme
UNDP	United Nations Development Programme
CSM	United Nations Climate Security Mechanism
UNSOM	United Nations Assistance Mission in Somalia
VHR	Very High Resolution
WFP	World Food Programme

2.4 APPLICABLE AND REFERENCE DOCUMENTS

Table 2. Table with applicable and reference documents.

ID	Document name
[1]	Copernicus Service in Support to EU External Action: https://sea.security.copernicus.eu/
[2]	Disaster Risk Reduction in EU external action - Council conclusions (28 November 2022): https://data.consilium.europa.eu/doc/document/ST-14463-2022-INIT/en/pdf

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3 SETTING THE SCENE

3.1 URBAN FLOOD DETECTION AND MONITORING

As the Anthropocene is stage of an acceleration and amplification of human-induced processes, water is set to play a crucial role in the coming decades as both a resource and a hazard. Due to climate change and complex, often unpredictable feedback loops, monitoring the hydrological cycle, including flood events, has become increasingly challenging. Notably, Tarasova et al. (2023)[8], Tabari (2020)[9], and Blöschl et al. (2019)[10] have observed anomalies in precipitation and flood distribution, frequency, and intensity across Europe over the past few decades. Disregarding the ten-fold increase in the number of reported flood events between 1950 and today[11] (Figure 2), such variability is anticipated to challenge existing prevention, management, and monitoring systems.

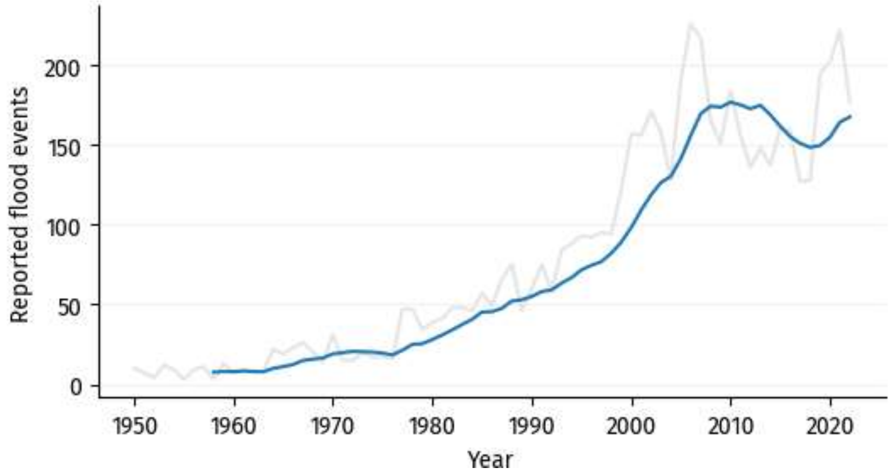

Figure 2: Annual number of flood events reported worldwide between 1950 and 2022. Data: EM-DAT/CRED.

As of now, it is estimated that 1.47 billion people worldwide are directly exposed to the risk of intense flooding, with nearly 600 million living in poor conditions[12]. This is particularly concerning for densely populated areas, like urban centres, where proper planning is essential to avert catastrophic events and facilitate efficient recovery efforts. It also includes coastal populations and urban areas that are especially vulnerable to extreme storm events and rising sea levels. In Europe, 51% of the EU population lives in coastal regions, concentrating in 2008 more than 200 million people[13] and many critical economic and social activities and infrastructures.

[8] Tarasova, L., Lun, D., Merz, R., Blöschl, G., Basso, S., Bertola, M., Miniussi, A., Rakovec, O., Samaniego, L., Thober, S., & Kumar, R. (2023). Shifts in flood generation processes exacerbate regional flood anomalies in Europe. Communications Earth & Environment, 4(1), 49. https://doi.org/10.1038/s43247-023-00714-8

[9] Tabari, H. (2020). Climate change impact on flood and extreme precipitation increases with water availability. *Scientific Reports*, *10*(1), 13768. https://doi.org/10.1038/s41598-020-70816-2

[10] Blöschl, G., Hall, J., Viglione, A., Perdigão, R. A. P., Parajka, J., Merz, B., Lun, D., Arheimer, B., Aronica, G. T., Bilibashi, A., Boháč, M., Bonacci, O., Borga, M., Čanjevac, I., Castellarin, A., Chirico, G. B., Claps, P., Frolova, N., Ganora, D., … Živković, N. (2019). Changing climate both increases and decreases European river floods. *Nature*, *573*(7772), 108-111. https://doi.org/10.1038/s41586-019-1495-6

[11] Jha, A. K., Bloch, R., & Lamond, J. (2012). *Cities and Flooding : A Guide to Integrated Urban Flood Risk Management for the 21st Century*. The World Bank. https://doi.org/10.1596/978-0-8213-8866-2

[12] Rentschler, J., & Salhab, M. (2020). People in Harm's Way : Flood Exposure and Poverty in 189 Countries. https://doi.org/10.1596/1813-9450-9447

[13] European Commission, Eurostat, Önnerfors, Å., Brandmüller, T., *Eurostat regional yearbook 2011*, Publications Office, 2011, https://data.europa.eu/doi/10.2785/1392

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As cities are projected to accommodate an additional 2.5 billion people worldwide by 2050 (United Nations, 2019), addressing urban floods has emerged as a defining challenge of the 21st century

3.1.1 Context

Climate change is presenting the main challenge to our planet. Global warming cause increase in overall world temperature, leading to evapotranspiration and atmospheric moisture content, and associated changes in rainfall patterns[14]. The effect of warming is also likely to be more severe for urban areas.[15] Urban areas face global challenges of flood risk not only due to climate change but also due to the continued densification of residential areas, infrastructure development, and urban sprawl.[16] Higher temperatures resulting from urban heat island (UHI) impacts the urban micro-climate, amplifying the climate variability resulting from global warming, and increasing the severity of rainfall events in these areas[17].

In parallel, all regions of the world are envisioned to be urbanized further considering the increasing population and migrations. Urban areas are already home to 55 per cent of the world's population, and that figure is expected to grow to 68 per cent by 2050.[18] A resulting impact is the increment of expected urban flood risk in many areas around the globe.[19] Consequently, sustainable development challenges will be increasingly concentrated in cities and managing urban flood risk can be seen as a key global task of the twenty-first century.

Many cities and urban areas are located in floodplains due to the suitability of flat, fertile land for agriculture and urban development, while rivers provide water supply, navigation, and transportation. Such benefits have been the driving force behind urbanization, the process by which population shifts from rural to urban areas. Urbanization is tightly related to the process of soil sealing, which replaces vegetation and natural land cover with impermeable structures such as buildings, roads, and parking areas[20]. This is the phenomenon by which the quantity of artificial surfaces has more than doubled between 1985 and today[21] . This change reduces or eliminates the soil's capacity to absorb water, increasing surface runoff and overwhelming urban drainage systems[22]. In this way, flood risk becomes more closely associated with the urban environment, affecting not only major cities but also medium and small communities. Thus, we can define urban flooding as the inundation of property in a built environment, particularly in densely populated areas, resulting from water flowing on increased impervious surfaces. This excludes flooding in natural or semi-natural areas and primarily affects buildings, infrastructure, the economy, and health and safety. Indeed, urban floods cause significant property damage, fatalities, and injuries, with repetitive, costly, and systemic impacts on communities. Both drivers and consequences will be discussed in further detail in the next subsection[23].

As urbanization continues to accelerate, it is crucial for policymakers, urban planners, and engineers to prioritize integrated flood management and incorporate it into the planning and development of new urban areas from the outset. Indeed, the rapid pace at which cities grow has increased exposition and severity of flood events, especially

[14] Wang et al., (2016);
[15] S. Hadi Pour et al., (2020);
[16] R. Berndtsson et al., (2019);
[17] Liu & Niyogi, 2019; Ren, (2015); Şimşek & Ödül, (2019); Yang, Ren, Hou, & Liu, (2013);
[18] World Cities Report - UN-Habitat, (2022);
[19] A. Alves et al., (2020);
[20] Bairoch, P. (1988). Cities and Economic Development: From the Dawn of History to the Present. University of Chicago Press.
[21] Zhang, X., Liu, L., Zhao, T., Gao, Y., Chen, X., & Mi, J. (2022). GISD30: Global 30 m impervious-surface dynamic dataset from 1985 to 2020 using time-series Landsat imagery on the Google Earth Engine platform. Earth System Science Data, 14(4), 1831-1856. https://doi.org/10.5194/essd-14-1831-2022
[22] Tobias, S., Conen, F., Duss, A., Wenzel, L. M., Buser, C., & Alewell, C. (2018). Soil sealing and unsealing: State of the art and examples. Land Degradation & Development, 29(6), 2015-2024. https://doi.org/10.1002/ldr.2919
[23] Hammond, M. J., Chen, A. S., Djordjević, S., Butler, D., & Mark, O. (2015). Urban flood impact assessment: A state-of-the-art review. Urban Water Journal, 12(1), 14-29. https://doi.org/10.1080/1573062X.2013.857421

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along coastlines and streams[24] [25]. This is particularly true in developing countries, where soil sealing often occurs in informal settlements. Additionally, in highly urbanized areas, the implementation of engineering measures for flood mitigation is problematic due to the presence of high-density buildings and complex underground infrastructure. Data shows the implementation of a proper blue-green infrastructure leads to a decrease of insurance claims related to flood events, indicating a better risk management system. However, such measures remain scarce at an international scale[26]. As a result, non-engineering approaches, such as flood risk warning systems, become the primary method for managing urban flood risk[27].

The Copernicus Emergency Mapping Service (CEMS), which is regularly solicited by risk and crisis management actors for its timely provision of flood data, is a good indicator of the prominence and ever-growing part of flood events worldwide. The scope of intervention of CEMS Rapid Mapping (RM) highlights that flooding is the most frequent hazard within CEMS and accounts for 34% of activations (Figure 3). Moreover, product demand for these events has been trending upward between 2012 and 2022 (Figure 4).

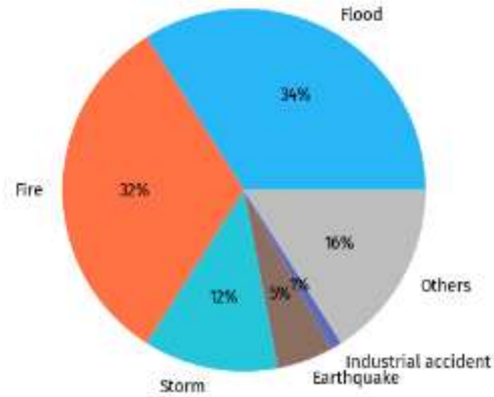

Figure 3: Distribution of event types for the available CEMS RM- activations. Data: Copernicus EMS RM

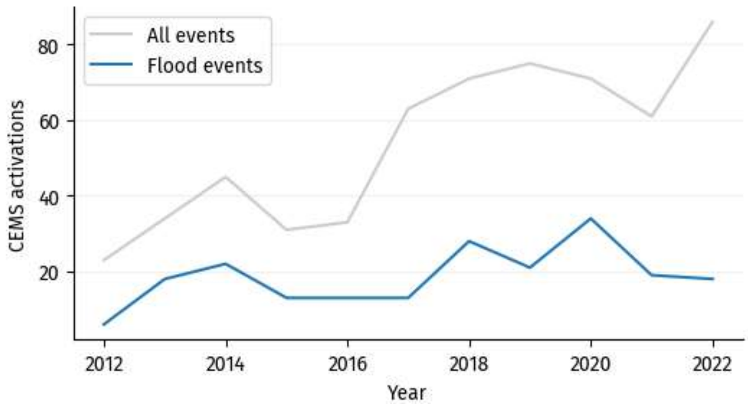

Figure 4: Demand for flood products within CEMS, against demand for all types of products combined, between 2012 and 2022. Data: Copernicus EMS RM

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[24] Chen, Y., Zhou, H., Zhang, H., Du, G., & Zhou, J. (2015). Urban flood risk warning under rapid urbanization. Environmental Research, 139, 3-10. https://doi.org/10.1016/j.envres.2015.02.028; World Bank. (2017). Land Use Planning for Urban Flood Risk Management. World Bank, Washington, DC. https://doi.org/10.1596/26654

[25] World Bank. (2017). Land Use Planning for Urban Flood Risk Management. World Bank, Washington, DC. https://doi.org/10.1596/26654

[26] Sörensen, J., & Emilsson, T. (2019). Evaluating Flood Risk Reduction by Urban Blue-Green Infrastructure Using Insurance Data. *Journal of Water Resources Planning and Management*, *145*(2), 04018099. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001037

[27] Tingsanchali, T. (2012). Urban flood disaster management. Procedia Engineering, 32, 25-37. https://doi.org/10.1016/j.proeng.2012.01.1233

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Of all the flood events processed within CEMS RM, approximately 90% impacted individuals, indicating that these disasters occurred in populated areas and thus constitute urban flooding, as per the definition proposed earlier. Floods, specifically urban floods, are the most consequential events in terms of human impact as well as damage to assets. The impact of flooding could be even greater if storms are associated with flooding, as these events typically result in the inundation of large built-up areas.

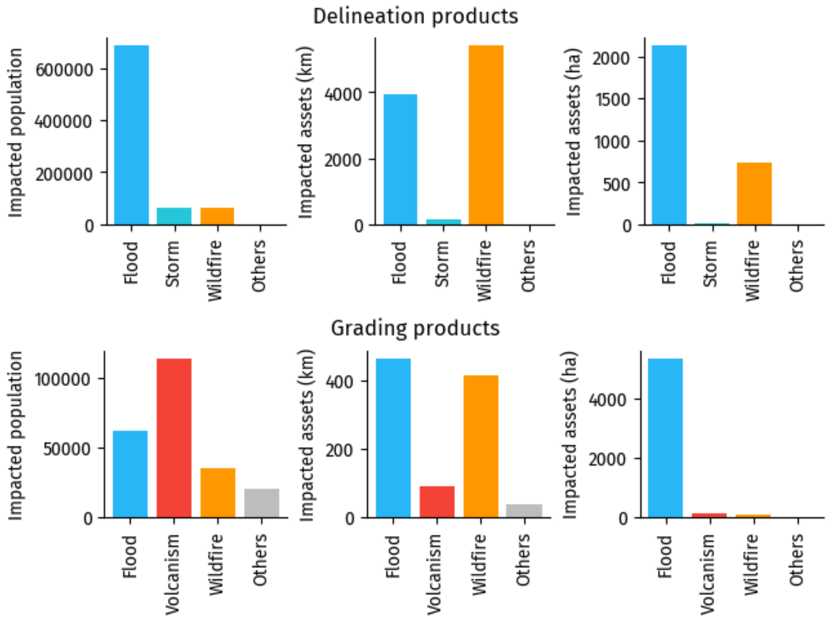

Figure 5: Impact on material assets and human populations resulting from events that triggered an activation within CEMS since 2021. Impacted assets encompass facilities and transportation infrastructure but exclude buildings. Only delineation and grading products were considered. Data: Copernicus EMS RM

Since 2021, floods have scored the highest in terms of impact for 4 out of 6 indicators for delineation and grading products (Figure 5). Considering delineation products only, floods have affected approximately 700,000 individuals, a figure that is more than ten times higher than the 65,000 individuals impacted by wildfires. The length of linear assets potentially affected by floods and wildfires was 4,000 and 5,500 km respectively. Additionally, 2,200 ha were potentially inundated, compared to 750 ha potentially affected by wildfires. Considering grading products only, 60,000 individuals were affected by floods, which is about twice less than volcanic activity. However, floods have impacted the most assets, both linear and surface, with 450 km and 5,500 ha respectively. The figures for other events were negligible and thus not discussed; however, flooding and urban flooding appear to be the most destructive hazards within CEMS RM activities.

3.1.2 Drivers of urban flood

In this subsection, the drivers and impacts of urban floods are addressed. First, the factors and drivers influencing urban floods are analysed. Then, the focus is shifted to susceptible areas, and finally, the effects of urban floods on population and infrastructure are assessed. The following infographic (Figure 6) created by The Associated Programme on Flood Management, which is a joint initiative of the World Meteorological Organization (WMO) and the Global Water Partnership (GWP), summarizes stakeholders, characteristics of urban floods, objectives, mitigation measures and challenges. The figure is designed for the general public and visualize key information in an easily understandable and sharable format, to promote a new approach to flood management.

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Figure 6: Summary of stakeholders, characteristics of urban floods, objectives, mitigation measures and challenges based on the Associated Programme on Flood Management (Source: Associated Programme on Flood Management)

Urbanization and land use changes

One of the main factors which influence urban flood is the urbanization phenomenon. The growing urban population and degree of urbanization put great pressure on the existing drainage systems, which results in reduced capacity for excess water. The high presence of asphalt and paved surfaces limit water infiltration and increase the amount of water running off the ground surface as well as its speed[28]. Soil sealing, which consists of the permanent covering of the land surface by buildings, infrastructures, or any impermeable artificial material,

[28] Ochoa Rodriguez S, Wang L-P, Thraves L, Johnston A, Onof Cet al., 2015, Surface water flood warnings in England: overview, Assessment and recommendations based on survey responses and workshops, Journal of Flood Risk Management, Vol: 11, Pages: S211-S221, ISSN: 1753-318X

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has been identified as a major threat in the Soil Thematic Strategy of the European Commission[29]. Stopping soil sealing and increasing the reuse of urban soils is one of the eight EU mission objectives of 'A Soil Deal for Europe' by 2030[30].

Nowadays, land is becoming scarce as safe spaces in urban areas become increasingly occupied, and new buildings are constructed on previously avoided areas such as flood plains, riverbeds or wetlands, leading to a greater risk for flooding. The world's urban settlements have grown by 85 percent, from 693,000 km2 in 1985 to over 1.28 million km2 in 2015. In 2015, 11% of all settlement areas (145,000 km2) were located in zones with high or very high flood risk[31].

Another important factor to consider in relation to urban flooding is soil erosion. Urban development can lead to increased runoff, which causes erosion in fragile soils and has significant impacts on the urban environment. Deforestation and farming also contribute to the loss of vegetation cover, leading to more frequent sediment production and river clogging. The heavy layers of sediment prevent streams and rivers from flowing smoothly and can eventually lead to flooding. And once soil erosion occurs, the probability that a flood event takes place again in that context is much higher. Additionally, improper waste disposal can also obstruct water flow. In some low-income nations in Africa and Asia, many informal settlements lack sewers, piped-in water, and solid waste collection and disposal services, leading to increased risk of flooding[32].

Climate change and extreme weather events

Climate change is another factor that exposes populations and infrastructure to urban flooding, significantly impacting poor people and critical infrastructure[33]. The intensity of extreme precipitation events is increasing with global warming. An increase in average atmospheric temperature leads to a higher moisture capacity of the atmosphere, creating more favourable conditions for intense rain and storms and making the hydrological cycle more unstable. Moreover, large urban agglomerations can function as "heat islands," further raising the air temperature in localized areas and resulting in an increase in the amount and intensity of precipitation in urban areas[34].

A further aspect to be considered is that global warming is causing the mean sea level to rise as glaciers and ice sheets melt and add water to the ocean. Secondly, the volume of the ocean is expanding as the water warms. Sea-level rise poses a significant threat to the lives and livelihoods of millions of people, infrastructure, ecosystems,

[29] European Commission, Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions. Brussels: Commission of the European Communities. Thematic strategy for soil protection. COM (2006) 231 final. European Commission, Brussels.

[30] European Commission, Directorate-General for Research and Innovation, Communication and citizen engagement initiatives in line with the Horizon Europe Mission A Soil Deal for Europe: report on A Soil Deal for Europe: 100 Living labs and lighthouses to lead the transition towards healthy soils by 2030 Publications Office of the European Union, 2022.

[31] Rentschler, J., P. Avner, M. Marconcini, R. Su, E. Strano, S. Hallegatte. 2022. Rapid Urban Growth in Flood Zones: Global Evidence since 1985. Policy Research Working Paper 10014 https://blogs.worldbank.org/developmenttalk/rapid-urban-growth-flood-zones-global-trends-exposure-1985

[32] Satterthwaite, David & Huq, Saleemul & Reid, Hannah & Pelling, Mark & Romero-Lankao, Paty. (2007). Adapting to Climate Change in Urban Areas: The Possibilities and Constraints in Low and Middle-Income Nations1. Adapting Cities to Climate Change: Understanding and Addressing the Development Challenges. 10.4324/9781849770361.

[33] Ajjur, S.B., Al-Ghamdi, S.G. Exploring urban growth–climate change–flood risk nexus in fast growing cities. Sci Rep 12, 12265 (2022). https://doi.org/10.1038/s41598-022-16475-x

[34] World Meteorological Organization (WMO) and the Global Water Partnership (GWP), Integrated flood management tools series: Urban flood management in a changing climate. Integrated Flood Management Tools Series No. 14, February 2012 https://library.wmo.int/doc_num.php?explnum_id=7333

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and world heritage in the low-level coastal zone[35]. Several major cities in coastal regions are quite vulnerable to sea level rise, especially in Asia (China, India, Bangladesh) and Southwest Asia (Indonesia, Philippines)[36].

Another important effect of climate change is related to the alteration of the groundwater cycle and the exacerbation of the unequal distribution of water resources. Groundwater is the world's third-largest reservoir of water resources and the largest reservoir of liquid freshwater on Earth[37]. It is also a vital natural resource for human survival, and it provides drinking water to more than 2 billion people worldwide[38]. Climate change affects groundwater systems by altering soil infiltration, deeper percolation, and thus groundwater recharge. Additionally, rising temperature increases water evaporation over land, reducing the amount of water available to replenish groundwater reserves. In contrast, anthropogenic effects such as groundwater pumping and changes in land use patterns and irrigation practices also have significant effects on groundwater resources[39].

Poor or inadequate risk mitigation practices

In general, the flood risk is increasing worldwide due to poor management and inadequate mitigation measures, especially in developing countries. Measures to mitigate flood risk are often categorized as structural and non-structural. Structural mitigation measures, such as embankments, dikes, and drainage, may be challenging to implement in highly urbanized areas due to resource and space limitations and the presence of high-density structures. Non-structural flood mitigation measures, such as improved flood warning systems, evacuation plans, and flood forecasting, are still not extensively applied[40]. There are still significant differences around the world in terms of information and political actions taken to design policies to mitigate the risk of flooding.

Susceptible areas in the context of urban flooding

World Bank estimates that 1.81 billion individuals, which accounts for roughly 23% of the world's population, are directly vulnerable to flood depths exceeding 0.15 meters in the occurrence of a 1-in-100-year flood event. This puts many people's lives and means of livelihood at significant risk. Among them, 89% reside in low and middle-income countries[41].

[35] IPCC, 2019: Summary for Policymakers. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. In press.

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[41] Flood risk already affects 1.81 billion people. Climate change and unplanned urbanization could worsen exposure. World Bank, June, 2022. Retrieved from https://blogs.worldbank.org/climatechange/flood-risk-already-affects-181-billion-people-climate-change-and-unplanned

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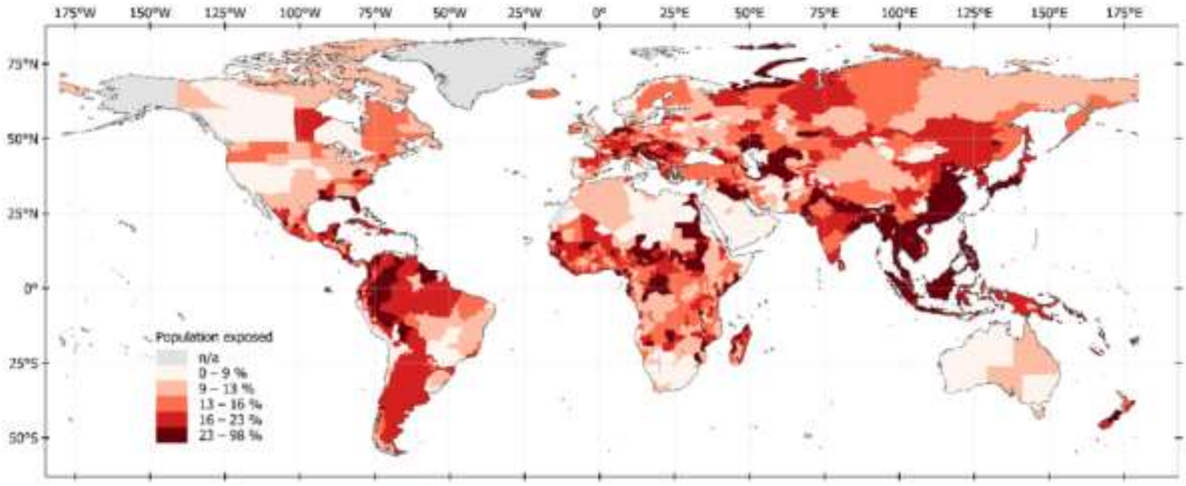

Figure 7: The share of people living in high-risk flood zones (Source: Rentschler, J, Salhab, M and Jafino, B. 2022. Flood Exposure and Poverty in 188 Countries)

Floods can cause significant damage and suffering, especially in lower-income countries where infrastructure systems, such as drainage and flood protection, are typically less developed. In these countries, floods often result in unmitigated damage[42].

The subject of urbanization in flood-prone areas in the process of urban renewal is currently being vigorously discussed for several reasons. It's an established fact that our cities have mostly been developed along waterways and at the seaside in the course of history for economic, political, and social reasons.

Rentschler, Salhab and Jafino[43] highlight that several nations have notably significant populations directly vulnerable to a high risk of flooding. It's evident that countries with larger populations are more likely to have greater numbers of people living in direct exposure to flood risk. India and China, the two most populous countries, have the highest headcounts in absolute exposure, with 390 million and 395 million individuals respectively, accounting for roughly one-third of all people exposed to flood risk worldwide. However, features like geography and patterns of urbanization can substantially increase the size of exposed populations. The ten nations with the highest headcounts of exposure comprise countries where large population clusters are concentrated along major river systems (such as Bangladesh, Egypt, and Vietnam) or in coastal regions (such as Indonesia and Japan).

Mapping and analysis of flood susceptibility are among the most important elements of early warning systems or strategies for the prevention and mitigation of future flood situations, as it identifies the most vulnerable areas based on physical conditions that determine the propensity for flooding. Therefore, the term susceptibility can also be perceived as one of the dimensions of vulnerability assessment[44] [45] [46]. Generally, flood susceptibility mapping techniques rely on various conditioning factors representing the physical characteristics of the investigated area. These factors usually include geology or lithology, morphometric properties (e.g., elevation, slope), river network density, soil types or hydrological soil groups, land use/land cover, etc. In order to identify

[42] Winsemius, H., Aerts, J., van Beek, L. et al. Global drivers of future river flood risk. Nature Clim Change 6, 381–385 (2016). https://doi.org/10.1038/nclimate2893

[43] Rentschler, J., Salhab, M. & Jafino, B.A. Flood exposure and poverty in 188 countries. Nat Commun 13, 3527 (2022). https://doi.org/10.1038/s41467-022-30727-4

[44] Adger, N.W. Vulnerability. *Glob. Environ. Chang.* 2006, *16*, 268–281

[45] Jacinto, R.; Grosso, N.; Reis, E.; Dias, L.; Santos, F.D.; Garrett, P. Continental Portuguese Territory Flood Susceptibility Index—Contribution to a vulnerability index. *Nat. Hazards Earth Syst. Sci.* 2015, *15*, 1907–1919.

[46] Vojtek, M.; Vojteková, J. Flood Susceptibility Mapping on a National Scale in Slovakia Using the Analytical Hierarchy Process. *Water* 2019, *11*, 364. https://doi.org/10.3390/w11020364

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and assess flood susceptible areas, various methods have been developed and applied in different geographic areas. The selected methodology should sufficiently represent the spatially continuous and cumulative nature of the parameters' influence on flood-generating mechanisms. In addition, selection of an appropriate methodology for flood susceptibility mapping should also depend on the spatial scale (local, regional, national, or global)[47].

Assessing the effects of urban floods on population and infrastructure

Floods can bring about a wide range of socioeconomic consequences, including negative effects on human lives, physical destruction to buildings, homes, and infrastructure, disturbance to critical and public services, and harm to agricultural and industrial production[48 49 50]. Damage from floods is typically divided into direct damage (e.g., damage resulting from physical contact with floodwaters) and indirect damage (e.g., damage caused by disruption to physical and economic connections, and other types of losses). Damage can then be further classified as tangible (e.g., damage that can be easily quantified as a monetary value) and intangible damage (e.g., damage that cannot be evaluated in monetary terms).

In terms of direct damage to residential buildings and assets, flood depth is a strongly related parameter[48 49], although various other parameters, such as flow velocity, flood duration, and sediment concentration, may also influence the extent of damage to residential areas[49 50 51 52].

The 2022/01 sigma publication by Swiss Re Institute reveals that floods have been responsible for more than a third of fatalities related to natural catastrophes since 2011. The record-breaking floods from 2021 demonstrate that a wide range of drivers contribute to losses, including, urbanisation and aging infrastructure, extreme rainfall from tropical cyclones, and climate change effects. Each year, floods destroy assets worth billions of dollars. In the last five years alone, losses from flooding worldwide amounted to USD 300 billion, of which roughly USD 45 billion was insured[53].

Europe had the highest losses both for economic and insured flood-related losses in 2021. The July floods in Germany and neighbouring countries generated economic losses of USD 41 billion and insured losses of USD 13 billion (Figure 8) – marking the costliest flood event of 2021 and the costliest natural disaster on record in Germany and Europe. This disaster pushed full-year economic losses from floods in Europe well above its roughly USD 10 billion average of the previous 10 years. In Asia and North America, flood-related economic losses in 2021 were in line with their respective 10-year averages[53].

[47] Vojtek, M.; Vojteková, J. Flood Susceptibility Mapping on a National Scale in Slovakia Using the Analytical Hierarchy Process. *Water* 2019, *11*, 364. https://doi.org/10.3390/w11020364

[48] Shrestha, B.B., Perera, E.D.P., Kudo, S. et al. Assessing flood disaster impacts in agriculture under climate change in the river basins of Southeast Asia. Nat Hazards 97, 157–192 (2019). https://doi.org/10.1007/s11069-019-03632-1

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[53] Lucia Bevere, Federica Remondi. (2022, March 20). Natural catastrophes in 2021: the floodgates are open. Retrieved from https://www.swissre.com: https://www.swissre.com/institute/research/sigma-research/sigma-2022-01/five-charts.html

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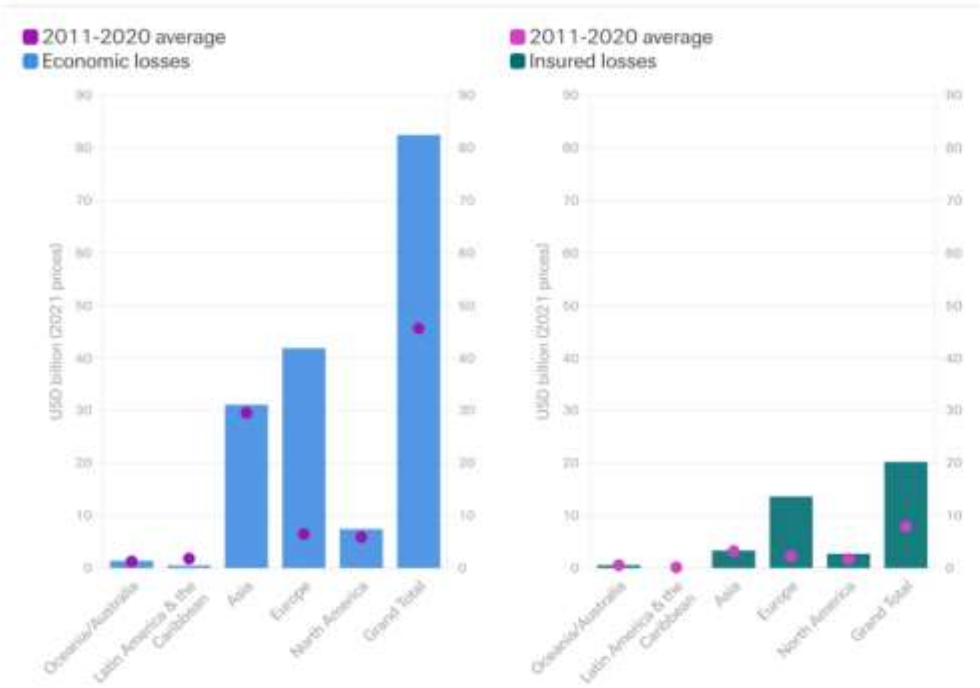

Figure 8: Economic and insured flood losses in 2021 by region and previous 10-year average by region (*Source: Swiss Re Institute*)

Figure 9 below indicates the top inland floods in 2021 in terms economic losses (excluding tropical cyclone induced floods) and illustrates the dimension of the loss in Central-western Europe disaster with respect to all the regions and all the other flood events.

Figure 9: Top inland floods in 2021 in terms of economic losses, excluding tropical cyclone-induced floods (Source: Swiss Re Institute)

From the remarkable disasters in 2022, unprecedented floods in Pakistan, The World Bank report indicates the overall damages resulting from the incident are estimated to surpass USD 14.9 billion, while the total economic

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losses are estimated to be approximately USD 15.2 billion. The estimated cost for rehabilitation and reconstruction of the affected areas in a sustainable manner is at least USD 16.3 billion[54].

3.1.3 Use cases

The project aims to support CEMS existing services by providing additional information both prior to flood events and during the emergency response phase. Its layered approach consists in the aggregation of geospatial data into indicators, that are used to build the final crisis indexes. The scope of the project is to gather more diverse data than the traditional satellite observations or flood models to assess the vulnerability of urban areas and enhance flood mapping during emergency activities.

CENTAUR focuses on a selection of use cases to iteratively assemble the complex crisis indexes, using past (cold cases) and ongoing events (hot cases). Each of the urban flood use cases is further described in this section and was selected for its high impact in urban areas. Those use cases are crucial to the development and implementation of the CENTAUR workflow, especially as they provide training and validation information to fine-tune indicators and indexes and evaluate the quality of the final products of the project.

Figure 10: Use cases overview from CENTAUR website (https://centaur-horizon.eu/project/)

The Ebro basin and the Rhine river both produced large urban floods but the hydrological processes were very different with snow melting driving the first case and complex terrain and local geology being the cause of the German case. The third example is from Mozambique where the heavy flooding was instead driven by tropical cyclogenesis as it is often the case in these regions.

[54] Pakistan: Flood Damages and Economic Losses Over USD 30 billion and Reconstruction Needs Over USD 16 billion - New Assessment. World Bank Press Release No: SAR/2022. Retrieved from https://www.worldbank.org/en/news/press-release/2022/10/28/pakistan-flood-damages-and-economic-losses-over-usd-30-billion-and-reconstruction-needs-over-usd-16-billion-new-assessme

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3.1.3.1 Landes, France

From December 2020 until the end of February 2021, the cumulated precipitations in France exceeded by 30% the seasonal average. Monthly precipitation records were set, with 412.9 mm observed in Dax in December 2020. The combination of intense precipitations with already saturated soils led to a series of flood events especially in south-western France. Amongst the most impacted, the cities located along the courses of the Midouze and Adour were flooded several times during the winter, with exceptionally high water levels.

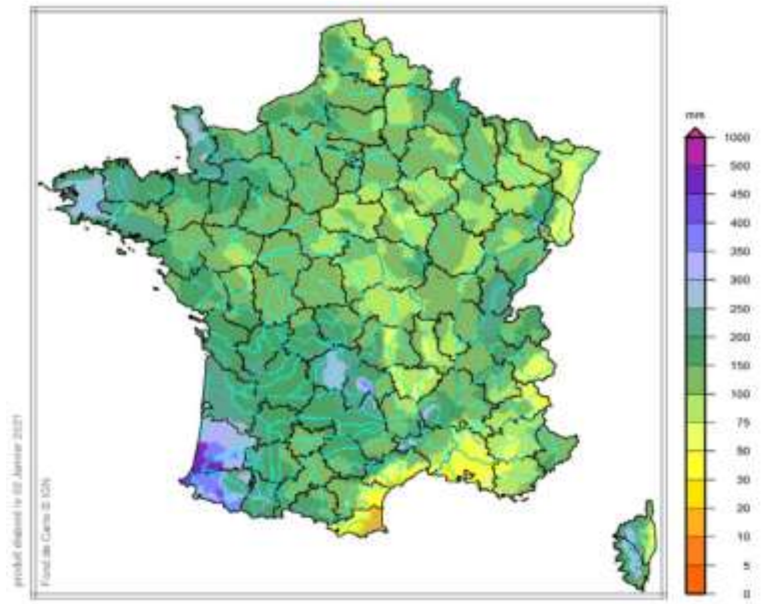

Figure 11: Total monthly precipitations, France, December 2020. [EauFrance]

In Dax, the gauge height reached 5.89m early January 2021 and 5.85m early February 2021, getting close to the 5.97m and 6.03 respectively measured in 1994 and 1981. In the city of Tartas, the Midouze reached 4.03m between January 1rst and 2nd, the second highest after the historical flood of 1843 (4.62m), resulting in the city flooded and 150 buildings impacted.

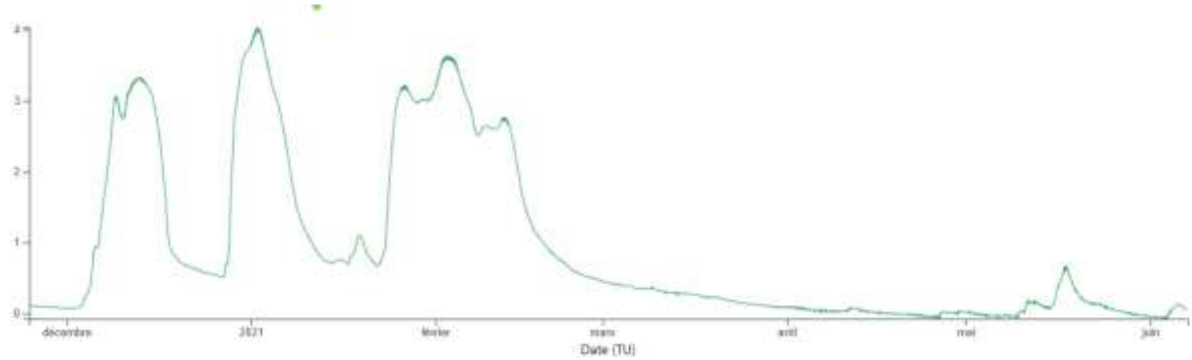

Figure 12: Gauge height at Tartas on the Midouze, [HydroPortail]

The CEMS Rapid Mapping service was activated for the event of early February 2021 and observed massive flood in the vicinity of Dax and Tartas.

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Figure 13: [EMSR492] Mont-de-Marsan, France: Delineation map

3.1.3.2 Ebro Basin, Spain

Given its morphology and location, floods are common in the Ebro basin. Among the most relevant past episodes are the floods of extraordinary intensity that occurred in 2015, 2018 and 2021. As all activations have in common the concomitant effect of heavy precipitation and snow melting in the Pyrenees, which produced significant impacts on the economy of the region. Here we concentrate on the event that took place in April 2018 for which several LIDAR acquisitions in urban areas are available. An activation took place on the 12.04.2018 (EMSR279) signalling, an extraordinary flood event occurring in the Ebro basin due to heavy precipitation in the region enhanced by the rapid snow melting in the Pyrenees. The first flooded areas were registered in Castejón (Navarra) and the peak in Zaragoza city was foreseen on 15th April 2018. A series of images acquisitions took place in sequence.

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3.1.3.3 Piemonte, Italy

Piedmont Region in Italy has a rich history of frequent and important flood events occurred in the past (Figure 14) due to intense precipitations that led to the fluvial flood of the Po River, one of the main watercourses of the Region.

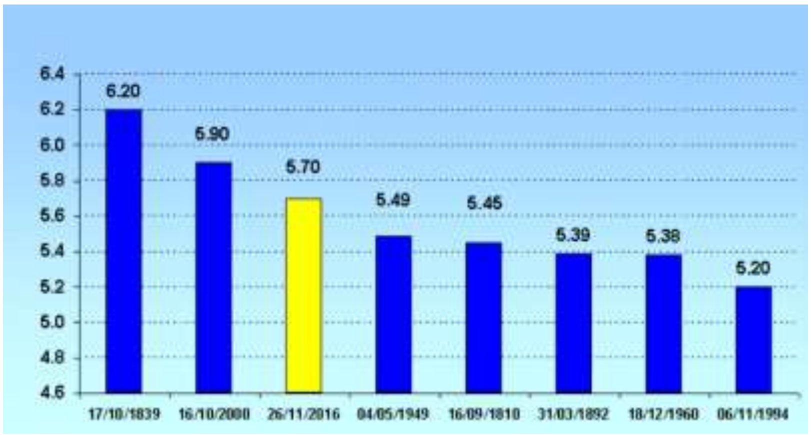

Figure 14: The most relevant flood events of the Po River in Turin since 1971. On Y-axis the maximum flood depth reached in meters (m) is indicated (Source: ARPA Piemonte)

The Piedmont flood 2016 is one of the most important floods recorded in the region, classified in some areas up to level 3 by the alert bulletin issued by the Civil Protection Department. The event affected the regional territory between November 21stand 25th, 2016, when intense south-eastern humid currents from the British Isles to the northern African coast were conveyed close to the Alpine chain. This meteorological event was characterized by persistent and abundant rainfall, especially close to the western and northern Alpine areas and those bordering Liguria region.

The hydrometric levels of the Po River began to increase markedly on 24th November, exceeding the danger levels from Moncalieri to Crescentino Po in the evening of 24th November, while in Carignano and Casale Monferrato in the morning of 25th November; in the Alessandria area in the afternoon of the 25th. Peaks were reached in Carignano with 6.71 m, in Moncalieri with 8.72 m and in Turin with 6.35 m between the afternoon and night of November 25, representing the second highest values after the flood of 1839. The levels dropped below danger levels on the morning of November 26th in the whole branch of the river, except in the stretch downstream of Turin between Castiglione and Crescentino, where it had already fallen on the evening of the 25th.

For the city of Turin, near the confluence with the Po River, the Dora Riparia River remained just above warning levels from the early morning hours of 25th November until the early afternoon, reaching a peak of 4.29 m. Instead, the Stura di Lanzo River remained above the warning level from the morning of 24thNovember to the morning of the 25th, approaching but not reaching the danger level with the ridge of 3.09 m in the early hours of 25th November.

Below are some rainfall totals recorded by some hydro-meteorological stations of ARPA Piemonte (Regional Environmental Protection Agency) present in the area during the event:

- Niquidetto: 613.2 mm
- Viu: 584.8 mm
- Pinerolo (Turin area): 324 mm
- Barge: 586.6 mm
- Nava Tanaro bridge (Cuneo area): 547.8 mm
- Calizzano (Savona area): 574.2 mm

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- The CEMS RM was activated on November 24th with the EMSR192 to support the Italian Civil Protection Department, producing 34 maps:

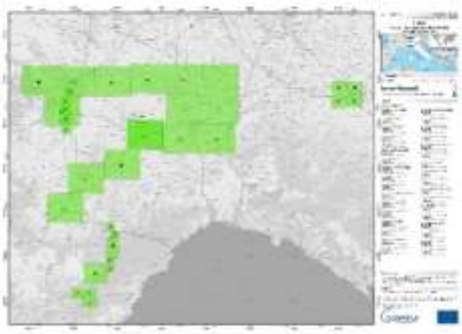

Figure 15: [EMSR192] Floods in Northern Italy (On the left: The spatial distribution of the areas analyzed for the event during the activation, on the right: Delineation map produced over Torino Lingotto area)

Since the first hours of the 3rd of October 2020 an intense weather perturbation affected the North of Italy, with heavy rain and strong winds (storm Alex). Both red and orange alerts were issued by the regional and National Civil Protection. The greatest damages are reported in the Liguria region, and in the northern and western part of Piedmont region where the amount of the precipitation recorded exceeds the historical rate since 1958. The heavy rainfall has caused the overflow of several rivers and flooding of many areas. The overflow of the Sesia river in the Piedmont region caused interruption of roads, the collapse of a bridge and the flooding of several areas. Two deaths have also been reported

3.1.3.4 German Floods 2021

On the 14th July 2021, parts of western Germany, north-eastern France, eastern Belgium, the eastern Netherlands and Luxembourg were hit by extreme rainfall leading to devastating flooding in small and medium-sized rivers, such as the Meuse and Ahr. The event caused more than 200 fatalities in Germany and Belgium. Two activations took place for western Germany (EMSR517) and Belgium (EMSR518).

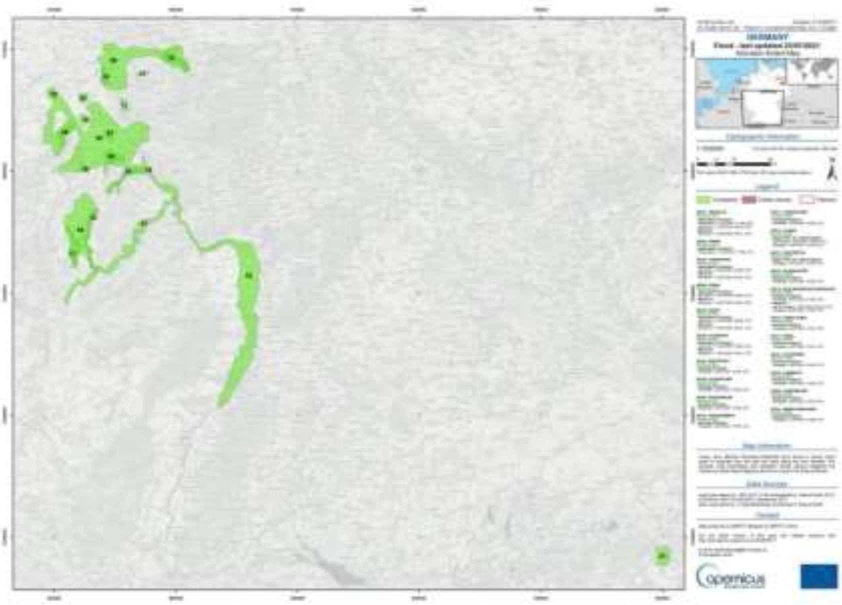

Figure 16: Series of acquisitions that took place during the German/Belgium event (EMSR517), [EMSR517] Flood in Western Germany.

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The event was connected to an upper-level trough that caused extreme weather from the UK to Romania during its propagation from the Atlantic to south-eastern Europe. In the days leading up to the event, Switzerland, south-western Germany and eastern France also saw heavy precipitation. From 13 July to the early morning of 15 July, exceptional rainfall occurred on the north-western side of the cut-off low, in the warm and moist air stream from the north-east. This led to extreme amounts of rain on the eastern side of the low mountain ranges on the border between Germany and Belgium. Several stations on the German side measured more than 150 mm/48 h. In eastern Belgium the observation coverage is sparse in the ECMWF verification system, but according to the Royal Meteorological Institute of Belgium the town of Jalhay received 271 mm and Spa 217 mm over the same period.

3.1.3.5 Mozambique

On the 4th March 2019, a tropical depression made landfall on the coast of Mozambique and propagated northwest. The depression brought anomalous rainfall and led to deadly floods across central Mozambique and southern Malawi from 5 March. On 8 March, the depression turned eastward, and on 9 March it moved back over the ocean. On 10 March, the depression intensified and became a tropical cyclone. A few days later, it started to propagate southwest and intensified further. The cyclone made landfall near Beira on 15 March and later moved further inland bringing heavy rainfall also to Zimbabwe. When Idai reached the coast of Mozambique, it brought winds of up to 170 km/h and a significant storm surge of about 4.5 m around Beira. According to NASA-GPM data, rainfall totals between 3 and 17 March reached 400–600 mm over much of the Sofala and Manica provinces of Mozambique, between Beira and Chimoio. These extreme rainfall amounts caused widespread flooding around most rivers in the region, including the Pungwe, Save, Buzi, Revue and Shire Rivers. According to the United Nations, an estimated 1.85 million people were affected by Cyclone Idai in Mozambique and required humanitarian assistance. This made Idai the deadliest cyclone in the southern Indian Ocean for more than 100 years. CEMS Rapid Mapping activation EMSR348 was requested on the 9th March to document the extent of the event over Beira and the neighbouring area.

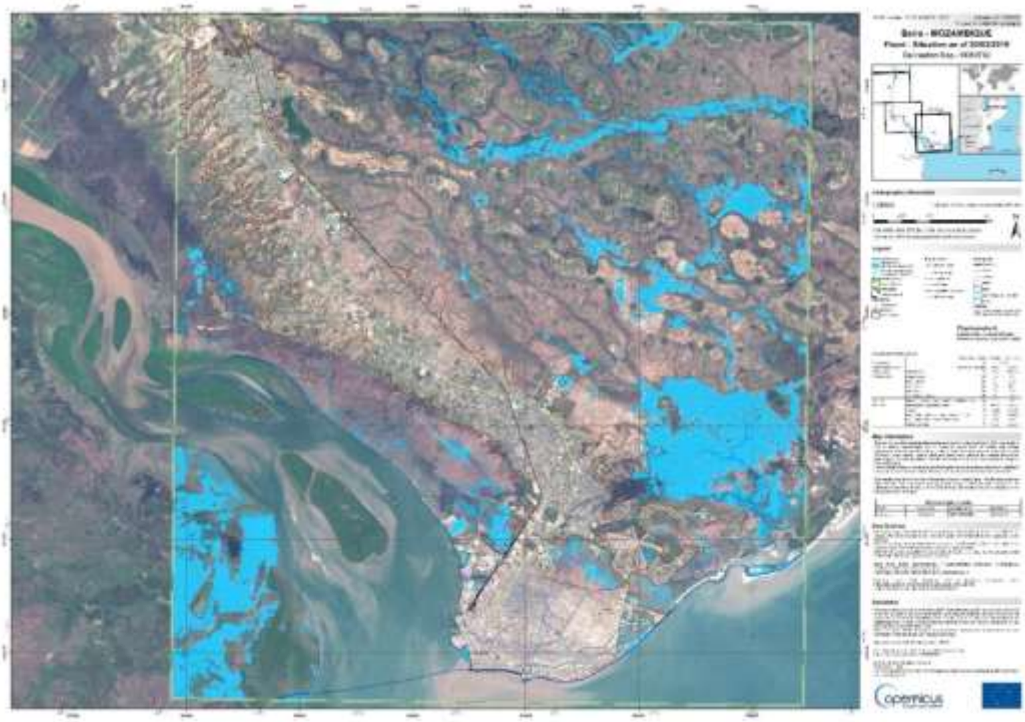

Figure 17: Activation for the Mozambique floods (EMSR348), [EMSR348] Beira, Mozambique: Delineation map Monitoring 02

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3.2 WATER AND FOOD INSECURITY IMPACTS

3.2.1 Context

The global food security situation is continually deteriorating. The annual report of the Food and Agriculture Organization of the United Nations 2022 showed that world hunger rose further in 2021, contrary to the expectations of a decrease in global hunger following the sharp increase in 2020 as a result of the COVID-19 pandemic.[55] The World Bank estimates that the number of people suffering acute food insecurity increased from 135 million in 2019 to 345 million in 82 countries by June 2022.[56] There are regional disparities, but Africa is by far the most affected continent with 20.20% of its population facing hunger in 2021. Many regions and countries on the continent have suffered food crisis and famines throughout the last centuries. Countries across the Sahel were plunged into famine due to a drought induced food crisis in the 1970's, in Ethiopia approximately one million persons died of famine in the mid-80's, Somalia faced famine in the 90's, just to mention some of the disasters that the continent has endured and continues to suffer today. Right now, the Horn of Africa is experiencing its longest drought in 40 years and in Somalia alone, 7 million people are on the verge of famine.[57] Mali is facing its most severe food and nutrition crisis since a decade and the Integrated Food Security Phase Classification (IPC) projected end November 2022 that nearly 1.5 million children under the age of five were expected to suffer from acute malnutrition from July 2022 – May 2023, 19 % higher than the cases forecasted for 2021.[58] In Mozambique, 73 % of the population faced moderate of severe food insecurity in 2020[59] and currently draughts in the South, floods in and around Maputo City and armed conflict in the North, provoking the displacement of with 976 000 persons, are putting the country in further distress.[60] Africa, being responsible for a mere 4 per cent of global CO2 emissions, is the continent most vulnerable to the effects of climate change and its related security risks. In addition, more than half of the states in the sub-Saharan Africa are facing these risks while suffering from political fragility and its associated burdens.

3.2.1.1 Definition of water and food security

The official concept of Food Security was first coined at the 1974 World Food Summit and succinctly developed and refined at the following summits. At the World Summit on Food held in Rome in 2009, food security was defined to *"exist when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life."* [61] Four dimensions of food security are outlined in this definition: availability, access, utilization and stability, while the nutritional dimension is integral to the concept as such.[62] To define water security, UN-Water proposes the following definition: *"The capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability."* [63]

3.2.1.2 Drivers of water and food insecurity

Each of the above-mentioned concepts and dimensions for food and water security can be challenged by a number of socio-economic, political and environmental factors, which can be nominated as drivers for food and water

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[55] The State of Food Security and Nutrition in the World 2022, Food and Agriculture Organization of the United Nations, p. iv
[56] Climate Explainer: Food Security and Climate Change (worldbank.org)
[57] British RedCross, https://www.redcross.org.euk/stories/disasters-and-emergencies/world/africa-hunger-crisis-100-million-struggling-to-eat
[58] https://www.ipcinfo.org/ipc-country-analysis/details-map/en/c/1156047/?iso3=MLI
[59] https://data.worldbank.org/indicator/SN.ITK.MSFI.ZS?end=2019&locations=ZG&start=2019
[60] https://fscluster.org/mozambique/about
[61] Declaration of the World Summit on Food Security, Rome 16-18 2009, p.1
[62] Ibid
[63] UN Water, https://www.unwater.org/publications/what-water-security-infographic

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insecurity. Today, these main drivers are by some authors considered to be climate change, violent conflict, Covid-19 and the rising cost of living.[64] Each of these drivers can of course be broken down into smaller parts depending on the scope and case of analysis.[65] The combination of these four drivers has created a critical situation, undermining the power of (re)action and adaptation of regional, national and local authorities, organisations and communities.[66]

Climate change, whether taking the form of extreme weather events, or of more long-term manifestations such as raise in temperature and rainfall variability, having impacts on vegetation such as crop and pastures, water resources and the access to them, changing seasonal patterns, acidification of sea water etc., affect and threaten the livelihood of millions of people on the African continent, being the continent most vulnerable to it. Climate change and its effects, exacerbates food and water insecurity, influences the mobility of people, from transhumance patterns and rural-urban migration to cross-border migration, widens inequalities and may lead to violent conflict due to heightened communal tensions and conflicts over resources and access to land and water and to disruption of established patterns of transhumance and other forms of mobility. [67] Loss of livelihoods and food security due to climate change can stir social unrest and disrupt established power structures in a country or region as well as create opportunities for violent extremism and armed groups to more easily recruit for example farmers and herders in search alternative incomes when their livelihood is threatened. Violent conflict may have a direct impact on food security due to confiscation and destruction of land, control of infrastructure and distribution of food and water supply.[68] As we can see, these two drivers are intimately linked; climate change can lead to food insecurity which in turn can contribute to violent conflict due to scarcity and shortages of food and water caused by the effects of climate change and other environmental stressors.[69] On top of these two drivers, governments, authorities and households have to deal with additional stressors entailed by the Covid-19 pandemic, causing compounding and interrelated environmental, socio-economic and political crises, increasing inequalities and exposing structural vulnerabilities in local and global food systems.[70] Just when experts predicted a global recuperation from grievances caused by the pandemic, the war in Ukraine further weakened the global food systems through interrupted exports of basic food staples such as cereals, leading to a lack of access to wheat and other products as a big number of African nations imported half or more (some even as much as 80 percent) of their wheat from Ukraine and Russia before the war in Ukraine started. The disruption to exports from these two countries and its impact on food prices are thus particularly dramatic for these African countries and have added on to already high food prices, shortage and delay in supply chains etc., caused by the Covid-19 pandemic. This situation has provoked skyrocketing global inflation causing raised interest rates, increasing the cost of borrowing and debt, which is particularly felt by low-income countries with fiscal reserves already depleted by the pandemic, while households are directly suffering from the rise of cost of living of imported food and energy. [71] As we can deduct, the world and Africa in particular, is facing a complicated scenario.

Obviously, these drivers play out differently in different contexts, giving variations in food security/insecurity in different countries and regions.[72] In section 3.2.5 there will be an analysis of the situation in each of the countries chosen as use cases for this deliverable, namely Mali, Somalia, and Mozambique.

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[64] Delgado, Tshunkert and Smith, Food Insecurity in Africa: Drivers and Solutions, SIPRI Research Policy Paper, January, 2023, p. 2
[65] Cepero, Desmidt, Detges, Tondel, Van Ackern, Foong and Volkholz, Climate Change, Development and Security in Central Sahel, Cascades H2020 project, 2021, p. 38, identifies Armed conflict and terrorism, Climate change impacts, Corruption, Forced displacement, Political instability Poor access to markets, Population growth, Social inequalities, water scarcity as principal drivers of food insecurity in Mali and Niger.
[66] Delgado and al,2023, p. 2
[67] Ibid p. 44
[68] Delgado and al.2023, pp. 2-3
[69] Ibid, p.3
[70] FSIN and Global Network Against Food Crises (note1) in Delgado, Murugani and Tschunkert, Food Systems ain Conflict and Peacebuilding – Pathways and Interconnections, SIPRI, 2021, p. 3
[71] Delgado and al. 2023, pp. 5-6
[72] Ibid, p. 7

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3.2.2 Implications and impacts on security

The conclusions from the survey carried out in the frame of the World Climate and Security Report 2021, [73] show that security risks stemming from different climate phenomena [induced by climate change] were considered to present severe and catastrophic levels of risk within the next twenty years. Though the surveyed group of experts perceived immediate climate security threats as low to moderate for the time of the survey (2021), they did foresee those threats and risks to be growing quickly and substantially in the coming decade. Particular concern in the short-term was given to the direct environmental impacts such as precipitation changes, sea-level rise and more severe natural disaster, and their impact on agricultural, economic and health care systems around the world. The surveyed group of experts were thus more worried about the risks that climate change poses globally to society than the concerning risks posed to military installations, missions and institutions. The group ranked human security risks, such as food, water, economics and infrastructure as more severe than the military security category of threats such as military over-reliance, mission failures and the degradation of key alliances, suggesting that the most demanding threats to security will come from the disruptions of social systems, than from the disruption of military assets and missions.[74] While debates on the links between climate change and insecurity are often criticized as oversimplifying complex relationships, particularly regarding violent conflicts[75], these conclusions do point towards a critical situation in which the risks and threats that climate change, and the subsequent food and water insecurity, pose on security cannot be solved by military means of threat assessment and resolution. As already seen in previous sections, climate change is one of the drivers of food and water insecurity while violent conflict can both be a driver of water and food insecurity as it may be a result of it. Conflict has a direct negative impact on food systems and in most conflicts, food systems are purposefully destroyed, with the result of long-lasting food insecurity.[76]

The specific ways in which climate effects impact violent conflict are, however, determined by local social, political and economic dynamics, meaning that while climate change is not the only cause of violence and conflict, it can have both direct and indirect consequences for local, national and regional security.[77] Climate change creates multiple risks and when interacting with existing vulnerabilities, it contributes to insecurity. The effects of climate change in developing countries interact with variables such as underdevelopment, high dependence on natural resource-based livelihoods, inequality, weak state institutions and marginalisation. Mobjörk, Krampe and Tarif (2020) identify four pathways between climate change impacts and implications for security, in order to help policymakers to navigate the aforementioned complex situation created by climate change in vulnerable countries and regions. These pathways being: *worsening livelihood conditions, increasing migration and changing mobility patterns, tactical considerations by armed groups, exploitation by elites and resource mismanagement*. [78] These were initially identified in research on East Africa but also feature in literature reviews on West Africa. The four pathways illustrate the relationship between short-and long-term environmental changes linked to climate change and their impact on root causes and dynamics of violent conflict.[79] Below follows a brief description of each pathway:

1. Worsening livelihood conditions

Worsening livelihood conditions due to the effects of climate change can, as seen before in this deliverable, increase the risk of conflict, marginalizing affected groups and communities and contribute to escalating

[73] The Report, produced by the Expert Group of the International Military Council on Climate and Security, presents the results of a survey administered to a selected group of 57 security and military experts and practitioners across the globe in February - March 2021. The survey assessed perceptions of climate security risks over three time periods: 2021, 2031, 2041.
[74] The Expert Group of the International Military Council on Climate and Security 2021, p. 13
[75] Mobjörk, Krampe, Tarif, Pathways of Climate Insecurity; Guidance for Policymakers, SIPRI, Policy Brief, 2020, p. 1
[76] Delgado, Murugani, Tshunkert, Food Systems in Conflict and Peacebuilding settings – Pathways and Interconnections, p.
[77] Tarif, Climate Change and Violent Conflict in West Africa: Assesing the Evidence, SIPRI Insights on Peace and Security, No. 2022/3, February 2022, p. 1
[78] Ibid, pp. 3 -7
[79] Ibid, pp. 3

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tensions and grievances. When there is competition for scarce resources and absence of alternative income, the greater is the risk of use of violence to protect or access resources. The adverse effects of climate change on agriculture and livestock means that the consequences are greater for those that directly depend on these resources. Effects of climate-induced phenomena such as flooding and droughts or longer-term environmental effects such as soil-degradation or desertification increase the risk of communal conflicts. An example of this being conflicts between herders and farmers in East and West Africa, where violence sometimes is used to secure resources when there is a decrease in livelihood security due to environmental impacts on grazing zones and migration routes, accelerating conflicts over land, fodder, forage, and water resources. Worsening livelihood conditions and the absence of alternatives also increase recruitment to armed groups or already existing conflict between groups and communities in a country or region.[80]

2. Increasing migration and changing mobility patterns

Climate-related migration is one of the adaptation strategies when livelihood and/or survival is threatened by the effects and impacts of climate change. Rapid onset disasters can result in sudden local displacement, while the impact of gradual climate change is more diffuse and intricately connected to demographic and economic asymmetries. Population movements in relation to the impacts of climate change are generally towards areas with better livelihood options as well as rural to urban migration. These movements can increase the risk of community –based violence and conflict when there is confrontation due to social, political and economic factors such as resource competition in the receiving area, when and if migration is perceived to increase livelihood insecurity for the host population or disturb local power dynamics.[81] As seen above, the effects of climate change can also, in rural communities, change patterns of herd mobility that could conflict with established transhumance protocols, corridors and calendars, creating clashes between farmer and herders or between herders over competition of grazing areas.[82]

Many experts foresee that most climate related mobility will remain intra-regional with, for example, a focus on movements towards the coastal areas in West Africa for people in the Sahel, which would not substantially change current migration patterns of the region [83]

3. Tactical considerations by armed groups

While climate change can increase the risk of breakout of conflict and violence due to climate induced losses of livelihood or food and water insecurity, it can also have an impact on already ongoing conflicts and hostilities. Research shows that climate change can influence the strategic decisions and tactics of armed groups in the following ways: a) when they use coping strategies to reinforce group food security, b) when they use the strain of climate related impacts to boost recruitment and c) when they adapt behaviour to capitalise on climate pressures in an opportunistic manner.[84] Mobjörk and al. state that this is evident when armed groups make tactical decisions to gain access to natural resources, or when their recruitment pool expands due to climate-related disaster or livelihood losses. An example of this is how Al- Shabab seized part of southern Somalia, following a drought in early 2000's, occupying sparse green areas of land, exploiting farmers and the soil to generate income for its own activities and to consolidate its stronghold in the region. Research also shows how armed groups can use climate-related disaster to position themselves as alternative service and relief providers in situations where governments and official authorities are not responding. However, this pathway is highly context specific and a range of variables, including governmental and institutional responses to local needs, can interrupt the pathway from climate pressure to armed group tactics.[85]

[80] Ibid, pp. 3-4
[81] De Juan pp.22-33 and Koubi in Mobjörk, Kempe and Tarif, p. 5
[82] Cepero and al., p. 42
[83] Ibid, p. 41
[84] Mobjörk and al., p. 6
[85] Mobjörk and al., p. 6-7

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4. Exploitation by elites and resource mismanagement

This pathway shows how small-scale tensions due to climate-change induced environmental degradation can increase the risk of broader conflict when exploited by individuals or groups belonging to the socio-economic elite. Local elites can use instability provoked by a climate-induced disaster to advance their control over resources, strengthen their strategic aims or seek alliances with national elites. They can also use political networks to control who receives aid, occupy land of displaced groups, and exploit vulnerable populations for political aims, especially in conflict-affected areas. [86]

3.2.3 Challenges

The world climate and security report 2021 states that "*currently understudied and novel risks to security stemming from climate change require more attention. Level of understanding and preparation for climate-induced disasters and their effects is exceedingly low within security services, to build resilience to such threats, policymakers and defence leaders must collaborate closely with natural- and social scientists to forecast how new risks might evolve.*" [87]

Among the many challenges to mitigate climate security threats, the following can be highlighted:

- Climate change adaptation and resilience building strategies for agriculture, water management, livelihoods such as pastoralism, farming, fishing, infrastructures, social capital, knowledge, and trust building for institutions, local authorities, governments, etc. ;
- Enabling mobility as an essential coping strategy;
- Redefining peacebuilding and security strategies to include climate-related risks, social inclusion and to address (gender) inequalities affecting livelihoods, distribution of wealth, access to land and infrastructures, possibilities of mobility.

3.2.4 Institutional Initiatives

As security challenges arising from climate change most often do not respect national borders and pose unique and multidimensional pressure on governments and institutions, responses from international and intergovernmental institutions and organisations are crucial to identify, assess, respond to, and prevent, their impact. In this section, the climate-related security capacities, policy, and programmes of three intergovernmental organisations involved in different initiatives, missions and operations on the African continent are reviewed.

3.2.4.1 United Nations

The United Nations have been working on strengthening its capacity to respond to climate-related security risks in recent years and it is an issue that has been increasingly debated in the Security Council during the last decade. [88]

In 2018, United Nations Climate Security Mechanism (CSM) was established. It is a joint initiative by the UN Department of Political and Peacebuilding Affairs (DPPA), The UN Development Programme (UNDP) and the UN Environment Programme (UNEP), launched with the aim to strengthening the capacity of the United Nations

[86] Mobjörk and al, p. 7

[87] The world climate and security report 2021 p. 13-14

[88] Camilla Born, Karolina Eklöw and Malin Mobjörk, Advancing United Nations responses to climate-related security risks, SIPRI Policy Brief, Sept 2019, p.1

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system to analyse and address the impacts of climate change on peace and security.[89] Its creation was made possible thanks to targeted financial support from a member state. [90]

The CSM is working with partners globally to enhance a gender-sensitive understanding of climate security and to support capacity building efforts across the entire UN system. The core team of the CSM is composed of staff from each of the entities mentioned; DDPA contributes with its global expertise in political analysis and early warning, conflict prevention, peace-making and sustaining peace. Its direct interaction with the Security Council, management of special political missions in the field and close relationship with the Department of Peace Operations, give the CSM a strong peace and security dimension; UNDP is the largest supplier of technical support for climate change mitigation and adaptation within the UN system and the primary partner for implementing the Peacebuilding Fund. It has expertise in conflict prevention and sustaining peace, governance, disaster risk reduction and recovery delivered by its network of 170 Country and Regional Offices. The UNEP is responsible for the promotion of a coherent implementation of the environmental aspects of sustainable development within the UN system and provides technical expertise on environmental issues. [91]

In parallel, a Group of Friends on climate security was created by non-permanent member countries of the Security Council, providing a second channel for advocacy of and support for the climate security agenda in the Security Council. According to Born and al., this overall progress has served to build a strategic confidence building process for climate security across the UN system, foreseeing that the Security Council, together with other organisations, will serve as an important actor for strengthening policy frameworks and institutional developments that will be able to withstand political uncertainties. The authors identify three interrelated areas for action that have emerged through debates and consultations held in various fora; a) delivering security and resilience in the field - the UN will have to deliver results. To build greater political consensus, field-based work will be needed to deliver proof of concept that investment in climate security actions support sustainable peace. Introducing climate knowledge to risk assessment processes is a shift that needs resources, leadership, and long-term thinking, hence the tendency to focus on short term timelines is not enough to accommodate the multiple time frames in which climate risks manifest themselves. b) deepening knowledge provision: knowledge of how, when, and why climate-related security risks emerge is developing rapidly in research and policy. Collaboration across these domains will enable the identification of responses to climate-related security risks, and the authors believe that the Climate security mechanism could function as broker between the UN system and the research community, underlining that there is a demand in the field for analysis that takes an holistic approach, and that insights from other institutional policy areas such as gender equality and cybersecurity could be useful; d) Financing action: The systemic character of climate-related security risks makes financing complicated as it is often siloed, which is an obstacle for integrated responses. Climate Security is not a budget line item in the UN budget and responses are often labelled as resilience, climate change adaptation or disaster risk reduction for example. The authors suggest integrating climate security into already existing funds such as the Peacebuilding Fund. Increasing sustainable financial support for responding to climate-related security risks requires institutional capacity and policy change. The Climate Security Mechanism needs a provision of sustainable funding and should in the long-term be incorporated into the UN Core funding instead of being subject to direct financing from UN member states. [92]

In the end of 2021 Russia vetoed an historic United Nations Security Council (UNSC) resolution that would have formally recognised climate change as a threat to peace and security at the global level. Drafted by Ireland and Niger and co-sponsored by 113 member states, it would have formalized discussions about climate security in the UN Security Council, calling for regular reports on how climate change could aggravate conflict risks in regions on

[89] Climate Security Mechanism Progress Report 2021, United Nations, p. 5
[90] Born and al. 2019, p. 2
[91] Climate Security Mechanism Progress Report 2021, United Nations, p. 5
[92] Born and al. p. 2

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the Council's agenda, for the inclusion of climate change impacts in security analysis, and for peacekeeping operations to consider these risks in their mandates.[93]

3.2.4.2 EU

Climate Security currently falls within the EU's external action, e.g., its Common Foreign and Security Policy (CFSP), Common Security and Defence Policy (CSDP) and external relations. It primarily involves members states in the Political and Security Committee (PSC) which prepares the Foreign Affairs Council (FAC) meetings. Decision making in these areas is by consensus, but the system that supports it, the EU External Action Service, which brings together EU Civil servants from the Council and the Commission, as well as diplomats from EU Member States, is not fully controlled by the Member States. It supports the High Representative of the EU Foreign Affairs and the Vice President of the Commission (HR/VP), who chairs the FAC, while a representative from the EEAS chairs the PSC meeting. [94]

The European Union is considered to be among the most vocal actors and one of the first bodies globally to identify and address security risks related to climate change.[95] [96] For instance, the EU Commission published already in 2008 a paper in which it identified climate change as a 'threat multiplier', concept that is still much present within the language of the different EU institutions and is reflected in the EU Global Strategy from 2016 stating that 'climate change and environmental degradation exacerbate potential conflict, in light of their impact on desertification, land degradation, and water and food scarcity'.[97] The strategy considers climate 'a threat multiplier' that catalyses water and food scarcity, pandemics and displacement'.[98] This concept of climate change is echoed through various policy documents such as the EU European Green Deal 2019 which recognises climate change as a significant threat multiplier and source of instability, emphasising the need to consider climate policy implications in the EU Common Security and Defence Policy; the EU Migration and Asylum Package 2020 , recognises that climate change and security (together with other societal challenges, such as demography and inequality) impact migration, describing these interconnections as a major phenomenon and global challenge for the years to come; the EEAS Climate Change and Defence Roadmap 2020, providing detailed operational steps to address climate insecurity, including strengthening partnerships and multilateralism and capability development; proposing a list of actions such as lowering the environmental footprint of military missions and including environmental advisors in EU CSDP missions and operations; the EEAS Concept for an Integrated Approach on Climate Change and Security 2021 views climate change as a risk multiplier and urges and integrated approach in EU external action and for full integration of climate and security in all EU instruments and policies., proposing a list of concrete actions, including strengthening the links between early warning, analysis, and action; The EU Strategic Compass for Security and Defence 2022 presents climate change as a threat multiplier and argues for an integrated approach to security combining diplomatic and economic instruments and close cooperation with various partners. Furthermore, the EU, its Member States and the European Investment Bank are the largest aid provider and largest climate finance donor with 30 % of the EU budget for 2021-2027 being directed at climate-related action. [99]

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[93] Climate Diplomacy,"After UNSC disappointment, African Union picks up the climate-security baton", After UNSC disappointment, African Union picks up the climate-security baton | Climate-Diplomacy 2021

[94] Bunse, Simone, Remling, Elise, Barnhoorn, Anniek, Du Bus de WWarnaffe, Manon, Meijer, Karen, Rehbaum, Dominik, Advancing European Union Action to Address Climate-related Security Risks, SIPRI Research Policy Paper, September 2022, p.3

[95] Bremberg, Niklas, Eu Foreign and Secuirty Policy on climate-related Security Risks, SIPRI Policy Brief, November 2019, p. 1

[96] Youngs Richard, The EU's indirect and Defensive Approach to Climate security,Chapter 1,p. 5 in Lazard, Oliver, Youngs, Richard, the EU and Climate Security: Toward Ecological Diplomacy, 2021

[97] European Union, "Shared Vision Common Action: A Stronger Europe AGllobal Strategy for the European Union's Foreign and Security Policy", p. 27

[98] Ibid, p. 29

[99] Bunse et al. p. 8

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However, climate security is not a distinct policy field within EU foreign and security policy and should rather be considered as a cluster of different policy fields linked by the EU's ambition to better respond to and prevent climate-related security risks.[100] In relation to EU Foreign Security and Defence Policy, climate-security would be part of EU's comprehensive approach to security, which includes climate change and environmental degradation, and, in addition, the growing base of policies mentioned above.[101] Despite the high level of ambition shown in the policy formulation of the institutions, analysts consider that an 'action-gap' remains.[102] The World Climate and Security Report 2021 considers that there is urgent work to be done across the union in terms of taking and implementing climate security actions.[103] Bunse and al. underline the variations in priorities and red lines among EU Member States While some Member States are acknowledging the impact of climate change on security and conflict contexts in developing countries, they are more concerned about immediate national security threats, while others push to shift the debate on climate security towards practical or technical discussions and tangible actions countering climate-related security threats. Some Member States have drawn their red line at operational efficiency, ensuring that climate-related ambitions and goals do not affect the operational effectiveness of their armed forces. [104] Some countries consider the Concept for an Integrated Approach to Climate Change and Security as a key opportunity to mainstream the climate security nexus both at EU level as at national level. Bunse et al. identify that the extent to which Member States are ready to prioritize the development of a common EU-level climate security strategy and empower the EU with a leadership role in this area with fund for implementation, is at the heart of the debate and that thus far, climate security has had a low profile on Council agendas. [105]

3.2.4.3 African Union

The policy-making organs in the African Union architecture are mainly the AU Assembly of Heads of State and Government the Executive Council, The AU Peace and Security Council (PSC) and the Permanent Representatives Committee (PRC). The PSC is the key pillar of the African Peace and Security Architecture (APSA) which is an umbrella term for the different AU mechanisms that are promoting peace, security and stability in Africa and is an operational structure for implementing decisions taken in areas such as conflict prevention, peace-making, peace support operations, etc. APSA includes, in addition to the PSC, the Panel of the Wise, the Continental Early Warning System (CEWS), the African Stand-by Force, the African Capacity for Immediate Response to Crisis and the Peace Fund. The African Union went through institutional reforms in 2016, focusing on fewer priorities to more effectively meet the evolving needs of the continent. According to Vane et al. there is a rapidly evolving discourse around climate security within the AU. [106] This discourse, being translated into new initiatives and programmes to be implemented, seems to arise from within the organisation and the African continent itself and not pushed by external donors. Different frameworks for agriculture and food security are the ones most prominent in underlining the impacts of climate change in Africa, which seems logical considering the dependence on agriculture for livelihood and food security, and the frequency of which the continent is hit by climate-related disasters such as droughts and famine. That being said, the Bamako declaration on Access to Natural Resources and Conflicts between Communities addressed directly the importance of climate security by "*noting the inextricable link between climate change, natural resources and peace and security, and mindful of the need to mitigate the negative effects on community cohesion and the need for innovative approaches to strengthen the resilience of affected populations in the Continent*" .

[100] Bremberg, p. 3

[101] Bunse et al., p. 1

[102] Ibid, p. 3

[103] International Military Council on Climate Security, p. 62

[104] Bunse et al., p. 7

[105] Bunse et al. Pp. 12-13

[106] Aminga, vane, Krampe, Florian, Policy Responses to Climate-Related Security Risks: The African Union, p.3

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Furthermore, the Peace and Security Council *"expresses deep concern over the growing complexity of conflicts related to the governance and management of natural resources between communities, acerbated by climate change, as well as the related governance challenges in Africa; underscores that the growing transnational nature of intercommunal conflicts linked to natural resources, threatens peace and security in Africa; in this regard calls for concerted and coordinated regional, continental, and international efforts to combat this scourge."*[107] When the UNSC resolution that would have formally recognised climate change as a threat to peace and security at the global level was vetoed by Russia in 2021, the Peace and Security Council of the AU was quick to release a communique on the theme of climate change, peace and security (on the same day as the Russian veto), which highlighted how climate impacts can aggravate conflict, and called for an "informed climate-security-development nexus", stressing the need to build capacity among member states on the nexus between climate, security and development, and reiterated the need to include the climate dimension in national and continental early warning activities, and acknowledged that the climate crisis is likely to impact the ability of communities to rebuild in the wake of conflict.[108] By its release, AU can be considered as a proof of *" ...how regions affected by climate security risks are stepping in to drive action forward."* [109] However, and even though climate security has found its way into the top leadership of the African Union, targeted responses and actionable commitments still have to be developed, and the many challenges that the African continent is facing such as extreme poverty, violent extremism, weak state capacity, together with the structural weaknesses of the AU remain the main obstacles to the operationalisation of the above formulated policies. Aminga and Krampe state that the challenge at hand is immense when looking at climate-related risks within the AU and underline that coordination, political leadership and new narratives are imperative to overcome existing issues dealing with climate-related security risks, and securing human livelihood, both in the present and the future.[110]

[107] African Union, "Bamako Declaration on Access to Natural Resources and Conflicts between Communities", 29 November 2019, pp. 1-2

[108] African Union, Communique of the 1051th meeting of the AU Peace and Security Council (PSC) held on 26 November 2021 : Climate Change and Peace and Security: The need for an Informed Climate-Security-Development nexus for Africa, pp. 1-2

[109] Vivekananda, Janani, Zwar, Claudia, After UNSC disappointment, African Union picks up the climate-security baton, Climate Diplomacy, After UNSC disappointment, African Union picks up the climate-security baton | Climate-Diplomacy

[110] Aminga and Krampe, p. 5, 10

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3.2.5 Use cases

3.2.5.1 Mali

Figure 18: Political and Administrative Map of Mali source: [Political Map of Mali - Nations Online Project]

3.2.5.1.1 Geography and Climate in Mali

Mali is a landlocked country part of the greater region of Sahel (other countries being part of the region are Djibouti, Eritrea, Ethiopia, Sudan, Chad, Niger, Nigeria, Burkina Faso, Mauritania, and Senegal). The country stretches through various climate zones; from the Sahara Desert in the north, semi – arid savannah in the centre, to wetter tropical savannah in the south. This makes the climate of Mali highly variable. There is only one rainy season between May/June and September/October and precipitation varies greatly from 100 mm/ year in the North to 1700mm in the South. The country has two major river basins, the Niger and Senegal, and is highly dependent on the Niger River for its water supply. While it extends over 10 countries, approx. 25 % of its waters are located in Mali. The inner delta of the Niger, forming the Mopti region, is a unique area of wetlands, lakes and floodplains, which is dependent on seasonal flooding to provide opportunity for agriculture, fishing, and livestock farming. The smaller river Senegal flows through the southern part of Mali where one third of the river basin catchment is located and where the majority of the basin's population is living. Furthermore, populations in Mali are also dependent on groundwater for drinking water, irrigation, and other domestic purposes. There are nine aquifer systems extending across the country that are mostly accessed through shallow wells. [111]

3.2.5.1.2 Livelihoods in Mali

Mali's agricultural livelihood activities consist mainly of farming, herding, fishing and forestry. The Malian socio-economic structure is a complex web of stratification by livelihoods, hereditary power holders within families, forming clientelist networks. Livelihoods are often linked to ethnical groups.

The agricultural sector contributes with 39 % of Mali's GDP and employs about 70% of its labour force. It is mainly based on cereals such as sorghum, millet, maize, and rice. The main issues for agriculture in the Sahel region are

[111] Hegazi, Krampe Seymour Smith, Climate –Related Security Risks and Peacebuilding in Mali, SIPRI Policy Paper 60, April 2021, p. 13-15
Hegazi, Krampe Seymour Smith, Climate –Related Security Risks and Peacebuilding in Mali, SIPRI Policy Paper 60, April 2021, p. 13-15

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its subsistence mode of production, lack of modern techniques and skills, and its low productivity. Nevertheless, agricultural production increased in Mali in the last decade. In Mopti, in the Niger delta, production has tripled during the last 15 years due to the expansion of agricultural land.[112] This expansion can be at the expense of grazing areas, and the challenge for the country and the region in general is to increase agricultural production in a sustainable manner, minimising the loss of grazing areas and as such avoiding conflict between agricultural farmers and livestock production, and pastoralism. Although agriculture is increasingly combined with livestock rearing, transhumant pastoralism is still an important practice in Mali. Routing decisions depends on the quantity and quality of accessible pasture areas, access to water points and livestock markets. Other factors are the presence of defence and security forces and the level of security in pastoral areas depending on the presence of non-state armed groups and self-defence groups. Mali has a pastoral charter in place since 2001, regulating livestock corridors in order to guarantee access to grazing areas, and at a regional level, the Economic Community of West African States (ECOWAS) established in 1998 a Protocol on Transhumance. These regulations are however difficult to implement due to rapid herd growth, land degradation, pasture availability and extensive and numerous conflicts in the region. Transhumance has often been seen as an unproductive and conflict-prone livelihood however, efforts have been made to address this narrative through various political initiatives such as the African Union's Policy Framework for Pastoralism in Africa in 2001, the first political initiative aiming to ensure, protect and improve the livelihoods and rights of African pastoralists, or the Global Alliance for Resilience Initiative for the Sahel and West Africa (AGIR) implemented by the EU between 2014-2020, placing pastoralism among its priorities for the long-term development of the region[113].

The Niger and its inner delta as well as the Senegal River are providing the country with fish, and it is estimated that 35,000 households in the inner delta of the Niger are dependent on fishing as a livelihood with fish production exceeding as much as 100,000 tonnes in a good year. In this area, fishermen often diversify their income by also developing agricultural activities such as rice farming or by seasonal migration to where the fish is gathering.

Mining is also an important economic activity; however, mines are mainly exploited by multinational companies and as such the economic contribution of mining of for example gold in Mali, does not contribute to an improvement of the macroeconomic situation of the country. In recent years there has been a growth of artisanal gold mines in Mali, which is also related to the increase in conflict and criminal networks.

3.2.5.1.3 Climate Change in Mali

Mali has experienced a consistent increase in temperature since the 1960s and temperatures are projected to further increase, global climate models indicating a projection of 1.2-3.6°C by 2060. While variability in climate, both geographically and over time, is not new to the country, it has seen a sudden change, especially when it comes to predictability of climate events. The temperature increase will be general for the whole country but will be higher in the arid, desert like areas of northern Mali, while the south will see a higher increase in the annual number of very hot days and in rainfall, extreme rainfall and flooding than in the rest of Mali. Projections of water availability are uncertain but taking into consideration the concentration of water resources along the Niger and Senegal rivers and the inner Niger Delta, and the projected population growth and demographic pressure in these areas, the overall water availability will most probably strongly decline in the future. [114]

The country experienced various severe droughts during the 1970-80, contributing to humanitarian crises and even though wetter conditions have returned, especially in the Niger River basin[115], droughts continue to be a recurrent phenomenon, with pronounced drought periods between 2002-2003, 2011-2012, and 2015-2018, with average precipitation levels decreasing generally. As both farmers and pastoralists depend on the rainy season,

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[112] Puig Cepero and al. p.13
[113] Ibid, p. 14-16
[114] Nagarajan, Binder, Destrijcker, Michelini, Rüttinger, Sanagaré, Sedova, Vivekananda, Zaatour 2022: Weathering Risk climate , peace and security assessment: Mali, Adelphi, 2022, pp. 18-22
[115] Hegazi and al.,

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climate variations affect massively their livelihoods; hence inadequate rain, multi-year droughts, and a later start to the rainy season, are issues of concern among these groups. In addition to these climate change effects, Mali is exposed to other environmental pressures (non-climate related) such as land degradation and deforestation, caused by an expanded use of land for agriculture and increased demand for firewood and charcoal. Between 2001 and 2020, Mali lost 366,000 ha of forest cover, with deforestation rates being highest in the Sikasso area, which experienced 73% of tree cover loss during the above-mentioned period. [116]

As Mali has experienced climate stressors and climate variability in the past, its population has developed adaptation strategies to these changes such as livelihood diversification, alteration of techniques, migration, sometimes through engagement in new trade, and sometimes in illicit trades. Pastoralists split herds to lower risks, spend more time in search of pasture and water, migrate longer distances with herds in search of pasture, in some cases they sedentarise and engage in agro-pastoralism, i.e., ranching, or diversify their livelihoods away from pastoralism. Farmers adjust planting to respond to rainfall patterns, intensifies agriculture, and expand farmlands, and fishers intensify fish farming in artificial ponds, change migration patterns, buy and resell fish (instead of fishing it themselves), and diversify livelihoods away from fishing or as seen earlier, combines it with farming such as growing rice or other crops. [117] For many communities, free movement is essential to cope with challenging climatic conditions and is part of climate adaptation strategies. Both rural-urban mobility and transhumance mobility is strongly affected by climatic conditions and follow rainfall patterns, both in the north and in the south and around the major river basins where people many times migrate seasonally to work in the fields during harvest periods and back towards the coast or to urban areas during the dry season.

Figure 19: Source: BBC News, Getty Images

3.2.5.1.4 Water and food Security in Mali

Poverty is on the rise in Mali, affecting 78 percent of people.[118] Reliefweb International reported in April 2022 that Mali was facing its worst food and nutrition crisis in a decade, foreseeing an increase with 53 per cent of children suffering from acute malnourishment, reaching 1.2 million children aged 6-59 month and projecting a further increase of 19 per cent for the period June 2022 to May 2023. [119] While Plan International is reporting that in five years, from 2017 to 2022, the number of people in urgent need of humanitarian aid doubled from 3.7 million to

[116] Ibid, p. 2
[117] Nagarajan and al. pp. 29-30
[118] World food programme, Mali country brief, https://www.wfp.org/countries/mali
[119] Reliefweb International, Breaking the spiral of Food and Nutrition Crisis in Mali, April 2022, p. 1 and Mali: IPC Acute Malnutrition Snapshot June 2022- May 2023 at https://www.ipcinfo.org/fileadmin/user_upload/ipcinfo/docs/IPC_Mali_Acute_Malnutrition_Jun2022_May2023_Snapshot.pdf

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7.5 million. It was estimated that during the lean season 2022 (June – September, period between planting and harvesting) an estimated 1.84 million people were suffering from acute food insecurity.[120] Food insecurity varies from one region to another with the northern and central regions being the most affected[121]. Identified main drivers of this hunger crisis are conflict, climate change and multiple economic crises (Covid -19, global inflation and in the case of Mali, sanctions and the impacts on food supply imports due to the war in Ukraine.) Food insecurity in Mali is heavily gendered since levels are twice as high in families headed by women, many times only men can access food distribution sites and women's access to land and credit is generally more difficult in a country suffering from widespread gender inequalities.

3.2.5.1.5 Security situation in Mali

After Mali's independence in the 1960 from France, the country has experienced numerous conflicts, uprisings, coups d´état and longstanding tensions between populations in the north and the south with the political power concentrated in the south while different groups in the north were economically and politically marginalised leading to several rebellions of for example the Tuareg population in northern Mali during various decades. [122] However, between 1990s and until 2012, Mali was seen as a stable democracy in a difficult neighbourhood. After the military coup in 2012 provoked by on the one hand, the change in character of the Tuareg rebellions in northern Mali, due to the return of heavily armed Tuareg fighters who had helped defend the Gaddafi regime in Libya in 2011, with The Mouvement National pour la Libération de l'Azawad (MNLA) carrying out attacks in the north and forming alliances with other armed non-state actors, including Ansar Dine (Defenders of the Faith), al-Qaeda in the Islamic Maghreb (AQIM) and the Movement for Unity and Jihad in West Africa (MUJAO), and on the other hand by deserters from the Malian Armed Forces, that, unsatisfied with the situation, staged a coup, forcing the democratically elected president Toumani Touré to leave his post in March 2012 . In April 2012, the MNLA claimed northern Mali's independence as the state of Azawad. The occupation was however brief since Ansar Dine, AQIM and MUJAO drove out the MNLA from various occupied cities in the north such as Timbuktu and Kidal. The situation continued to escalate even after ECOWAS had negotiated a framework for inter-Malian dialogue between the MNLA, Ansar Dine and the Malian transitional government, leading to the Malian authorities requesting external military assistance from France in 2013. Operation Serval was launched and succeeded to regain control over the occupied cities in the north, with support from the UN authorised, African led International Support Mission in Mali (AFISMA). Shortly after, the UN Security Council established the Multidimensional Integrated Stabilization Mission in Mali (MINUSMA), mandated to support political processes and improve the security situation. Peace talks, led by Burkina Faso and supported by the UN and the African Union, led to a preliminary agreement and ceasefire in June 2013. Political progress was however slow and non-state armed groups clashed with Malian Armed Forces in Kidal in May 2014 leading to the defeat of Malian forces and Algeria stepping in to negotiate a multi-step peace process leading to the signing of an Agreement for Peace and Reconciliation in Mali, by the fighting parties in June 2015, an agreement that has been very slow to implement.

Meanwhile, central Mali has seen conflicts and violence arise, with communal violence escalating since 2015, in particular between pastoralists and farmers, with the presence of armed groups intensifying local disputes and fuelling tensions between communities. Socio-economic and political factors are contributing to tension, as ethnic identity and livelihoods are closely interwoven in Mali. As an example, the Fulani are pastoralists, the Bozo fishermen and the Dogon are farmers. [123] While it is important to keep in mind that Mali has a history of good relationships between and within these different groups and conflicts that would arise were normally resolved

[120] Plan International,Hunger crisis in Mali, Advocacy Brief, November 2022, p. 3
[121] World Food Programme.
[122] Hegazi and al. p. 5

[123] Hegazi and al., pp 4-7

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peacefully, relations have become strained due to different factors partly linked to climate change and to the different adaptation and resilience strategies, eroding social cohesion and creating tension both within and between different livelihoods. The competition of resources and the presence of armed non-state groups and limited state presence authorities have further increased tensions and violence. [124] Extremism, banditry, self-defence militias have grown in the region, partly due to the crisis in the north and the access to arms that it provides.

Weak governance and absence of government representation outside the main cities and towns and rent seeking and corrupt behaviour by government and community leaders and their inability to resolve conflict and protect citizens, made democratic norms erode along with the population's trust in the government. In August 2020 the elected President Keita had to resign after months of anti-government protests led by a group calling themselves the Movement of June 5 – Rally of patriotic Forces (M5). Coup leaders, creating the National Committee for the Salvation of the People (CNSP), put Colonel Assimi Goïta in charge. In September 2020, a transitional government with civilian and military actors was formed, but as soon as in May 2021, military officers arrested the heads of Mali's transitional state and government, and Colonel Goïta, interim Vice President, was appointed as interim President. As a consequence, ECOWAS and the African Union suspended Mali's membership and the US stopped its security assistance and France reduced its military presence in the country. In February 2022, the interim parliament approved a five-year democratic transition plan, but without a date for future elections. [125]

3.2.5.1.6 Violent Extremism in Mali

This continuum of conflict has led to a normalisation of violence, criminality and insecurity, a situation that has, as already reported, facilitated the surge of various violent extremist groups in Mali and throughout the Sahel region since early 2000s, many operating mainly in northern Mali (see p. 14). However, the group Katiba Macina appeared in central Mali, in the area of the Inner Niger Delta in 2016, and in 2017 a coalition of Ansar Dine, Katiba Macina, al-Mourabitoun and AQIM was created under the name of Jama'a Nusrat ul-Islam wa al Muslimin (Group to support Islam and Muslims, JNIM). The coalition has carried out numerous attacks against MINUSMA and the Malian Armed Forces and has been responsible for 78 per cent of attacks perpetrated against civilians in central Mali and Northern Burkina Faso since 2018. Violent confrontations between JNIM and the Islamic State in the Greater Sahara (ISGS) are also taking place in the central region of Mopti and north-eastern region of Gao since 2019.

Figure 20: Fighters from Islamist group Ansar Dine prepare to hand over a hostage for transport by helicopter to Burkina Faso, in the desert outside Timbuktu, Mali. Source: africanews.com

[124] Nagarajan and al., pp 31, 34
[125] Nagarajan and al., p. 10

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French engagement in order to control the increase of extremist violence in the Sahel and Mali through Operation Serval, followed by Operation Barkhane in 2014, was a first seen as a success, the French forces and its allies (various EU countries and Canada) recuperating occupied areas in northern Mali, strengthening the Malian armed forces and expanded its contra insurgence presence across the Sahel. Nevertheless, and despite efforts to withhold extremist activities, the Sahel region saw an increase of 70% in extremist violence during 2021, with thousands of Malian civilian and military casualties, and more than 2.5 million displaced persons. [126] For the Malian population, contra insurgence activities became associated with high rates of violence towards civilians, contributing to a widespread resentment towards French presence in the country. In addition, diplomatic relations between France and the Malian government began to deteriorate following the 2021 coup leading to President Macron announcing the withdrawal of the 2400 troops stationed in Mali in 2022, stating as primary reason for France's withdrawal as the transitional government's unwillingness to solve its growing security issues. Other issues such as the refusal of France to negotiate with extremist groups, going against popular demand, and the invitation from the Malian government to mercenaries from the Russian Wagner Group to help in the fight against violent extremism, were also part of the reasons why France decided to withdraw from Mali. [127]

3.2.5.1.7 International engagement in Mali

The UN mission in Mali, MINUSMA, with more than 15000 international personnel deployed, including more than 12000 troops, has struggled to adapt to the resurgence of extremist violence and to the increasing attacks on its peacekeepers. With the withdrawal of the French troops of the Operations Barkhane, mandated to protect MINUSMA personnel, the security situation for the mission's staff has worsened. The continuously deteriorating security situation, tensions in relations with the Malian authorities and the presence of Wagner legionnaires in the country strongly contributed to various countries announcing in 2022 their withdrawal of troop contribution earlier than planned. [128]

The European Union, has currently two missions in place in Mali, The EU Cap Sahel, since January 2015, with the mission to support the security sector reform and the strengthening of governance and accountability of the Malian internal security sector reform ,[129] and EUTM Mali, a military training mission put in place in 2020, with the aim to provide training, education and advice to the Malian Armed Forces and to the operationalization of the G5Sahel Joint Forces. However, the High Representative of the Union for Foreign Affairs and Security Policy/Vice-President of the European Commission (HR/VP) Joseph Borell announced in April 2022 the suspension of the mission, citing the lack of guarantees from Malian authorities that Russian military contractors would not interfere in the work as one reason for this suspension[130]. On the mission's webpage it is stated that *"All operational and non -operational activities are temporarily and reversibly suspended while maintaining the capacity to resume when conditions are met, and PSC (Political and Security Committee EU) so decides."*[131]

[126] Surge in Militant Islamist Violence in the Sahel Dominates Africa's Fight against Extremists – Africa Center for Strategic Studies
[127] BBC, Why are French troops leaving Mali, and what will it mean for the region? - BBC News
[128] MINUSMA at a Crossroads | Crisis Group
[129] EUCAP Sahel Mali | EEAS (europa.eu)
[130] EU leaves military training in Mali suspended, stops short of ending mission – EURACTIV.com
[131] PowerPoint Presentation (eutmmali.eu)

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Figure 21: Source: EUTM Mali

3.2.5.2 Somalia

3.2.5.2.1 Geography and Climate in Somalia

Figure 22: Political Map of Somalia. Source: Political Map of Somalia (1200 pixel) - Nations Online Project

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Somalia is part of the region of the Horn of Africa (Somalia, Ethiopia and Kenya), located to the very east of the Horn. It's population of 18,1 M (as per 2023)[132] is among the fastest growing in the world, with a distribution mostly in and around cities such as Mogadishu, Marka, Boorama, Hargeysa and Baidoa. The regions along the Kenyan border and the northeast and central regions are the least populated. The landscape is mountainous in the north, gradually flatten out into flat plateaus towards the south. The two main rivers, Juba and Shabelle Rivers, with their sources in the Ethiopian highland, provide southern Somalia with water and flood deltas, creating fertile soils for agricultural activities. [133] Somalia has the longest coastline of continental Africa (3025 km along the Indian Ocean and the Gulf of Aden).

The country has arid and semi-arid climates (80% of its land mass)[134] with two rainy seasons annually from March to June and from October to December, with dry seasons in between. This may vary between seasons and years and Somalia is influenced by natural phenomena such as El Niño- Southern oscillation (ENSO) with more rainfall during El Niño years and more droughts in La Niña years.[135] This is making it prone to extreme weather conditions such as periods of prolonged draughts, erratic rainfalls, and disruption to the wet seasons, strong winds, sand and dust storms.[136] Its long coastline makes it vulnerable to cyclones coming from the east.[137] The average rainfall in Somalia is 200 millimetres, with the north receiving an average of 50 mm, the south 400 mm and the south-west 600 mm. The average annual temperature are 30˚C with the hottest periods occurring in April – June.

3.2.6.2.2 Livelihoods in Somalia

Nearly 70% live below the poverty line and 90% live in multidimensional poverty which includes great need for education, improved access to water, improved sanitation and access to electricity, according to figures provided at the occasion of the World Bank's Somalia Economic Update in November 2022.[138] Agriculture is the country's main economic sector, employing approx. 80 percent of the population, although it is mainly an activity of subsistence, with limited opportunity to earn wages. The total agricultural land is making up 70,3% of the country, but only 1,8% is arable and permanent pastures are taking up the rest of the land surface, making most of people's livelihood centred around pastoralism and trade of livestock.[139]

[132] United Nations Population Fund, World Population Dashboard -Somalia | United Nations Population Fund (unfpa.org)
[133] Lisa Binder, Barbora Šedová, Lukas Rüttinger, Julia Tomalka, Stephanie Gleixner, Weathering Risk: Climate Risk Profile Somalia, February 2022, pp. 2-3
[134] Expert Working Groups on Climate–related Security Risks, Somalia, Climate-related security risk assessment, December 2018, p.4
[135] Emilie Broek and Christophe M. Hodder, Towards an integrated Approach to Climate Security and Peacebuilding in Somalia, SIPRI, June 2022, p. 3,
[136] Expert Working Group on Climate-related Security Risks, p.4
[137] Broek and al. p. 3
[138] The World Bank, Somalia Economic Update: Investing in Social Protection to Boost Resilience for Economic Growth, https://www.worldbank.org/en/news/feature/2022/11/29/somalia-economic-update-investing-in-social-protection-to-boost-resilience-for-economic-growth, accessed on 11 May, 2023
[139] The World Bank, https://data.worldbank.org/indicator/AG.LND.AGRI.ZS?locations=SO

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Figure 23: Somali pastoralists. Source: www.fao.org

Fishing as a livelihood system involves fishermen along the Somali coast and labour migrants from further inland. The Somali coastline, the longest in Africa, has been underutilized primarily by local artisan fishermen with little large-scale commercial activity. International fleets primarily exploit the Somali marine resources. It is estimated that Somalia loses approximately 100 million US dollars to illegal, unreported and unregulated fishing activities, resources that could go a long way towards improving the livelihoods of Somalis. 140 The lack of accurate data on Somalia's fisheries, approx. 86% of the fisheries are currently unreported, makes it complicated to predict the social and economic dependency of Somalia on its fishing industry.

Many fishermen and young unemployed men, out of necessity, have engaged in piracy, which, for at least during three decades, has been a huge security threat to the heavy traffic of commercial ships passing through the Gulf of Aden and the Gulf of Guinea, and which have required extensive effort from the international community and private shipping companies in order to enforce the maritime security in the region as well as assuring the security of the ships passing navigate these waters.

3.2.6.2.3 Climate Change in Somalia

According to the University of Notre Dame's Country Ranking on vulnerability, Somalia is the second most vulnerable country in the world to climate change. Its vulnerability is predicated on a unique combination of environmental, social, and economic factors, including high levels of poverty, conflict, and displacement, as well as limited access to resources and services. Depending on the future GHG emissions scenario, the temperature over Somalia is very likely to rise by 1.4 to 3.4°C by 2080.141 This rise in temperature will most likely be accompanied by an increase in the frequency of rapid-onset disasters such as flooding and droughts.142 With rising annual temperatures, the annual number of very hot days with daily maximum temperature above 35° C, is projected to rise with high certainty all over Somalia with central Somalia particularly affected. Somalia is currently facing its worst drought in four decades after five executive failed wet seasons, with more than 80% of water

[140] What are the causes of Maritime Piracy in Somalia waters?, https://www.marineinsight.com/marine-piracy-marine/causes-of-piracy-in-somalia-waters/
[141] Expert Working Group on Climate-related Security Risks, p. 6
[142] World Bank Climate Change Knowledge Portal (note 11), in Broek and al., p. 3

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sources dried up. An early start of the long wet season, with moderate to heavy rains in the Ethiopian highlands overtopped banks of the Shabelle and Juba rivers in March 2023. Homes, schools, and health facilities were destroyed along the banks of the two rivers, in southern Somalia, affecting nearly 100,000 people, causing human and livestock fatalities.143 Land degradation, deforestation and desertification have rapidly accelerated. It is estimated that the lower Juba area lost 50 % of its forest cover between 1993-2014.144

As a result of the increase of the global average temperature, the sea level at the Somalian coasts is projected to rise with high certainty. Projections foresee a sea level rise by 12 cm until 2030 and 20 cm until 2050. This sea level rise threatens the livelihoods of coastal communities, particularly in southern Somalia, including the country's capital Mogadishu, and may cause saline intrusion in coastal waterways and groundwater reservoirs, rendering water unusable.[145] Overall, precipitation will very likely increase over Somalia in the long run (until 2080), nevertheless increasing overall precipitation might not translate into more water availability as the additional water resources from precipitation can be expected to run off at the surface, increasing the risk of soil erosion and flooding, rather than infiltrating into the soils.

3.2.6.2.4 Water and food Security

Currently, prevailing La Niña conditions have pushed Somalia into its fifth failed wet period. Unlike previous droughts and food emergencies in Somalia, the current crisis is further aggravated by the war in Ukraine. Before the Russian invasion of Ukraine, Somalia imported nearly all of its wheat from the two countries (more than 90%). Together with the disruption of importation of crude oil from Russia, it has led to a soaring increase of costs for fuel, transportation and food production. Food prices, that already reached high levels during the Covid 19 pandemic, have climbed even higher since the start of the war. In addition, the scarcity of food produced in Somalia due to the drought, is further pushing the already very high prices.

Figure 24: Image: UN Photo/Tobin Jones

Many communities and nomadic pastoralist depend on the rainy periods for food and pasture. The current drought has wiped out millions of livestock animals and devastated farmland and crops., leading to massive displacement, currently there are approximately 3 million Internally Displaced Persons (IDPs) in Somalia, a number which is rapidly increasing.[146] Currently, around 6.5 million people are facing acute food insecurity, among which 1.84 million children under 5 are facing acute malnutrition, and a total of 478,000 face severe malnutrition[147] It caused 43,000 deadly victims in 2022 according to international organisations and the Somalian government reports, at least half were children under five years old. However, due to the fact that many children die at home and are not

143 Flash Flood Update nº 2, Somalia Gu rainy season 2023, April 2023, OSHA, p. 1
144 Eklöw, Karolina, Krampe, Florian, Climate –Related Security Risks and Peace building in Somalia, SIPRI Policy Paper 53, October 2019, p. 11
145 Binder et al., p. 7
146 Broek, Emilie and Hodder, M. Christophe, Towards and Integrated Approach to Climate Security and Peace building in Somalia, p. 10
147 World Food Programme, Somalia emergency | World Food Programme (wfp.org), accessed 10 May 2023

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reported to the authorities, the real figures are estimated to be much higher. Diseases such as diarrhoea, cholera and measles are further aggravating the situation.[148,149]

In addition, increased frequency of floods and cyclones has led to surges in desert locust plaques, causing heavy damage to the little amount of crops left and loss of income.

Water scarcity is persistent in Somalia.150 Unicef reported in 2019 that only half of Somalia's population had access to a basic water supply. Limited regulation of private water suppliers results in often excessive prices, forcing people to get water from open wells that most often are far away and unsafe. Without access to clean water and sanitary installations, diseases that are otherwise easily preventable, spreads easily. In conflict areas and in camps for displaced persons, the access to safe water is even more difficult.151 As already described in previous section, the current draught is drying up more than 80% of the country's fresh water resources, including the country's two main rivers that already last year were at below historic minimum levels making water a real scarcity.

Coping strategies in such conditions are often maladaptive, having the opposite of their intended effects and are many times exacerbating already vulnerable conditions.

3.2.5.2.2 Political and Security Situation in Somalia

The Republic of Somalia was constituted in 1960 by the federation of a former Italian colony and a British protectorate. It was under the dictatorial rule of Mohamed Siad Barre from 1969 to 1991.[152] His dictatorship was marked by extreme brutality, suppression of opposition groups, and aggravation of inter-clan rivalries. The dissatisfaction with this leadership led to the prompting of the First Somali Civil war in 1988 by nationalist groups and clan based guerrillas and led to the fall of Said Barre's regime in 1991. The civil war and the fall of the regime led to a power vacuum in which nationalist and Islamic groups, warlords, clan and sub-clan militias aimed t dominate territories for their own rule. Therefore, regional and international institutions put in place various peace and reconciliation processes to stabilise the country and create a strong federal government. However, this was a difficult process since inter clan rivalries had created tensions between the Federal government and the regional states, resulting in the declaration of independence by Somaliland in 1991, which still today is not recognised by any nation in the world, and Somalia maintaining its authority. The region of Puntland in northern Somalia declared partial autonomy in 1998, reserving themselves the right to operate independently but still being part of the Federal Government. The civil war and conflict in general have prevailed in Somalia ever since, related to both internal and external factors, and have resulted in more than 1 million deaths and many more fleeing the country.153

However, with renewed efforts to rebuild the central government, involving a dual state-building and peacebuilding effort led by the regional Institution Intergovernmental Authority in Development (IGAD), the Arta Declaration in 2000 was signed. This declaration asserted that all future Somali governments would use the 4:5 formula which states that the country's four main clans (Dorad, Hawiye, Dir and Rahanweym) will have equal representation, while smaller clans would share the rest of the representation, in an intent to address clan grievances. Despite these efforts, the following transitional governments' work was marked by inefficiency, internal strife, and corruption. In 2012 the Transitional Federal Government /Parliament however managed to create a new constitution which led to the country's first election since 1969. The Federal Government of Somalia (FGS) was installed in August 2012. In line with the transitional governments, the FGS aimed to stabilise the country through building a national consensus between the government and the newly defined regional states – Jubaland,

[148] The Washington Post, Africa's desperate hunger: Ukraine war pushes Somalia toward famine, https://www.washingtonpost.com/world/interactive/2022/somalia-famine-ukraine-war, accessed 28 April 2023
[149] Integrated Food Security Phase Classification, Somalia: Acute Malnutrition Situation January – March and Prjection for April- June 2023, https://www.ipcinfo.org/ipc-country-analysis/details-map/en/c/1156239/?iso3=SOM, accessed on 24 April
150 Eklöw and Krampe, p. 11
[151] Unicef,Water, sanitation and hygiene, https://www.unicef.org/somalia/water-sanitation-and-hygiene, accessed 9 May, 2023
[152] Somalia, Somalia | Election, President, News, Capital, & Economy | Britannica
[153] Somali Civil War, Somali Civil War – The Organization for World Peace (theowp.org)

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Puntland, HirShabelle, South West, Galmudug and Somaliland. Each regional state, which is representative of the traditional clan and sub-clan territorial boundaries, was tasked with creating spaces where clan rivalries and grievances could be addressed. According to analysts, and even though each federal government has focused on creating a cohesive and inclusive political space that considers clan politics and alliances, the obstacles preventing Somalia from moving forward cohesively is the role of clan interest, i.e., clannism, in politics. The majority of the people in power push the interests of the clan and sub-clan rather than the interest of a united Somalia. As a result, there are a general scepticism concerning the intentions of others between politicians, making them unable to significant changes.154 The traditional way to solve conflict and dispute in Somalia, xeer, has no single authority and is applied ad hoc between two conflicting parties, with a third party deciding the outcome and compensation, and has become weakened or replaced, partly due to the civil war, and partly because of conflict and climate-related migration, tearing communities apart and losing its elders and local experts of xeer law. Al Shabaab has for example replaced xeer with Sharia law in occupied territories. As such there are few lasting and effective measures for conflict resolution and reconciliation for conflicts over territory, livestock, natural resources, etc. Climate-induced changes such as rain fall variability and drought often result in heightened tensions and conflicts between farmers and herders. Nomadic mobility patterns are changing with the decrease in grazing fodder and vegetation, which often results in conflicts over land, access, and resources. Local political elites often exploit the grievances of the general population to strengthen their own agenda.155

3.2.6.2.6 Violent extremism in Somalia

During the power vacuum created after the fall of the dictatorship in 1991, several autonomous Islamic courts were constituted throughout the country as a response to the lawlessness and chaos that followed. In the beginning these were not officially linked to each other but part of the same informal movement which originally started in northern Mogadishu. Until 2000, these courts only controlled limited areas and relied on recruited local clan militias to enforce their power. When the courts united to form what later became the Islamic Courts Union (ICU), they also united their militias and by doing so, created the first significant Somali militant organisation not controlled by warlords or ruled by a single clan. It started to extend its power beyond Mogadishu and gained popularity for its provision of security and other services, such as managing schools and hospitals in Mogadishu, and ICU controlled areas were considered much safer than regions controlled by warlords. Somalia's Transitional Government aimed to reduce ICU's influence but since it couldn't provide enough security to citizens and therefor declined in power, the ICU re-emerged and by 2005 Mogadishu contained 11 Islamic Courts, all under the umbrella of the ICU. Around this time, the US and CIA were trying to capture individual linked to Al-Qaeda in Somalia, fearing that the country would become a haven for radical Islamists and terrorists. In this attempt, the US supported a formation of a coalition of warlords in Mogadishu called the Alliance for the Restoration of Peace and Counter-Terrorism (ARPCT) charged with helping out in the search for these targets. However, these warlords were locally infamous and their objective to apprehend individuals created resentment and increased support for the ICU. Tensions between these two groups quickly translated into violence and the ICU defeated ARPCT in June 2006 and gained control over all Mogadishu. ICU's militant wing, Al Shabaab, had a central role in the take-over of Mogadishu.

[154] Ibid

[155] Eklöw et al. pp. 18-21

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Figure 25: Al-shabaab fighters in Somalia. Source: AP News

The ICU governed the city for several months and during that time it implemented urban improvement projects and reopened the airport and seaport that had been closed for ten years. By October 2006, ICU also controlled most of southern central Somalia. Motivated by international concerns, the Transitional Federal Government (TFG), that had been forced to govern from Kenya due to the insecurity in Mogadishu and in the country in general, engaged in negotiations with ICU in June to September 2006 regarding power-sharing governance structures, however, Ethiopia, fearing an expansion of ICU's influence over its own borders, started to increase its support for the TFG, and together they expelled ICU from Mogadishu and other urban strongholds in December 2006, making the ICU disintegrate shortly after. Its military wing, Al-Shabaab, however broke away at this time to become an independent militant group.[156] The Ethiopian invasion was a crucial event for Al- Shabaab, allowing the group to become the major force for resistance in the country, conducting attacks against Ethiopian and TFG forces and later on troops from AMISOM, the African Union mission trying to contribute to stabilise Somalia. After having strengthened its links with Al Qaeda, the group launched a campaign in revenge for the death of its leader killed in a US missile strike in May 2008, focusing on attacks against U.S and UN targets in the country. Among other attacks during that campaign, Al Shabaab simultaneously executed five suicide attacks against UN and government targets on 29 October 2008. Even though the country faces multiple security risks in the format of illegal activities such as human trafficking, piracy, illegal fishing, clan and warlord conflicts etc., in an environment marked by drought and famine and environmental deterioration, Al Shabaab continues to be seen as the most immediate security risk in Somalia today. Even though AMISOM, the African Union Operation in Somalia, has succeeded to regain some of the territory occupied by Al Shabaab, it still has control of large areas of the countryside and continues to carry out attacks both within Somalia and in neighbouring Kenya, targeting civilians, the Somali state, and the African AMISOM.[157] Report state that the group's violence increased in 2022. It carried out more than 2400 political violent events, including more than 1700 battle events and around 300 incidents of violence

[156] Islamic Courts Union, MMP: Islamic Courts Union | FSI (stanford.edu)
[157] Expert Working Group on Climate-related Security Risks, p. 11

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targeting civilians. [158] Al Shabaab is often capitalising on the country's exacerbated situation and recruits children, young and unemployed men from IDP camps or exploit population that has suffered climate-related losses and conflict.159

3.2.6.2.7 International engagement in Somalia

UN - Early interventions in the 1990's were marked by the chaos that Somalia found itself emerged in following the fall of the dictatorship in 1991 and the civil war that followed. In addition to this, a rampant inflation and lack of fuel, electricity and food, as well as drought, exacerbated the situation and the starvation of the population. Private relief organisations couldn't prevent the theft of food and provisions by armed militias and the use of food as a political weapon. The first UN mission (UNOSOM I) with the mission to provide, facilitate and secure humanitarian relief in Somalia, as well as to monitor the first UN-brokered ceasefire of the civil war, continued to struggled to reach those in need due to theft of provisions and to make respect the agreed ceasefire, due to difficult relationships between warlords and to have to negotiate with these in order to carry out food distribution. As a response to this the United States-offered to establish a multinational force under U.S leadership to secure humanitarian assistance, accepted by the Security Council, the Unified Task Force (UNITAF) began in the summer of 1992. In early 1993, the Secretary-General convened a meeting in which 14 important Somalia political and rebel factions agreed to hand over all of their weapons to UNITAF and UNOSOM, and over $130 million was pledged by donors at an aid conference that year to assist in reconstruction. However, Somalia continued the stumble, and in March the UN decided to transform the UNITAF mission into what came to be known as UNOSOM II. The mandate of UNOSOM II stipulated that the operation was to secure continued relief efforts and, more significantly, to restore peace and rebuild the Somali state and economy. The presence of the UN and the U.S was however marked by the Battle of Mogadishu in October 1993 in which 18 US soldiers and hundreds of Somali fighters and civilians were killed and U.S. troops had to be rescued by an international force after 17 hours of continuous fighting.[160] Soon after the incident, all U.S. troops were withdrawn from Somalia and a year later UN also withdrew its troops.

More recently, the United Nations Assistance Mission in Somalia (UNSOM) was established on 3 June 2013 by UN Security Council Resolution 2102, following a comprehensive assessment of the United Nations in support of the establishment of the Federal Government of Somalia. Its mandate has been renewed yearly and its current mandate is valid until 31 October 2023 and includes *"the provision of policy advice to the Federal Government and the African Union Mission in Somalia (AMISOM) on peacebuilding and state-building in the areas of governance, security sector reform and rule of law (including the disengagement of combatants), development of a federal system (including state formation), constitutional review, democratisation (including preparations for the 2016 political transition) and coordination of international donor support."*[161]

Concretely, and in relation to security and climate security, the Federal Government and the UN have implemented several actions to respond to armed groups and their manipulation of climate-related vulnerabilities. In 2016 FGS adopted a national strategy and action plan on preventing and countering violent extremism (PCVE) as part of its approach to security in Somalia, UNSOM has an adviser to support the FGS in implementing this plan and strategy.

EU - EU is currently the largest donor both in terms of political engagement as well as financial and technical support and expertise. Since 2008 the EU and its Member States provided €3.7 billion to the country in development and humanitarian aid as well as peacekeeping operations, state building and peace building, food security and resilience, and education. It has also deployed three Common Security and Defence Policy missions in the country:

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[158] The Armed Conflict Location & Event Data Project, Context Assessment Heightened Political Violence in Somalia, March 2023, retrieved from https://acleddata.com/2023/03/03/context-assessment-heightened -political-violence-in-somalia/, accessed on 11/05/2023

[159] Eklöw et al. p. 20

[160] Somalia intervention, military operation (1992 – 1993), Somalia intervention | military operation [1992-1993] | Britannica

[161] UNSOM webpage, Mandate, Mandate | UNSOM (unmissions.org)

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- EUNAVFOR ATALANTA – with the mission to contribute to the maritime security in North Western Indian Pacific through protection of WFP and other vulnerable vessels within the Area of Operations, piracy and armed robbery at sea, prevention, deterrence & repression, illicit maritime flows disruption and deterrence, including illicit trade financing criminal and terrorist networks, deconfliction, cooperation with and support to International organizations: naval forces (CMF & EMASOH), independent deployers and commercial shipping;

Figure 26: Source : EU NAVFOR ATALANTA

Figure 27: Source: EU NAVFOR ATALANTA

- EUCAP Somalia – launched 2012, under the name EUCAP Nestor, a regional civilian maritime capacity building mission which aimed at supporting hosting countries across the Horn of Africa and Western Indian Ocean in developing self-sustaining capacity to enhance maritime security sector, working with a focus on counter-piracy, it was rebranded as EUCAP Somalia in 2016EUCAP Nestor was mandated to work, focusing solely on Somalia.
- EUTM Somalia - was launched in April 2010 with the mission to provide capacity building through strategic level advice and training to Somali authorities within the Security Institutions in the Mogadishu Area. It is currently implementing its 7th mandate with changes reflecting circumstances on the ground.

African Union – The African Union has been engaged actively in Somalia since 2007 when it replaced the Inter-Governmental Authority on Development (IGAD) Peace Support Mission to Somalia or IGASOM, which was a proposed Inter-Governmental Authority on Development protection and training mission in Somalia approved by the African Union in September 2006, with the African Union Mission in Somalia (AMISOM). It was created by the African Union's Peace and Security Council on 19th January 2007 with an initial six month mandate, approved by

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the UN Security Council, and with the aim to *"support a national reconciliation congress, take all measures, as appropriate, to carry out support for dialogue and reconciliation by assisting with free movement, safe passage and protection of all those involved in a national reconciliation congress involving all stakeholders, including political leaders, clan leaders, religious leaders and representatives of civil society."* [162] This mandate has been renewed twice by the UN Security Council (in 2014 and 2017), with the latest mandate enabling the gradual handover of security responsibilities from AMISOM to the Somali security forces.[163] In order to facilitate this handover AMISOM was reconfigures into the African Union Transition Mission in Somalia (ATMIS) mission in 2022 with the mandate to a) degrade Al Shabaab and other terrorist groups; b) provide security to population centres and open the main supply routes; c) develop the capacity of the Somali Security Forces to enable them to take over security responsibilities by the end of the transition period, that is, December 2024; d) support peace and reconciliation efforts of the FGS; and e) help develop the capacity of the security, justice and local authority institutions of the Federal Government of Somalia and Federal Member States. This mandate shall be carried out in a four-phased approach: Phase I –Reconfiguration; b) Phase II – Joint shaping and clearing operations and the handing over of some Forward Operating Bases to Somali Security Forces; c) Phase III – Decisive operations and handing over of the remaining Forward Operating Bases; and d) Phase IV – withdrawal and liquidation of ATMIS. [164]

3.2.5.3 Mozambique

Figure 28: Country Map Mozambique Source: theworldmap.net

[162] AMISOM webpage, https://amisom-au.org/amisom-background/
[163] Ibid
[164] African Union, Peace and Security Council, Communique Rev. 1, Adopted by the Peace and Security Council (PSC) of the African Union (AU) at its 1068th meeting held on 8 March, 2022, on the reconfiguration of the AU Mission in Somalia (AMISOM), p. 3-4

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3.2.5.3.1 Geography and Climate in Mozambique

Mozambique is a country located on the east coast of southern Africa with a 2,500 km long coastline along the Indian Ocean facing east to Madagascar. In 2022 its estimated population was around of 33 million with an annual population growth slightly above 2%. The majority of the population are living in rural areas and along the coast.[165] The country is mostly coastal lowlands, with uplands in the centre, high plateaus in the northwest, and mountains in the west. The northern part of Mozambique is rugged, with mountain as high as 2400 meters. Africa's fourth longest river, the Zambezi, in the centre of the country, divides Mozambique in half and has a length of 819 km through the country. Mozambique has numerous other rivers, which all provide alluvial deposits and offer both hydroelectric and irrigation potential. Other rivers are the Rovuma River which defines most of the country's northern border with Tanzania, the Maputo River, forming part of the southernmost border with Swaziland and South Africa, just to mention a few. 166 The agriculture sector is a source of income to more than 70% of the population, with approx. 60% of total land area being agricultural but only 7,5 % of the land is arable.

A warm, rainy season occurs from October to April, while a cool, dry season follows between May and September. There are also two distinct climate regimes: the tropical and sub-tropical climate in the Central and Northern regions; and the arid and semi-arid climate in the southern region. Rainfall is mainly driven by the Inter Tropical Convergence Zone (ITCZ). The ITCZ movement up and down along the equator results in higher and more reliable rainfall amounts in the northern regions (around 1000-1500 mm per year) and lower and more variable rainfall amounts in the southern regions (less than 500 mm per year in some parts). The position and intensity of the ITCZ varies year-to-year as it is influenced by macro dynamics in the climate system, such as the El Niño Southern Oscillation. The country is prone to severe climate related disasters such as cyclones, flooding and droughts.[167]

3.2.5.3.2 Livelihoods in Mozambique

Mozambique has experienced strong economic growth over the last two decades, with significant increase of tertiary services and light industry and, to a lesser extent, commercial agriculture.[168] The country's agricultural potential is estimated at 62% of the total land area, but only 7% of the land area is currently cultivated, with the most common crops being rice, maize, sorghum, millet, and cassava.169 Four out of five Mozambicans rely on agriculture to provide for themselves. The agricultural production of 4.6 million smallholder farmers accounts for 75 percent of the country's total production, with 90 percent of all agricultural land cultivated by these smallholder farmers. The major cash crops are sugarcane, tobacco, and cotton, mostly cultivated and processed by large multinational or state companies. Mozambique has some of the lowest cereal yields in southern Africa. Low agricultural productivity and growth is linked with small farm size and limited investment in infrastructure and technologies for production efficiency, among others. Even though the country has good water resources through its many rivers, the number of hectares of irrigated soil is little, most of it thus being rain-fed.170

The agricultural sector also plays an essential role for women's livelihoods, as 90% of the active female population earn a living from agriculture. Moreover, women constitute 61% of the agricultural labour force. Livestock rearing and pastoralism covers 55% of the total agricultural land. Livestock production is also small scale and plays a significant role in livelihoods, food security and nutrition. The most common livestock types include cattle and goats, reared largely in Tete and Gaza provinces. Approximately 2.3 million households raise poultry. In the northern parts of the country, livestock production is challenged by animal disease incidence, such as African Animal Tripanosomiasis (AAT), which causes anaemia, weight loss, emaciation and sometimes death of cattle.

[165] The World Bank, Mozambique overview, https://www.worldbank.org/en/country/mozambique/overview, accessed on 5 May 2023
[166] Brittanica, Drainage of Mozambique, https://www.britannica.com/place/Mozambique/Drainage
[167] World Bank, Climate-Smart agriculture in Mozambique, 2019, p. , p. 3 World Bank, Climate-Smart agriculture in Mozambique, 2019, p.
[168] Ibid
[169] World Food Programme, Food security and livelihoods under a changing climate in Mozambique Preparing for the future, 2021, p. 13
[170] World Bank, 2019, p. 3

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Fishery plays a crucial role in Mozambique's economy, supporting the livelihoods of about 380,000 small-scale, artisanal fishers, however, only 2-3% of the boats owned by artisanal fishers are motorized.[171]

3.2.5.3.3 Climate Change in Mozambique

Mozambique is among the most vulnerable and least prepared countries with regard to natural disasters, ranking 171 out of 182 nations on the Global Adaptation Index (NDGAIN).[172]

Climate change projections for the 2050s for Mozambique indicate a substantial warming trend across the country, with an increase in temperature up to +3˚C. The World Food Programme indicates that Mozambique already experienced a rise of +1˚C in 40 years and that the areas of warming also experienced high rainfall variability, resulting in late starts to the rains, early cessation, and intense rains in short time periods. The combination of hotter and drier conditions is making drought more common, affecting populations that rely on rain-fed agriculture.[173] Increased evaporation will negatively impact water availability. Extreme events, such as floods and droughts, will increase in frequency and intensity. In addition, the intensity of tropical cyclones is projected to increase, though the overall number of cyclones is projected to remain about the same.[174] Mozambique is often hit by cyclones occurring typically before and/or after the rainy period (May-June and October Novembers).[175] In 2019 the country was hit by two violent cyclones, Idai and Kenneth, with just 6 weeks apart, the first time in recorded history that two strong tropical cyclones hit the country in the same season. The scale of damage caused by cyclone Idai that hit the Mozambican city of Beira was massive and with estimates that 90% of the area was destroyed. Idai has since been labeled the deadliest cyclone in southern Africa. The winds and flooding from the storm caused the displacement of 19,660 households or 95,388 people, with 81% of the displaced population in Sofala and Manica Provinces. Half of the population affected were children. The cyclones hitting the country since is most often leaving devastated areas behind, destroyed by strong wind and heavy flooding. [176] Recently, in March 2023, Mozambique was hit by another violent cyclone, Freddy, now under evaluation as the strongest in history, with an accumulated cyclone energy equivalent of an average full North Atlantic hurricane season. It affected 1.1 million people, brought heavy floods and a cholera epidemic and caused significant crop losses just before harvest season.[177]

Figure 29: General view after Cyclone Freddy hit the city of Quelimane, in Zambezia Province, causing severe damage to infrastructure, trees, and power. Picture: Alfredo ZUNIGA / UNICEF / AFP

[171] World Bank, 2019, p. 4
[172] Notre Dame Global Adaptation Initiative, ND_GAIN, https://gain.nd.edu/our-work/country-index/rankings/
[173] World Food Programme, Food security and climate change the pressing reality of Mozambique, 2019 p. 3-4
[174] World Food Programme, Food security and livelihoods under a changing climate in Mozambique Preparing for the Future, 2021, p. 10
[175] World Data, Cyclones in Mozambique, https://www.worlddata.info/africa/mozambique/cyclones.php
[176] Reliefweb, https://reliefweb.int/report/mozambique/mozambique-tropical-cyclones-idai-and-kenneth-emergency-appeal-ndeg-mdrmz014-final-report
[177] Mozambique: Tropical Cyclone Freddy, Floods and Cholera - Situation Report No.1 https://reliefweb.int/report/mozambique/mozambique-tropical-cyclone-freddy-floods-and-cholera-situation-report-no1

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3.2.5.3.4 Water and food security in Mozambique

Poverty affects close to half of the population, mainly in rural areas, who live below the poverty line set at 1.9 USD per day by the World Bank. While progress has been made in terms of poverty reduction in recent years, due to growth economic growth thanks to emerging sectors (like the service and extractive sectors), evidence but since distribution of income is not equal, undermining the overall poverty reduction potential of the economic growth experienced poverty persists. Food insecurity rises during the lean season (December to March, with some regional variations between North and South), when food from the previous harvest have been consumed. In addition, with the high occurrence of climatic disasters, food production and stores are minimized, and the duration of lean season has increased. Disasters occurring with little time in between to allow households to recover, creates a negative trend in terms of food security, in turn provoking a complex relationship between chronic and acute food insecurity in the country, even if Mozambique is a country with a potential for food and water production, rich of natural resources, with fertile flood plains, a long coastline and other natural resources available. Drivers for food security are many, the global once seen in earlier sections, such as the Covid-19 pandemic, raised food and fuel prices due to the war in Ukraine and the global inflation, but specific to Mozambique are also the underdevelopment of agricultural value chains, characterized by challenges across different section across the chain; production, harvesting and transport, processing, distribution and sales, undermining the potential of the sector and also the country's progress in terms of food security and nutrition.[178]

Last year most rural household faced minimal Acute Food Security levels (IPC Phase 1), while in areas covering from natural disasters are at Phase 2 levels, such as drought effected areas in southern and central Mozambique and the Nampula province that was affected by cyclones in 2022 and 2023. Cabo Delgado in northern Mozambique, emerged in violent conflict, are in Food security Crisis level (Phase 3). With the access to the March / April harvest of 2023, these levels were supposed to improve slightly during the second half of 2023,179 but the hit of the tropical Cyclone Freddy in March 2023 in the central and southern parts of Mozambique destroyed most of the crops just before harvest season, leaving 3.15 million people in IPC Phase 3.180

Constant destruction due to cyclones provokes damaged water infrastructure and the spreads of diseases such as cholera. Currently, humanitarian organisations are seeking to provide assistance to 815,000 people affected by cyclone Freddy, cholera, and flooding, with interventions in water, sanitation, and hygiene (WASH).181

3.2.5.3.5 Political and Security Situation in Mozambique

Mozambique gained independence from Portugal in 1975 after a long guerrilla war, launched in 1964 by the Marxist – Leninist Frente de Libertação de Moçambique (Frelimo). Frelimo ruled the country until 1989, when it adopted a multi-party system and started opening up the economy. Frelimo still dominates political life, in the latest elections, in 2019, Frelimo won the presidency, with 74 % of the vote. The Mozambican National Resistance (Renamo), which has carried out a guerrilla war on Frelimo for 14 years, before the reach of a peace agreement in 1992, entered politics as the main opposition party, yet some factions continued their military activities. In line with the third and most recent peace agreement of August 2019 between Frelimo and Renamo, some disarmed Renamo insurgents have been incorporated into the army and the police. Although the agreement is generally holding, giving the government a chance to focus on the northern insurgency (see next section), some breakaway groups are still creating conflict and tension.

A huge debt scandal was uncovered in 2016 relieving that three state companies between 2013 and 2014, had taken out external loans for public projects worth more than US$2billion, backed by government guarantees. The loan was supposedly for a tuna fishing fleet, but the boats have hardly caught any tuna in the last decade. This was

[178] World Food Programme, 2021, p.13-16
[179] Famine Early Warning Systems Network, Mozambique Food Security Outlook October 2022 to May 2023
[180] OCHA, Mozambique: Tropical Cyclone Freddy, Floods and Cholera Situation Report No.1, 2023.
[17]Reliefweb, Mozambique – Food Security Outlook Update, April 2023

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followed by a further loan for high-speed patrol boats, and then in 2014 a loan supposedly for dock equipment. Many of the loans were subsequently sold on to other speculators. More than half of this debt was not made public and the parliament was never informed. Corrupt officials linked to the government party, among which the son of the former president, Armando Ndambi Guebuza, had been drawing off significant amounts of money. The multinational bank Credit Suisse, which London branch had been given some of the loans, was fined £147 million in late 2021 for its role in causing the crisis. [182]

As a consequence, the IMF, the EU and other donors, froze their direct budget support to the government, which was used for financing around a third of the budget. Inflation rushed and GDP growth, which since 2001 had been around 7% annually, diminished by half over the following years.[183]

3.2.5.3.6 Violent Extremism in Mozambique

Northern Mozambique has a Muslim majority, whereas the rest of the country is predominantly Christian. The Muslim population adheres to the traditionally peaceful and tolerant Sufi tradition. In recent years though, Islamic groups from eastern African countries have spread radical ideas among disenfranchised youth in the region, exploiting local grievances relating to marginalisation, corruption and criminal networks. Since 2017, an Islamist insurgency has destabilised Cabo Delgado, causing a spiral of violence fuelled by poverty and deprivation, similar to that witnessed in the Sahel. It is driven by Ansar Al-Sunna Wa Jamma (ASWJ), known locally as al-Shabaab, but without any connection with the Somali group of the same name. The group declares its affiliation to the Islamic State Central Africa Province (ISCAP) and, while ties are unclear, ISIS has taken credit for the attacks the group has launched. Insurgents have attacked both security forces and civilians, burning villages and committing atrocities. In 2020 and 2021, they also temporarily occupied the port towns of Mocímboa da Praia and Palma. The Mozambican authorities and armed forces have been ineffective in halting violence and the joint offensives against armed groups by the Mozambican, Rwandan and Southern African Development Community Mission in Mozambique (SAMIM), didn't have much success neither in halting the insurgency, on the contrary, armed groups dispersed and launched new fronts of attack in previously unaffected regions, moving west and southwards into Niassa and Nampula provinces.184 To make up for this lack of capacity, the government has turned to foreign mercenaries such as the Russian Wagner Group in 2019, which soon had to downscale and retreat after suffering heavy losses. The Dyck Advisory Group, a private South African company, provided Mozambique with aerial support and training between 2020 and 2021. There have been reports on abuses on civilians by the armed forces in the area and accusations of indiscriminate attacks.[185] The expansion of the armed conflict aggravated the humanitarian situation. OCHA estimates that at least two million people in northern Mozambique need life-saving and life-sustaining humanitarian assistance and protection in 2023 in Cabo Delgado, Nampula and Niassa as a result of the continued impact of armed conflict, violence and insecurity in the region.[186] Amnesty International Reports that approx. 80% of displaced people were hosted by friends and families, placing a heavy burden on their limited resources.[187]

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[182] https://debtjustice.org.uk/blog/the-mozambique-debt-scandal-the-storm-before-the-storm
[183] European Parliament, In brief, Security Situation In Mozambique, 2022, https://www.europarl.europa.eu/RegData/etudes/ATAG/2021/689376/EPRS_ATA(2021)689376_EN.pdf
[184] Amnesty International; Mozambique 2022, https://www.amnesty.org/en/location/africa/southern-africa/mozambique/report-mozambique/
[185] Ibid
[186] OCHA, MOZAMBIQUE 2023 Humanitarian Response Dashboard, March 2023, p. 1
[187] Amnesty International, 2022

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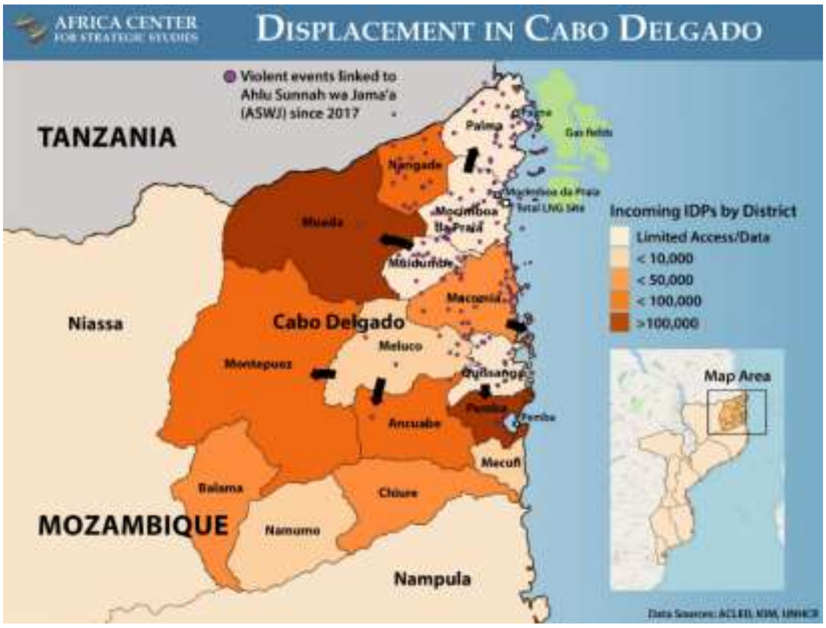

Figure 30: Displacement in Cabo Delgado. Source: African Centre for Strategic Studies

In addition, locals feel marginalised in the exploitation of resources, notably the recently discovered gas outside the northern coastline, and of some of the world's largest ruby deposits in Cabo Delgado, attracting fortune hunters and informal miners from across East Africa, but since chased away when multinationals took over the mine, leading to protests in 2019. Local population blame this marginalisation for the escalation of terrorism and the loss of their land and livelihoods.[188]

3.2.5.3.7 International engagement in Mozambique

UN - The United Nations is present in Mozambique since its independence in 1975 through 22 specialized agencies, funds, and programmes supporting the Government and civil society. Different UN agencies are working in areas such as health, work, economic growth, education, culture, and the protection of all, including children, refugees, migrants, displaced people, and the environment. Fighting AIDS, malnutrition, crime, and corruption, working in all provinces from Rovuma to Maputo. [189]

EU - Under the 2021-2027 multi-annual indicative programme agreed between the EU and Mozambique, EU development aid is geared towards supporting social cohesion and conflict-sensitive interventions through an integrated approach. In 2022, The EU established a military training mission in Mozambique (EUTM Mozambique) with the mission to provide training and support to the Mozambican armed forces (it will train eleven companies: five companies of Mozambique navy marines in Katembe, and six companies of Army special forces, in Chimoio) to protect the civilian population and restore security in the Cabo Delgado province. More specifically its mandate includes:

- military training including operational preparation;
- specialised training, including on counterterrorism;
- training and education on the protection of civilians and compliance with international humanitarian law and human rights law;
- promotion of the agenda Women, Peace and Security.

[188] African Institute for Security Studies, The many roots of Mozambique's deadly insurgency, https://issafrica.org/iss-today/the-many-roots-of-mozambiques-deadly-insurgency,2022
[189] UN Sustainable Development Groupd, Mozambique, https://unsdg.un.org/un-in-action/mozambique

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The mission has a non-executive mandate and will end two years after the mission has reached Full Operational Capability. EUTM Mozambique will be one of the tools to address the crisis in Cabo Delgado, in conjunction with support for peacebuilding, conflict prevention and dialogue support, humanitarian assistance and development cooperation.[190]

African Union – the Southern African Development Community (SADC) launched in 2021 the SADC Mission in Mozambique, SAMIM, to support Mozambican army to combat terrorism and violent extremism in Cabo Delgado by neutralising terrorist threat and restoring security in order to create a secure environment; strengthening and maintaining peace and security, restoring law and order in affected areas of Cabo Delgado Province; and supporting the Republic of Mozambique, in collaboration with humanitarian agencies, to continue providing humanitarian relief to population affected by terrorist activities, including internally displaced persons (IDPs). Contributing troops are coming from Rwanda, Angola, Botswana, Democratic Republic of Congo, Lesotho, Malawi, South Africa, United Republic of Tanzania, and Zambia[191]. However, the success of the mission is difficult to assess, and its troops have been accused of civilian casualties, abuse[192], and to protect the interests of the big companies interested in extracting natural resources in the area[193].

[190] European Union Training Mission in Mozambique, https://www.eeas.europa.eu/eutm-mozambique/about-european-union-training-mission-mozambique_en?s=4411
[191] Amnesty International, 2022
[192] Amnesty International, 2022
[193] United States Institute of Peace, Regional Security Report: A Vital First Step for Peace in Mozambique, 2022 https://www.usip.org/publications/2022/06/regional-security-support-vital-first-step-peace-mozambique

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3.2.6 Pathways between climate impacts and implications for security

Climate change has significant implications for security. Worsening livelihood conditions, increasing migration and changing mobility patterns, tactical considerations by armed groups, and exploitation by elites and resource mismanagement are key pathways through which climate impacts manifest and contribute to security challenges in these countries. Understanding these pathways is crucial for developing effective strategies to address the security implications of climate change in these regions. Table 3 provides a summary of the pathways between climate impacts and implications for security in Mali, Somalia and Mozambique.

Table 3.Pathways between climate impact and implications for security.

	Mali	Somalia	Mozambique
Worsening livelihood conditions	- Desertification and drought in Northern parts of Mali are forcing pastoralists to move further south, closer to fertile areas. Risk of conflict between farmers and pastoralist for access to grazing land, water etc. Farmers diversifying their livelihood with fishing, may enter in competition with fishers and vice versa when fishermen are looking to diversify their livelihood by combining it with farming - Worsening livelihood conditions due to climate-induced disasters may push people to engage in illicit activities such as illicit trade, or engage in violent extremist groups operating in the country. - Linked to these dynamics, the Sahel has seen a rise in religious radicalisation over the two last decades, particularly among marginalised groups such as young people, landless and from socio-	- Climate change, soil deterioration due to illegal logging, several failed rainy seasons leading to massive drought in the country, have destroyed the livelihoods of the majority of the Somali population as 80% depend on agriculture, pastoralism and livestock rearing. - Increased frequency of floods and cyclones has led to surges in desert locust plaques, causing heavy damage to the little amount of crops left and further loss of income.	- Climate change and its effects such as increased frequency and intensity of extreme weather events such as flood, droughts and cyclones are repeatedly causing damages to infrastructures, crops and cattle, affecting the livelihood of a great part of the population. - Disasters occurring with little time in between to allow households to recover, creates a negative trend in terms of food security - In northern Mozambique, violent conflict has forced people to leave their homes and livelihoods behind, with the result that at least two million people in northern Mozambique are in need of life-saving and life-sustaining humanitarian assistance and protection (Cabo Delgado, Nampula and Niassa.)

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	Mali	Somalia	Mozambique
	economic groups that are seen as formerly enslaved.		
Increasing migration and changing mobility patterns	- Seasonal, circular and cross border and short-term migration were a way to live for generations. A third of the rural delta workforce migrated each season to urban areas in search of work. These patterns have change in favour of longer and more permanent southward and urban migration due to ecological, climate and conflict factors. - This has created conflict in the southern regions, where traditionally there has been a culture of receptiveness towards newcomers, due to higher population density and increased livelihood precarities. - It also creates conflict between farmers and herders, with communities banning migratory pastoralists from moving southwards. - The decrease in seasonal migration has also affected the food security on the country since farmers many times cannot find enough work force for harvest season.	- Climate change, drought, food insecurity and violent conflict have caused the displacement of 3 million persons, the majority having self-settled in over 2400 sites in urban and peri-urban areas across the country. Their return to home is extremely limited since most of them have lost their livelihoods and are dependent on humanitarian services. Camps are often managed informally and sometimes by armed groups. - For those people that can still carry out some kind of economic activity, changed mobility patterns of, for instance, nomadic pastoralists and their herds in search of fodder, often results in conflicts between farmers and pastoralists over access to land and resources such as water.	- Due to increased frequency and intensity in natural disasters linked to climate change people are leaving areas particularly affected by those. Currently, humanitarian organisations are seeking to assist 815,000 people affected by cyclone Freddy, cholera, and flooding, with interventions in water, sanitation, and hygiene. - Amnesty International estimates that 80% of the displaced persons in the Northern provinces are hosted by friends and families, putting strain on already limited resources.

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	Mali	Somalia	Mozambique
Tactical considerations by armed groups	- Violent conflict is something that has been normalised in Mali after several decades of conflict, whether it is carried out by the state armed forces, Tuareg rebels, jihadi armed groups or the Movement for the National Liberation of Azawad or others. - Governance is often weak and consist of state law and policy and an interwoven community system with little presence of state officials outside regional capitals and major towns. Armed groups use this power vacuum by controlling rural areas and their actions further undermines state legitimacy. In some cases jihadi armed groups a have been providing more equitable management of natural resources than the government.	- Armed groups, the strongest being Al – Shabaab, is capitalising on the country's desperate situation and recruits children, young and unemployed men from IDP camps or exploits the desperation of populations that has suffered climate-related losses. - In controlled areas, they are often replacing local or international agencies when it comes to ensuring the distribution of food or digging wells or other services. It has also replaced the traditional system for conflict resolution, xeer, with sharia law.	- The insurgency in Cabo Delgado is exploiting local grievances related to marginalisation, corruption and criminal networks, causing a spiral of violence fuelled by poverty and deprivation, similar to that witnessed in the Sahel - In addition, the exploitation of recent discoveries of gas outside the northern coastline and some of the world's largest ruby deposits in Cabo Delgado by multinational companies, marginalising the local population from its exploitation, creating resentment towards the government, is claimed to further fuel terrorism, violence and loss of land and livelihoods in the region.
Exploitation by elites and resource mismanagement	- The Malian socio-economic structure is a complex web of stratification by livelihoods, hereditary power holders within families forming clientelist networks. - This is a social order that can be seen as a structural conflict factor and research assesses that structural factors play an	- Power and access to resources are mainly clan-based in Somalia. Almost all public and political positions are linked to clan affiliations and inter- and intra-clan armed competition over natural resources are common. - Elites and powerful clans often exploit their position to occupy and grab land from weaker minorities.	- The elites in the country are concentrated around the ruling party FRELIMO, in power since the country's independence from Portugal in 1975. - Corruption remains widespread at the highest levels of government. Patronage networks are deeply entrenched, with various groupings competing for state resources.

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	Mali	Somalia	Mozambique
	essential role in food insecurity and scarcity. - Linked to these dynamics, the Sahel has seen a rise in religious radicalisation over the two last decades, particularly among marginalised groups such as young people, landless and from socio-economically marginalised groups (as seen under previous pathway).	- Activities such as Illegal logging and charcoal trade has caused deforestation and soil erosion as a consequence, impeding the land to hold water. - Unregulated fishing in Somali waters is threatening Somalia's maritime sector and is often carried out by international fleets with the support of local enablers, both state and non-state.	- Economic inequality exacerbated by FRELIMO's political dominance has generated resentment among many Mozambicans who perceive that government policies enrich elites rather than the country as a whole. - Government aiming to formalize the mining sector in the north, for example, displaced artisanal miners and consolidated control of these enterprises among FRELIMO elites. Communities living near mining projects are protesting over displacement and lost access to rivers, or access to farmlands.

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4 USER REQUIREMENTS ANALYSIS

The main objective of the User Requirement Analysis is to collect and synthesize the view of the users on urban floods and water & food insecurity related to climate change. It aims to gather comprehensive and accurate information about the desired functionalities, features, and constraints that the users require. This way the CENTAUR project expects to ensure that the final solution meets the specific needs of the users and provides value to them. The output will serve as the foundation guiding the design and development of the system, including aspects such the delivery format, frequency of analysis and relevant background data to be used.

The applied methodology pursues to run a co-design process together with the Advisory Board members and interested users to develop and set up the most suitable tools and services fulfilling their needs. To gather the relevant information of interest directly from the users, the following steps were undertaken:

Figure 31: Methodology Schema

1. Preliminary Analysis: Based on the state of the art of the urban floods and water & food insecurity, including the general issues, international and national policies, existing products/services in the market, etc. as described in Section 3, the main trends and overarching priorities were identified. In addition, a user interaction exercise performed prior to the start of the CENTAUR project will be used as a starting point.
2. Collection of User Needs: The User Needs Analysis is the first step to understand the priorities and interest of key actors within the urban floods and water & food insecurity issues. It includes the following sub-tasks:
   - Categorize the users represented within the Advisory Board and elaborate the user profiles. Similarly, as drafting *user personas*, the user profiles help to better understand the characteristics, behaviours, needs and goals of the users that may have interest in the project.
   - Definition of the specific expected results from the survey and identification of the most relevant questions to obtain such results.
   - Elaboration of the operational questionnaire.
   - Distribution of the questionnaires and follow up of reactions.
   - Collection of questionnaires.
3. Information Analysis: Statistical analysis of the answers provided. Analysis of the questionnaires received and synthesis of findings, in addition to other general requirements known to be necessary for implementing a successful service.
4. User Requirements Definition: The final outcome is strongly related with the further development of the project. Once the information analysis is finalised, the functional requirements and non-functional requirements are drafted. For validation purposes, acceptance criteria will be defined for each of the requirements identified.

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4.1 PRELIMINARY ANALYSIS

This section discusses the two approaches used to gather user requirements for the CENTAUR project. The **first approach** involved an internal activity conducted by SatCen in the frame of Climate Security. In the process of defining the relevant topics to address, SatCen explored possible ways ahead to help define more precisely the most promising ones. A list of 22 pre-selected use cases were presented to the users for them to prioritize according to their needs/interests. These topics were shared with relevant EU entities that SatCen cooperates with on security and defence issues and considered very relevant players on this topic.

Mainly, several units of the EEAS were contacted and requested for their feedback, including the CPCC (Civilian Planning and Conduct Capability), the EU INTCEN (intelligence analysis), the EUMS and MPCC (environmental footprint of EU military missions) and the ISP (Integrated approach for Security and Peace Directorate).

In general terms, the users find that there is a large amount of information regarding climate and environment indicators, but there is a lack of links between these indicators and security issues. There is a need to establish a clear causal link between climate change/environmental degradation and conflict, and in terms of relevant datasets. This link should be translated into easy and understandable products/services.

According to the different user profiles/interests, we can define two main possible "lines of work":

- Relationship between Climate and Migration and/or Conflict: the impact that climate change can have on agriculture/exploitation (for example), has direct effects on security matters that should be measured/represented in some way. This impact could have therefore an increase in migration, or it could even lead to an escalation of violence. This could end with more people recruited by violent/terrorist groups. Climate change is a threat to regional/country stability.
- Climate effect on M&O: Regarding European Missions and Operations, their interests are more focused on the impact that environmental factors have on the mobility (roads status, floods, etc.) and on critical infrastructures. For them it would be very useful to have analysis of the vulnerability of transportation networks to climate conditions, as well as weather trend analysis (storms, cloud cover, sea currents, salinity, etc.).

When analysing the above general interests of the users, they highlight the importance of focusing on situations that may unfold in short term, at a small scale and with immediate effect, with specific need for the assessment of food security as a precursor of conflict, and the analysis of damage to critical infrastructures resulting from different weather conditions (power plants, lines of communication, supply chains, gas pipelines, fuel storage, airports, ports, military installations, etc.).

Though there is less interest on situations that brew over the long term, take place at a big scale and may have distant and gradual effects, some topics such as rare earths mining (e.g. lithium, coltan) driven by technological development, were mentioned to be important for most of the users.

The **second approach** involved the design of a specific questionnaire that was designed for the CENTAUR user community to tailor anticipative operational tools to respond to climate change effects related to emergency and security crisis, taking into account the general requirements described above.

The main objectives of this questionnaire are:

- Understand the user understanding on the climate security topic.
- Collect user information and data needs with regards to food insecurity, water scarcity, climate security and socio-economic data.
- Identify the solutions (methods and tools) that will support the users in their day to day work and understand the current limitations.
- Confirm their interest on the preliminary identified use cases and collect feedback to tailor them.

The final questionnaire was designed with 6 different question blocks:

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1. Personal Information: Informed consent for treatment of personal data, organization, point of contact, contact details.
2. Background Information: organization's activities, awareness of the security implications of climate change, other activities related with climate security, expectations towards the project, field activities, etc.
3. Current Data and Operational Tools: existing data, use of data, missing data, previous experience with CEMS, limitations encountered.
4. Value Proposition:
   a. Food and Water Insecurity: operational tools of interest, datasets of interest, preferences regarding scale, format, delivery, timeliness, etc.
   b. Urban Flooding: operational tools of interest, preferences regarding scale, format, delivery, timeliness, etc.
5. Use Cases:
   a. Food and Water Insecurity: three use cases proposed, regions of interest, input data available for the system.
   b. Urban Flooding: four use cases proposed, regions of interest, input data available for the system.
6. Information Delivery and Way Ahead: delivery of data, integration into other systems, interest in scaling up to other regions.

The final questionnaire can be found in Annex I.

In the following sections, all answers received for each of the question blocks have been analysed.

4.2 USER PROFILES

The engagement of users becomes a significant factor when defining needs, ensuring the validity of the project results, and obtaining support for sustainable solutions. For CENTAUR, two main groups of users were identified:

- Users/Potential Users of the Copernicus Emergency Service (Urban Flooding)
- Users/Potential Users of the Copernicus SEA Service (Water and Food Insecurity)

The following users filled in the questionnaire:

Table 4. Users Contacted

ORGANIZATION	COPERNICUS SERVICE INTEREST
European External Action Service - EEAS (Situation Room)	Copernicus SEA Authorized User
European Commission (EC) Joint Research Centre (Unit E1-Disaster Risk Management)	Copernicus Emergency Authorized User
CCR (Department R&D Cat & Agriculture)	Copernicus Emergency Potential Future User Copernicus SEA Potential Future User
UN Environment Programme (Disasters and Conflicts Division)	Copernicus Emergency Potential Future User Copernicus SEA Potential Future User
German Federal Foreign Office (S05 crisis early warning)	Copernicus Emergency Potential Future User Copernicus SEA Potential Future User
WAVE (IoT)	Copernicus Emergency Potential Future User Copernicus SEA Potential Future User
International Commission for the Protection of the Danube River (ICPDR)	Copernicus Emergency Potential Future User

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ORGANIZATION	COPERNICUS SERVICE INTEREST
Environment and Water Agency (REDIAM)	Copernicus Emergency Potential Future User
General Directorate of Civil Protection (Natural Hazards area)	Copernicus Emergency Authorized User
Helpcode (NGO)	Copernicus Emergency Potential Future User Copernicus SEA Potential Future User
EC Joint Research Centre (E1)	Copernicus Emergency Authorized User Copernicus SEA Potential Future User
Danish Refugee Council (Evidence, Knowledge and Learning Division)	Copernicus Emergency Potential Future User Copernicus SEA Potential Future User

The first sections of the questionnaire aimed at getting to know and understand better what the users expect from the project, their interests (if any) in new products/services/capabilities, and their knowledge/use of any similar services or in similar fields.

The users that answered the questionnaire were mainly from organizations/institutions related to Risk Assessment, though there was also a high percentage of representatives of Preparedness and planning, and Programme and project management.

Their main activities are mainly related to Early warning and forecasting, and Emergency relief-response, followed by Climate Change, Humanitarian actions and Environmental protection. (Table 2).

Table 5. User distribution by categories and activities

Activity	% Of Users
Early warning and forecasting	83%
Emergency relief-response	75%
Climate change	58.33%
Humanitarian actions	41.60%
Environmental protection	41.60%
Conflict prevention/ Peacekeeping	25%
Migration management	25%
Foreign affairs	25%
Rule of law	8.33%

Category	% Of Users
Risk assessment	83.33%
Preparedness and planning	50%
Programme and project management	50%
Decision making	33.33%
Field operations	33%
Strategy and policy development	25%

Most of the users (58.33%) declared that their organization had high awareness about the security implications of climate change and had already implemented some measures to address the risks. The users (41.6%) that declared having a “moderate awareness” on the topic, described that there was a basic understanding in their organizations but required more knowledge to integrate it into their daily work. Given this, several users declared that their organizations were already participating (or have participated in the past) in different activities related to water and food insecurity, and even have experience in different field activities. These are described in the table below:

Table 6. User experience on water and food related activities

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Activity	Description	Field Experience/Collaborations
Climate Change and Security Partnership with the EU (2023-2027).	Field projects on climate security assessments and environmental peacebuilding in Sudan, Côte d'Ivoire, and the MENA region; Strata data platform for customised climate security analytics.	Local peacebuilding Civil Society Organisations and initiatives within highly fragile communities to climate change and conflict in transboundary regions of Sudan and Côte d'Ivoire, UN field and country offices, EU representatives in those countries.
Contact with national and international stakeholders related with water and food insecurity.	WFP FAO Use of data from ASAP Project (JRC)	-
ICPDR Climate Change Adaptation Strategy	https://www.icpdr.org/main/resources/icpdr-climate-change-adaptation-strategy-2018-3	The structure of the ICPDR contains the Flood Protection Expert Group composed from the representatives of the ICPDR Contracting Parties. The FP EG meets regularly to discuss flood risk management issues in the Danube River Basin.
Assessments to inform its project design.	Social impact assessment in Mozambique	Low income countries.
Mapping Floods at European and International Levels.		Civil Protection.
Anticipatory action regarding droughts in Somalia.	Support communities 3-4 months ahead of drought to avoid loss of livelihoods and displacement by providing cash and water assistance	40 countries around the world supporting displacement-affected populations.

In general, the users do not have experience using any flood models or CEMS products. The experienced users describe that the existing flood models do not have enough accuracy for their work. Some portals or information systems that were mentioned to be used to access conflict risk or food/water security indexes were UNEP Strata, WPS models and ASAP data to identify hotspots for anomalies in agricultural production, and ADAM Platform.

The main problems described regarding this data is that users find the data too global and not tailored to specific areas, as well as insufficient timelines of the imagery acquisition and lack of quality of the flood delineation within the urban areas. Only one user declared being familiar with the CEMS RM and RRM flood products.

On the other hand, all users declared having Extensive/Good technical knowledge with the use of geospatial data and, in general, were familiar with the use of social media data.

The following two sections will analyse separately the user needs of urban flooding, and water and food insecurity. This will facilitate, at the end of this section, to analyse the common needs for both topics in order to design a common solution for all CENTAUR users covering their main requests and interests.

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4.3 URBAN FLOODING USER NEEDS

The following analysis will focus on the users that expressed their interest in urban flooding. Several Use Cases and operational tools focused on urban flooding were presented to the users in order to analyse their needs and interests related to this topic.

The users described that flood models do not have the sufficient accuracy and that the geographical scale was not appropriate (normally global data) to be used for their activities. Based on the user's experience, the users described several limitations and needs on the existing flood models:

- Need for real time data about flood extent during flood events.
- In many urban areas, standard methods of SAR-based flood mapping are not technically feasible, because SAR is not sensitive to flooding (or any other type of change) of the ground surface in these areas.
- Flood models are not user-friendly for non-technical decision makers.
- The accuracy of flood models decreases in areas with dam presence and is not sufficient in urban and forested areas.

The following sections aim at understanding the user's needs regarding specific operational tools and use cases, to analyse the best solution for CENTAUR.

4.3.1 Value Proposition – Urban Flooding

In this section the analysis on the users' needs in terms of forecasting and operational tools to evaluate the effects of climate change, due to the increase in the number of extreme events is presented.

The users were asked to give a score to the different operational tools, ranging from "1" (very low interest) to "5" (very high interest), to assess which could be the most useful and relevant to them.

The proposed operational tools are:

A. Early warning system, alerting when pre-defined triggers and drivers for crises are met.
B. Early warning system based on more precise meteorological data.
C. CEMS pre-tasking success (75%), in terms of number of pre-tasking alert, timeliness and improvement in the definition of the AOI for crisis-time satellite acquisitions.
D. Increase of the accuracy of urban flood mapping (>75%) using SAR and InSAR processing combined with urban flood modelling.
E. Reduction of the temporal or spatial resolution of the current datasets, products or services delivered by a Copernicus operational service by 50%.
F. Improvement of other more traditional map quality indicators owing to a more integrated and accurate input information and to more effective AI/ML modelling (thematic accuracy, speed of delivery, resolution, etc.).

When analysing the average score of the tools proposed, the tool B, Early warning system based on more precise meteorological data, was the tool with the highest value. This tool was scored with values of 4-5 by all users, except for one. Also, tool A, Early warning system, alerting when pre-defined triggers and drivers for crises are met, obtained a high average score (4.27). Thus, it can be stated that the operational tools related to the Early warning system are the ones that most interest raised among users.

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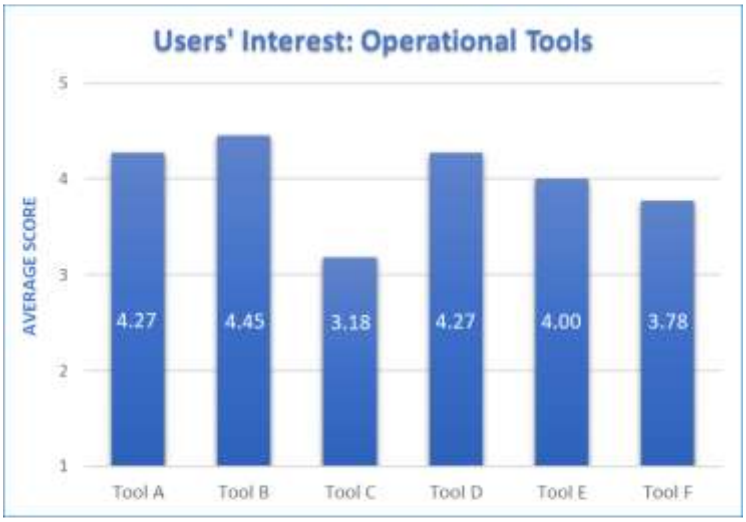

Figure 32: Average scores given to the different Urban Flood Operational Tools (1=very low interest; 5=very high interest)

The tool C, *CEMS pre-tasking success (75%), in terms of number of pre-tasking alert, timeliness and improvement in the definition of the AOI for crisis-time satellite acquisitions,* was the lowest ranked tool, with the 54% of scores ranging from 1-3.

Furthermore, considering all the five operational tools proposed, the percentage of users' preferences of output products are:

- In terms of scale analysis: 73% voted Local.
- In terms of information format: 64% voted Notification alerting of changes.
- In terms of delivery: 55% voted Alert notifications by email.
- In terms of delivery time: 45% voted 1 day and 36% voted 3 days.

Finally, regarding the tool D, *Increase of the accuracy of urban flood mapping (>75%) using SAR and InSAR processing combined with urban flood modelling*, the 64% of users preferred a Monthly time horizon for predictive analysis.

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4.3.2 Use Cases – Urban Flooding

In this section the users' preferences on four use cases are reported. The use cases proposed to the users are summarized in the table below:

Table 7. Urban Flood Use Cases

Country	Description
Ebro basin, Spain	Given its morphology and location, floods are common in the Ebro basin. Among the most relevant past episodes are the floods of extraordinary intensity that occurred in 2015, 2018 and 2021. Due to a combination of heavy rains and fast melting snow, severe effects on agriculture, population and infrastructures were observed. CEMS RM monitored these events in EMSR118, EMSR120, EMSR279, and EMSR555 activations. In the Navarra Region of the Ebro basin an extensive repository of information exists including cadaster, land cover, soils, infrastructure, edaphology and hydrography, amongst others 18. Complete meteorological data acquired by the Government of Navarra and the National Meteorological Agency (Agencia Estatal de Meteorología, AEMET) and up-to-date hydrological data provided by the Ebro Hydrographic Confederation (CHE) are also available. In addition, the LiDAR coverages of Navarre 2017 and the urban area of Pamplona 2021 are especially noteworthy, acquired at a minimum density of 14 point/m2 and 50 point/m2, respectively. These combined cold case datasets enable model training, preparing for a highly likely upand-coming hot spot during the project where the system can be validated.
Piemonte, Italy	Piemonte Region has a rich history of frequent and important flood events occurred in the pastdue to intense precipitations that led to the fluvial flood of the Po river, one of the main watercourses of the Region (last event 2016, covered by CEMS RM activation EMSR192). For the city of Turin, located along this important fluvial channel, a high resolution aerial data acquisition with photogrammetric cameras hasrecently been performed. This not ordinary dataset will be used to produce a high definition 3D model of the urban area in order to test its integration within flood modelling. Beside Turin, another minor urban area located along a different river, but still characterized by high flood risk, e.g. the Tanaro river, will also be chosen for ad hoc acquisitions. In addition, since the first hours of the 3rd of October 2020 an intense weather perturbation affected the North of Italy, with heavy rain and strong winds (storm Alex). Both red and orange alerts were issued by the regional and National Civil Protection. The greatest damages are reported in the Liguria region, and in the northern and western part of Piedmont region where the amount of the precipitation recorded exceeds the historical rate since 1958. The heavy rainfall has caused the overflow of several rivers and flooding of many areas. The overflow of the Sesia river in the Piedmont region caused interruption of roads, the collapse of a bridge and the flooding of several areas. Two deaths have also been reported.
German Floods	On the 13 July 2021 catastrophic rains led to devastating flood events destroying many areas, like the Ahr Valley, mostly in tributaries to the Rhine in the Saar, Rhineland Palatinate, North Rhine-Westphalia States. The German Joint Information and Situation Centre (GMLZ) triggered the CEMS Rapid Mapping (RM) Service to monitor the floods evolution20. At the time the Authorised User made aerial imagery available to CEMS RM to supplement the satellite data coverage. Now, this highly engaged user, in a joint effort with the Service Provider, is highly motivated to explore innovation in CEMS RM products and is willingly to make aerial imagery, pre and post LIDAR, differential LIDAR DEMs, river gauge measurements to help in the realization of detailed forecast and modelling enhanced products. These are

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Country	Description
	to be combined with traditional and social media enrichment to provide enhanced products especially in and around urban areas.
Mozambique	In these last years Mozambique has been hit several times by Tropical Cyclones. In 2019, Idai TC brought huge precipitations over the Beira hinterland badly affecting the lower oceanside parts of the city, including slums. Due to the urban context, the usual storm time SAR data such as Sentinel-1, COSMO-SkyMed and Radarsat-2 did not lead to good flood extent extraction within built-up areas (cf. Copernicus EMSR34821). Only VHR optical data acquired more than 10 days after the event provided the first insight on the remaining traces and impacts. CENTAUR proposes to replay this CEMS activation by integrating ICEYE VHR InSAR data combined with a 3D modelling of the city to better estimate the flood extent and associated potential impacts within the city. Considering the frequency of such events in this area, this cold case scenario could most likely become a hot case scenario within the projects' lifespan, supported by the recent integration of ICEYE data within Copernicus Space Component Data Access.

The users were asked to give a score to the different use cases, ranging from "1" (very low interest) to "5" (very high interest) and the results in terms of average score are shown in the figure below.

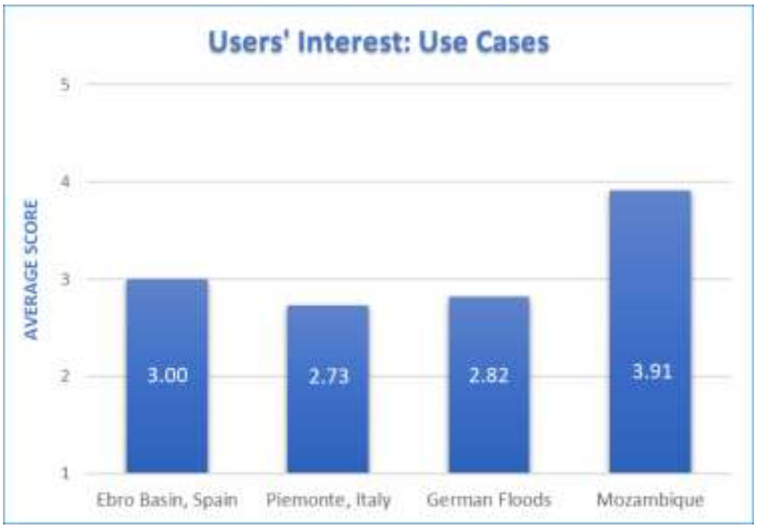

Figure 33: Average scores given to the different Urban Flood Use Cases (1=very low interest; 5=very high interest)

On average, the Use Case with the highest ranking was Mozambique, while the Use Case with the lowest interest was Piemonte (2.73).

Moreover, considering the four Use Cases, 36% of users are interested in flood assessment and climatic aspects. They also proposed some specific regions of interest: Cabo Delgado, Maputo and Manica for Mozambique, Navarra for Ebro Basin, and Danube river basin for German Floods.

Three users out of eleven stated they have In-situ data and two of them also have Meteorological and Hydrological data that could be used for validation purposes. The General Directorate of Civil protection and Emergencies suggested to involve Navarra Civil Protection and Ebro Basin authorities.

Conclusively, the users proposed further locations as Use Case: South of Tuscany (Italy), Danube River Basin (Trans-national river basin in Europe), Yemen and South Sudan.

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4.4 WATER AND FOOD INSECURITY USER NEEDS

The following analysis will focus on the users that expressed their interest in water and food insecurity. Several Use Cases and operational tools focused on food and water insecurity were presented to the users to analyse their needs and interests related to this topic.

During the consultation process, users agreed that there is not enough up-to-date data/information available to assess the effect of climate change on different dimensions of human security. More information is needed to better understand/anticipate displacement, political and security instability, and violent conflicts. There is also lack of:

- seasonal (e.g., monthly, bi-monthly or 3-monthly) projections of extreme weather events (droughts, floods, storms);
- geospatial human mobility data, at regular time intervals, long-term trends and with decent geographical coverage of the globe (or at least conflict-affected settings to address the most vulnerable societies).
- geospatial data on the quality of institution locally: e.g., governance, justice institutions and conflict mediation mechanisms, equality of access to such institutions, inclusiveness of such institutions (ethnic minorities, gender, age etc.).
- geospatial data on unemployment rates, mainly youth unemployment.

The following sections aim at understanding the user's needs regarding specific operational tools and use cases, to analyse the best solution for CENTAUR.

4.4.1 Value Proposition – Water and Food Insecurity

The questions included in this section of the questionnaire were specific about the anticipative and operational tools to assess climate change effects on security issues that could be relevant for the users. The users were asked to give a score to the different operational tools, ranging from "1" (very low interest) to "5" (very high interest).

From the four different tools proposed in the questionnaire, the users gave individual higher scores (57% of the users assigned value "5") to:

- A catalogue of datasets on water and food insecurity and its relationship with political instability and conflict.
- Simulation and predictive analysis allowing to launch "what if" analysis.

When analysing the average score of the tools proposed, the Early-warning system, Alerting when Pre-defined Triggers and Drivers for Crises are met, was the tool with the highest value. This tool was scored with values of 4-5 by all users. The *Situational Awareness Portal providing Continuous Monitoring of Climate Security Risk Indicators and Indexes* was the tool that raised least interest among the users that answered the questionnaire.

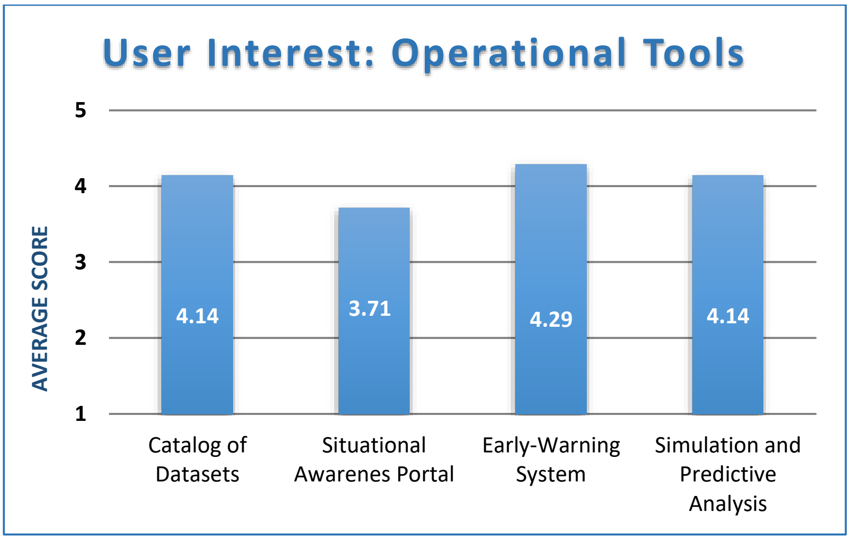

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Figure 34: Average scores given to the different Water and Food Insecurity Operational Tools (1=very low interest; 5=very high interest)

To further understand the user needs and interests, several datasets were proposed in the questionnaire for the users to give scores to ("1" for "very low interest" to "5" for "very high interest"). The highest interest was focused on Water Availability and Crop Production Monitoring, though there were other datasets that also obtained average scores above 4:

- Climate and Meteorological Data
- Changes in Land Use
- Population Distribution and Evolution
- Migration (e.g., border restrictions, flows)
- Other Socio-Economic Variables (e.g., hunger/malnutrition, incomes)

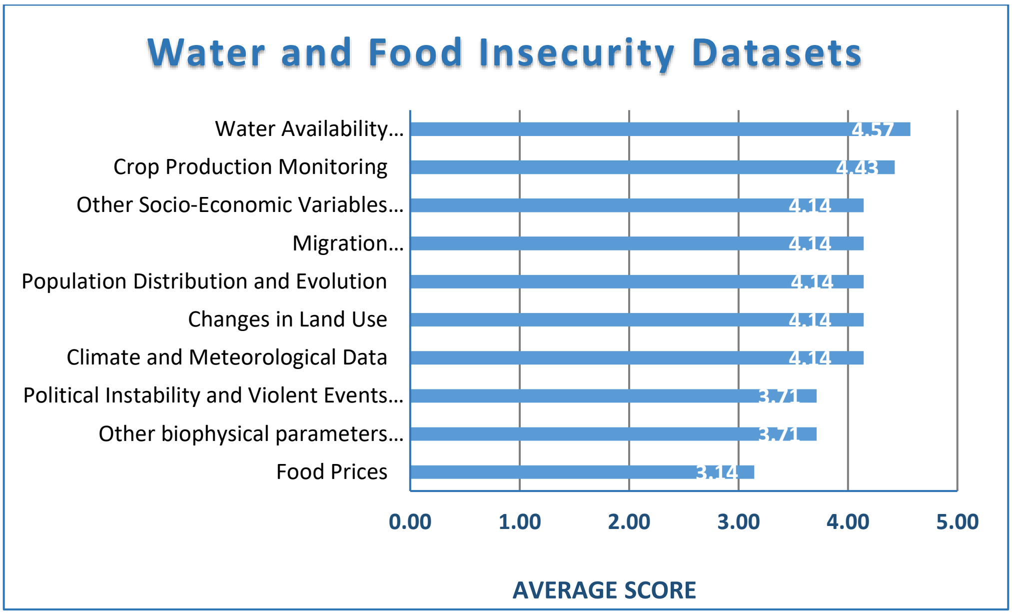

Figure 35: Activation - Average scores given to the different datasets (1=very low interest; 5=very high interest)

Regarding the *Situational Awareness Portal* and *Early-Warning System,* most of the users (85.7%) were interested in a local scale analysis rather than other larger scales. As for the delivery format and time, 71.43% of the users preferred receiving notifications alerting of changes and 85.71% of the users expressed their interest in having online information access (e.g., Geoportal). The reasonable delivery time for the users would be between 3 days and 1 week. A summary of the results of the consultation to the users is summarized in the table below:

Table 8. User Needs: Information Format and Delivery (Situational Awareness Portal and Early-Warning System)

Information Format	% Of Users
Notifications alerting of changes	**71.43%**
Disaggregated datasets visualization	57.14%
Indexes and indicators visualization	57.14%
Statistical analysis over data (e.g., graphs)	28.57%
In-depth analysis and reports prepared by analysts	14.28%

Delivery	% Of Users
Online information access (e.g., geoportal)	**85.71%**
Alert notification by email	57.14%
Data download	57.14%
IT interface (e.g., API, web service) for ingestion in end-user system	14.28%

Reasonable Delivery Time	% Of Users
1 week	**42.86%**
3 days	**42.86%**
1 day	14.28%

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When using *Predictive Analysis Tools*, the time horizon in which the users would be mostly interested is either monthly (42.86%) or quarterly (57.14%).

4.4.2 Use Cases – Water and Food Insecurity

For this section in the questionnaire, three different use cases were presented to the users, and they were asked to give a score to the different use cases, ranging from “1” (very low interest) to “5” (very high interest). The three use cases are briefly described in the table below:

Table 9. Water and Food Insecurity Use Cases

Country	Description
Mali	Lies between the most arid and the rainy equatorial regions, water is seasonally scarce and precipitations increasingly unpredictable, often marked by low and high extremes. Climate change effects are intensifying conflict between communities, increasing poverty, and weakening traditional means of survival. The recent increase of farmer-herder conflicts in the western Sahel is exacerbated by violent extremists and other armed groups operating in the area. This model may also be applied to other regions of the Sahel.
Somalia	Below average rainfall during the rainy season led to worsening droughts in different parts of the country. This situation forced tens of thousands of people to leave their homes, in search of water, food and work, mostly to urban areas. These climate impacts are usually used by armed groups (i.e., Al Shabaab) to position themselves as aid providers after severe impacts of droughts and floods. Outputs of this demonstrator could also be exported and applied to other countries in the Horn of Africa.
Mozambique	Composed mostly of coastal lowlands, Mozambique is highly exposed and vulnerable to temperature increases, cyclones, and tropical storms. Over 80% of the population depend on agriculture for their livelihoods. Much food storage, fisheries infrastructure and livestock assets are washed away, and thousands of hectares of crops are destroyed due to flooding. In addition, since 2017, an Islamic group has staged a destabilizing insurgency in the predominantly Muslim Northern Province of Cabo Delgado.

On average, there was a higher interest in the Use Case of Somalia (specially for the regions of Kissmayo and Horn of Africa), though the highest score (5) was given evenly for all three use cases. For Mozambique, regions such as Cabo Delgado, Maputo or Manica were of special interest for the users. Mali and Central Sahel are also of high importance for the users. The following figure summarizes the average scores for all three use cases described:

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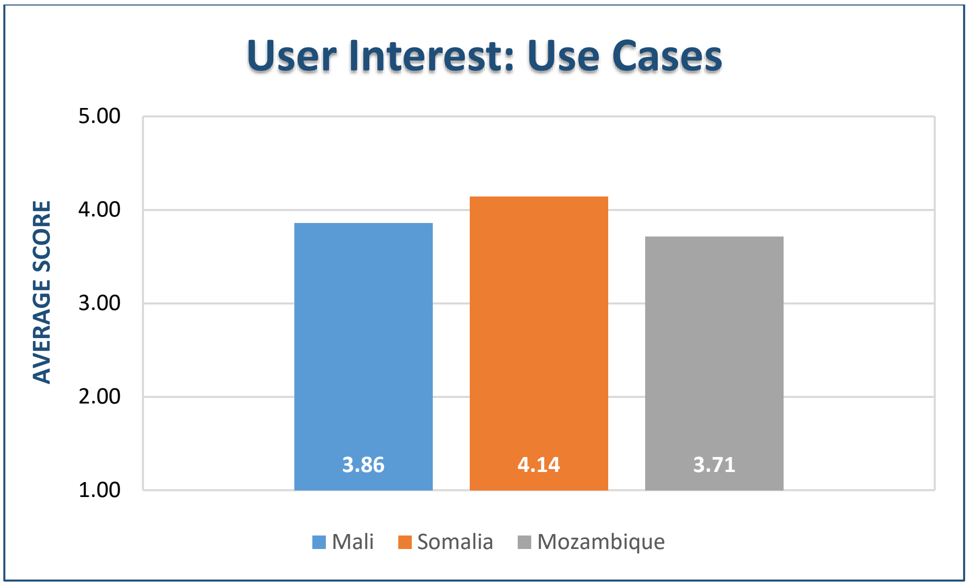

Figure 36: Average scores given to the different Water and Food Insecurity Use Cases (1=very low interest; 5=very high interest)

Other regions of interest mentioned by the users were Burkina Faso, Niger, Central African Republic, Kenia, Sudan, Yemen, and Ethiopia.

The main climatic, geographic and/or social aspects of interest described by the users were:

- Social, political and security aspects.
- Pastoralism, transhumance, forced displacement, rural to urban migration, etc.
- Economic analysis (e.g., inequality).
- Food security.
- Multi-hazard confluence of drought and conflict.

Some of the users have data that could either be used as inputs for the system (in-situ data; conflict/violent events data) or for validation purposes (in-situ data; Reference geospatial data for land-use; Conflict/violent events data) but, in general, the use of this data by CENTAUR will need to be further analysed with the users on a case by case scenario. One user described having protection monitoring data from Central Sahel region, and even drought-displacement simulation and conflict-displacement models that could support and provide forecasts and data.

4.5 INFORMATION DELIVERY USER NEEDS

For the delivery of the future products and services from CENTAUR, the users show a clear preference to receive the data via and Online Geoportal (91.67%). The other options for delivery and the percentage of users that selected them, is summarized in the table below:

Table 10. User Needs: Delivery Method

Delivery Method	% of Users
Online geoportal	91.67%
Email - notification	66.67%

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Delivery Method	% of Users
Web service - API	58.33%
Data catalogue	50%

Most of the users (60%) do not have any information legacy systems in place in which they would like the information produced by CENTAUR to be ingested. But it should be taken into consideration that 40% of the users would have interest in ingesting the data coming from CENTAUR into their systems. For these users, to enable the ingestion of data it would be important to consider:

- The system should be suitable for ingestion in a web service-based product access and dissemination system following the Representational State Transfer (REST) software architecture.
- For some users, the most efficient way of integrating and using the data from CENTAUR would be the ingestion through Google Earth Engine.
- Other users specified that the best way of integrating the data into their systems would be following the technical requirements of the PREVIEW project.

67% of the users are interested in scaling up the CENTAUR general capabilities to other regions such as Central Asia, Spain, Yemen, Ethiopia, Ukraine, Cambodia, Nepal, etc. In general, the methods developed within the CENTAUR urban flood activities should be suitable for application in an operational, automated mode in diverse global environments, and all conflict-affected regions with focus on transboundary regions.

4.6 USER EXPECTATIONS

All users involved in this consultation process expressed their interest in the project's outcomes and results to improve the existing data regarding floods, and water and food insecurity issues. Given that most users were coming from organizations whose main activities are related to Early Warning and Forecasting, and Emergency relief-response, and that users have high awareness about the security implications of climate change, the main expectations towards CENTAUR project are related to:

- Early-warning system: alerting every time a new event occurs.
- Situational awareness at strategic and operational level, to anticipate crisis to warn personnel deployed/EU citizens in the affected countries.

In general, all users were highly interested in an operational tool based on an Early-Warning System including both, more precise meteorological data and Alerting when Pre-defined Triggers and Drivers for Crises are met. Users also expressed high interest in obtaining a Catalogue of Datasets for water and food insecurity, especially Water Availability and Crop Production Monitoring as well as other data such as *Population Distribution and Evolution,* or *Migration (e.g., border restrictions, flows).* The operational tool is required to be functional at a local scale analysis, through an online information access (e.g., Geoportal), and with an alert system that will notify users of any event of interest.

The users described that flood models do not have the sufficient accuracy and that the geographical scale was not appropriate (normally global data) to be used for their activities. In this sense, users expect from CENTAUR:

- To contribute/enhance the CEMS global flood monitoring product, by developing Urban Flood Indicators, urban flood mapping, assessing urban flood impacts on population and assets, etc.
- To implement an application in an operational, automated (unsupervised) mode in diverse global environments, for characterizing river overflow and pluvial runoff floods in urban areas by processing SAR and optical imagery at High Resolution (10, 20 meters) and Very High Resolution (less than 1 meter).
- Provide information on urban flood extent and impacts on population and assets in areas where standard SAR-based flood mapping is not technically feasible.

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- Improvement of the flood extent definition in urban areas, and the inclusion of a flood extent layer within EFAS.
- Improve flood detection especially in urban and forested areas.

Regarding Climate security, the users declared that there was not enough up-to-date data/information available to assess the effect of climate change on different dimensions of human security. In this sense, the users expect from CENTAUR:

- Near-real time and projected geospatial data not available now (e.g., different types of migration, flooding, institutional capacity at a local level and access to it).
- Improving the predictive capacities for climate security events.
- Better understanding of the underlying mechanisms related to climate change and conflict.
- Tools and services for support to local administration in urban planning and climate change adaptation.
- Getting useful information in case of climate related disaster to inform potential humanitarian intervention.
- Innovative ways of analysing the links between climate change, environmental degradation, conflict, and displacement.

4.7 USER REQUIREMENTS

This chapter presents the outcomes of the methodological approach described at the beginning of this section (Section 4), resulting from analysing the end-user needs and transforming them it into user requirements. To this end, the existing operational experience of the consortium partners, the open discussion carried out with the users and the outcomes from the user questionnaires have been combined to draft the final requirements for the CENTAUR project.

The requirements covered in this document refer to “Functional requirements” which describe qualitatively the system functions or tasks to be performed in operation. Other requirements such as “Performance requirements” that define quantitatively the extent, or how well and under what conditions a function or task is to be performed (e.g., rates, velocities), will be further described in the system design documentation.

For the functional requirements defined, the following information is provided:

- User requirement code: unique identifier code to identify each of the UR (User Requirements).
- Name
- Description: concise description of the requirement/need.
- Category: The requirements have been classified into eight different categories:
  - General Requirements
  - Accessibility Requirements
  - Operational Requirements
  - Data/Indicators Integration, Management and Processing Requirements
  - Interoperability Requirements
  - Training Requirements
- Suggested prioritization. Each requirement will be prioritized according to the MoSCoW method (with 4 categories: must-have, should-have, could-have and will not have).

These requirements are listed and described in the following subsections.

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4.7.1 General Requirements

This category provides requirements related with general aspects that the future service should consider.

Code	Requirement Name	Description	Priority
GR-01	Security	• The early-warning platform must ensure the security of the monitored data. • The system shall provide encryption mechanisms to protect data in transit and at rest. • It must adhere to industry-standard security practices, such as vulnerability assessments, penetration testing, and regular security updates.	MUST HAVE
GR-02	Reliability	• The platform should be highly reliable, ensuring continuous operation and minimizing downtime. • It should include fault tolerance and failover mechanisms to mitigate the impact of hardware or software failures. • The system should be designed to handle concurrent user access and support high availability.	MUST HAVE
GR-03	Ethics	• Technical and organizational measures shall be implemented in the system for ensuring that personal data protection and privacy issues are considered.	MUST HAVE
GR-04	Scalability	• The system should be scalable to able to handle increasing data volumes. • The system should be prepared to be extended to other similar regions such as Burkina Faso, Niger, Central African Republic, Kenia, Sudan, South of Tuscany, Yemen, Ethiopia, South of Tuscany and Danube River Basin.	SHOULD HAVE
GR-05	Notifications	• The user must be notified through a notification inbox and by email when a relevant event occurs, like new alerts of the early-warning system.	MUST HAVE
GR-06	Information	• The platform could include access to information communities, such as open slack community, for having a more dynamic notification feed.	COULD HAVE
GR-07	Licensing	• For those services/products/data provided subject to certain agreements or licenses (e.g. ESA license, Copernicus copyright, etc.), the corresponding copyright clauses must be displayed.	MUST HAVE

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4.7.2 Accessibility Requirements

These requirements encompass access and design of interface aspects, describing specific requirements needed to ensure correct and simple access to the data.

Code	Requirement Name	Description	Priority
AR-01	Access regulation	Regulate access by providing identity and access management based on access control policies, roles, permissions, and attributes. This should include "admin" and "super admin" roles for batch updates/bulk user addition.	MUST HAVE
AR-02	User Authentication	Integrate authentication with the OpenID Connect identity provider of SatCen (Identity Server).	SHOULD HAVE
AR-03	Data Access Restrictions	Ensure that data (non-classified) are accessible only to those authorized to have access, in a secure way.	MUST HAVE

4.7.3 Operational Requirements

This section addresses the type of information, products and services the system should provide based on the users' needs.

Code	Requirement Name	Description	Priority
OR-01	Risk Assessment and Early-warning System	• The CENTAUR solution should mainly consist in an early-warning system based on more precise meteorological data and a combination of several biophysical and socio-economic inputs to alerting the user when pre-defined triggers or anomalies driving for crisis are met. • The system shall be able to generate, display and send user selected/configured alerts automatically. • The system should provide intelligent alerting mechanisms (e.g. group related events, double check mechanisms) to reduce false positives	MUST HAVE
OR-02	Urban Flood Mapping	• Increase of the accuracy of urban flood mapping (>75%) using SAR and InSAR processing combined with urban flood modelling. • To implement an application in an operational, automated (unsupervised) mode in diverse global environments, for characterizing river overflow and pluvial runoff floods in urban areas by processing SAR and optical imagery at High Resolution (10, 20 meters) and Very High Resolution (less than 1 meter). • Provide information on urban flood extent and impacts on population and assets in areas where standard SAR-based flood mapping is not technically feasible.	MUST HAVE

OR-03	Catalogue of Datasets	A catalogue of datasets on urban flooding and water and food insecurity covering the following areas:
		• Urban Flooding
		  o Real time data about flood extent during flood events.
		  o Use of SAR and optical data for flood extent
			MUST HAVE

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		○ Flood model in urban areas and in the areas blind to SAR satellite sensors ○ Flood assessment and climatic aspects ○ Improved damage assessment based on exposure elements to floods risks. ○ Flood assessment based on ground truth (social-media markers) • Water and Food Insecurity ○ Seasonal projections of extreme weather events ○ Geospatial human mobility data. ○ Near-real time and projected geospatial data not available at the moment (e.g. different types of migration, flooding, institutional capacity at a local level and access to it). ○ Water availability ○ Crop Production Monitoring ○ Other Socio-Economic Variables (e.g. hunger/malnutrition, incomes) ○ Migration (e.g. border restrictions, flows) ○ Population Distribution and Evolution ○ Changes in Land Use ○ Climate and Meteorological Data ○ Political Instability and Violent Events ○ Other Biophysical Parameters ○ Food Prices ○ Social, political and security aspects. ○ Pastoralism, transhumance, forced displacement, rural to urban migration, etc. ○ Economic analysis (e.g. inequality). ○ Food security. ○ Multi-hazard - so confluence of drought and conflict.	
OR-04	Simulation and Predictive Analysis	• The system shall incorporate predictive analytics techniques to forecast future trends on climate security events. • It should utilize historical data, statistical methods, and machine learning algorithms to generate accurate predictions. • It should allow users to experiment with different forecasting models and algorithms to identify the most effective approach and launch "what if" analysis.	MUST HAVE
OR-05	Improved Situational Awareness	• Situational Awareness Portal providing continuous monitoring (with a predefined cadence) of Climate Security Risk Indicators and Indexes. The final aim is to support the decision-making process. • Better understanding of the underlying mechanisms related to climate change and conflict at regional level (e.g. admin 1, admin 2). • Tools and services for support to local administration in urban planning and climate change adaptation. • Innovative ways of analysing the links between climate change, environmental degradation, conflict and displacement.	MUST HAVE
OR-06	Improved Existing Indicators	Improvement of other more traditional map quality indicators owing to a more integrated and accurate input information and to more effective AI/ML modelling (thematic accuracy, speed of delivery, resolution, etc.).	SHOULD HAVE

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OR-07	Improved CEMS pre-tasking	CEMS pre-tasking success (75%), in terms of number of pre-tasking alert, timeliness and improvement in the definition of the AOI for crisis-time satellite acquisitions; To contribute/enhance the CEMS global flood monitoring product, by developing Urban Flood Indicators, urban flood mapping, assessing urban flood impacts on population and assets, etc.	SHOULD HAVE
OR-08	CEMS Products and Services	CENTAUR must supply the products and services based on the following characteristics: • Capabilities: • Real time data about flood extent during flood events. • Use of SAR data for flood extent • Flood model in urban and forested areas • Flood assessment and climatic aspects • Regions for flood: • Mozambique (Cabo Delgado, Maputo and Manica) • Ebro Basin (Navarra) • German Floods (Danube River) • Piemonte, Italy	MUST HAVE
OR-09	CSS-SEA Products and Services	CENTAUR must supply the products and services based on the following characteristics: • Capabilities • Risk Assessment and Early-Warning System for Water and Food Insecurity-related crises • Foresight capabilities • Access to catalogue of datasets for enriching service production and incorporate a climate security perspective • Regions covered by Water and Food Insecurity Use Cases: • Somalia • Mozambique • Mali	MUST HAVE
OR-10	Maturity level	The CENTAUR solution must be validated and demonstrated up to the pre-operational level.	MUST HAVE

4.7.4 Data/Indicators Integration, Management and Processing Requirements

This category lists the type of data/information that CENTAUR should be able to analyse, and how this information should be managed by the system.

Code	Requirement Name	Description	Priority
DP-01	Big data	• The system shall give the capacity of ingesting and exploiting large amount of data (big data). • In order to save disk space, non-required intermediate products or imagery input data should be automatically removed after a certain period of time.	MUST HAVE
DP-02	Satellite Imagery Access	The platform shall provide access to the CENTAUR services online satellite imagery services, optical and SAR.	MUST HAVE
DP-03	Multisource data	The system shall provide systematic access to data, background information and time series.	MUST HAVE

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		The following list of data sources must be managed and offered to the user by the platform (preliminary list, more can be added in accordance to the developed services and system needs): 1. EO data 2. Non-EO data collected systematically (e.g. climate, socio-economic, crowdsourcing, and social media data) 3. Products from other Copernicus services (e.g. Climate Change Service, Atmosphere Service, and Land Monitoring Service).	
DP-04	Metadata	• All products, services and datasets stored and managed by the system shall include its metadata. • Metadata may be compliant with INSPIRE requirements. • Whenever possible, the process of collecting and completing the metadata should be automatized.	SHOULD HAVE
DP-05	Catalogue	• The system shall integrate a product/service/datasets catalogue to explore, browse and access all the different products/services/datasets available and managed by the platform. • The catalogue shall list external datasets, product and services produced by the system itself and other ancillary and complementary data (e.g. personalized AOIs, thematic layers). • It shall allow to apply personalized filters and queries to restrict the results subsets.	MUST HAVE
DP-06	Asynchronous jobs	The platform must be able to process synchronous requests for the execution of simple functions over limited amount of data and asynchronous requests for the executing long-running processes.	MUST HAVE
DP-07	Tools and AI algorithms	The platform shall integrate tools and AI trained algorithms to automatically process and interpret large-scale data.	MUST HAVE
DP-08	Model Development and Simulation	• The system shall allow the development and customization of simulation models that represent the dynamics of the water and food insecurity system. • The platform should offer an interface to define model parameters, relationships, and scenarios.	MUST HAVE
DP-09	Orchestration of processing chains	• The system shall be capable of automatically executing in a pre-defined, ordered and consecutive or parallelized manner concurrent EO processing chains. • Processing chains should be able to be launched automatically each time new input data (e.g. satellite imagery) is available.	MUST HAVE
DP-10	Efficiency and reactivity	• The system should implement Near Real Time data processing to minimize delay from event occurrence to alert notification. • Efficient data handling capabilities should be implemented to accommodate large volumes of data from various sources.	SHOULD HAVE

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4.7.5 Platform Requirements

Code	Requirement Name	Description	Priority
PR-01	Graphic User Interface	The CENTAUR solution shall have intuitive and user-friendly graphical user interfaces (GUI), ensuring the best level of usability and user experience, and guaranteeing a good customization with respect to user needs. As a general indication, GUIs shall be in line with the following characteristics: • Simplicity (e.g. reduce screen complexity, use progressive disclosure). • Aesthetically pleasing (e.g. contrast between elements, use colours and graphics appropriately and customized to the user/group). • Clarity – visual, conceptual, language (e.g. visual elements, words and text, forms filling). • Easy to understand • Consistency • Efficiency (e.g. minimize eye and hand movements via proper screen layout, number of clicks and paths for each task). • Compatibility (user characteristics respect to the task and job to be done). • Forgiveness, recovery (e.g. tolerate errors and allow commands to be abolished or reversed, warnings). • Predictability (e.g. user should be able to anticipate natural progression in the task, user should know all the time where he/she is, what is the next step, how to go back, how to abort). • Configurability (e.g. allow personalization and configuration of settings). • Familiarity (e.g. follow a common style for each technical area). • Responsiveness. Whenever possible, the use of frameworks and standards, incorporating best practices, last trends, and features for building a rich and modern user interface is recommended.	MUST HAVE
PR-02	Cloud architecture	• The CENTAUR solution must be based on a cloud architecture to help manage and process large amounts of data more efficiently, to provide easy access to users and service delivery, facilitate integration and provide reliability and robustness for handling large volumes of data.	MUST HAVE
PR-03	Geoviewer component	• The CENTAUR solution should integrate a navigation panel to easily explore, navigate and display the Areas of Interest, Indexes and Indicators and different datasets available and selected by the user (e.g. from drop down lists). • The geoviewer GUI shall allow to display, navigate, zoom in/out, pan or overlay spatial data sets or layers, measure areas and distances, transparency control, print and display legend information. • Users should be able to select basemaps of different type (e.g. satellite imagery, dark, light).	MUST HAVE
PR-04	Graphs and statistical visualization	• The platform shall facilitate the display of historical series of data, trends or statistical analysis to identify anomalies. • The visualization should be customizable and include different interactive charts and graphs (e.g. lines, bars, KPIs)	MUST HAVE

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PR-05	Datasets visualization	All different types of information and derived products shall be displayed with adapted symbology to be configured. Metadata information should be easily accessible.	MUST HAVE
PR-06	Alerts and thresholds configuration and management	• Alerts shall be generated automatically without requiring user intervention (push notifications). By clicking on the alert, the user will access context information and metrics about the alert. • The system should provide a user-friendly interface to customize alerting services. • User should be able to easily specify, edit and manage thresholds for different metrics, indicators or indexes. • User should have the flexibility to set absolute values or percentage-based thresholds, depending on the indicator/index being monitored.	MUST HAVE
PR-07	Web access	The web interface shall support the following browsers: Internet Explorer 9, 10 and 11, Edge, Firefox and Chrome (in their latest version available).	SHOULD HAVE
PR-08	Single access point	The CENTAUR platform should have a single access point and get an overview of the complete service catalog when landing in the homepage.	MUST HAVE
PR-09	Display	CENTAUR system should be prepared to be accessed mainly through computers and should be designed for an average resolution of Computer Monitors (21' – 24').	SHOULD HAVE
PR-10	Responsivenes s	The platform should be developed following responsive design principles, prepared to be accessed from different devices and screen resolutions (tablets, laptops, large screens and any other platform).	SHOULD HAVE
PR-11	Language	All the GUI and documentation must at least be available in English.	MUST HAVE
PR-12	Other languages	All the GUI and documentation could be available in other European languages.	COULD HAVE
PR-13	Search tools	The platform may include filtering tools to conduct very specific searches (e.g., by date, by, country, by theme, by product type) tools.	COULD HAVE
PR-14	Download data	The platform may include easily accessible and user-friendly download tools	COULD HAVE
PR-15	Configurable AOIs	The system shall allow to an administration user drawing, saving, editing, removing and storing personalized Areas of Interest (AOI) that will serve to launch specific analysis.	MUST HAVE
PR-16	Personal Area Component	The platform should contain a personal area allowing the user to set its personal preferences (e.g. modify email address; enable or disable email notifications; configure alerts etc.).	MUST HAVE

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4.7.6 Interoperability Requirements

As required by the users for an optimization of the information received and analysed by CENTAUR, the information needs to be easily integrated into other systems and workflows. The following table summarizes the key aspects to ensure this integration is possible.

Code	Requirement Name	Description	Priority
IR-01	Data delivery: on-line platform or web service.	The data provided by the service should be made available to the user by either a web service or an on-line platform. The availability of the data requested by the user could be notified to the user by an email.	MUST HAVE
IR-02	Information Delivery	The CENTAUR solution shall support the dissemination of information in form of services to be easily ingested by other existing systems/workflows, with standard interfaces: • sFTP • OGC Web Services (WFS, WMS…) • RESTful services • APIs	MUST HAVE
IR-03	Geospatial Data Format	In case the user has to download/receive the data, to ensure interoperability of geospatial data and enable its integration with other existing systems, the geo-referenced maps, vector and raster data and satellite imagery should be produced and delivered in standard formats: Geospatial TIFF, JPEG 2000, gdb, .shp, .kml, GeoJSON…	COULD HAVE
IR-04	Information consumption	The system should be prepared to consume and display third-party geospatial web services and data (e.g. sentinel imagery, other Copernicus issued products).	MUST HAVE

4.7.7 Training Requirements

Training and support for the users in order to help them use efficiently all the information processed by CENTAUR is essential for the success of the system. These requirements are listed below as part of the needs that should be covered when designing the CENTAUR system.

Code	Requirement Name	Description	Priority
TR-01	Training	Support training processes through the organization of different workshops where the users will be able to learn the capabilities of the CENTAUR solution.	MUST HAVE
TR-02	Helpdesk section	A helpdesk section should be available to the users, in HTML format, accessible through the user profile and serving as the user manual of the application.	SHOULD HAVE

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5 EMS OPERATIONS GAP ANALYSIS

5.1 REVIEW OF CURRENT EMS SERVICE PORTFOLIO AND PAST PRODUCTION

5.1.1 Copernicus EMS services

The Copernicus Emergency Management Service is one of the six main services that the Copernicus Programme, the European Union's Earth Observation programme, provides on a global scale. The Copernicus Emergency Management Service (CEMS) supports all actors involved in the management of natural or man-made disasters by providing geospatial information to inform decision making. CEMS constantly monitors Europe to forecast, analyse, and provide information for resilience strategies. In predicted events, the service immediately notifies users of their findings and can be activated on-demand and offers to provide them with maps, time-series or other relevant information to better manage disaster risk. CEMS products are created using satellite, in situ (ground) and model data. These show information about a disaster event on a scale, timeline, and perspective that only geospatial information can provide. CEMS products can examine changes to an area of Earth over a series of days, weeks, months, or years. The high level of detail allows disaster and risk management authorities to visualise the comprehensive impact of an event. The products can be quickly shared among all agencies involved in an incident to enable timely and consistent response actions.

The Copernicus EMS components linked to urban flood monitoring are listed below:

- On-demand mapping: The Copernicus Emergency Management Service (CEMS) uses satellite imagery and other geospatial data to provide free of charge mapping service in cases of natural disasters, human-made emergency situations and humanitarian crises throughout the world. It covers in particular: floods, earthquakes, landslides, severe storms, fires, technological disasters, volcanic eruptions, humanitarian crises, tsunamis. The Copernicus EMS - Mapping is provided during all phases of the emergency management cycle. The maps are produced in two temporal modes:
    - Rapid Mapping provides geospatial information within hours or days from the activation in support of emergency management activities immediately following a disaster. Standardised mapping products are provided: e.g. to ascertain the situation before the event (reference product), to roughly identify and assess the most affected areas (first estimate product), assess the geographical extent of the event (delineation product) or to evaluate the severity of the damage resulting from the event (grading product).
    - Risk and Recovery Mapping it provides on-demand geospatial information in support of Disaster Management activities not related to immediate response. This applies in particular to activities dealing with prevention, preparedness, disaster risk reduction and recovery phases. Three product categories included: Reference Maps, Pre-disaster Situation Maps and Post-disaster Situation Maps.
- Early-warning & monitoring: it offers anticipatory critical geospatial information at European and global level through continuous monitoring and forecasts for floods through the following system:
    - The European and Global Flood Awareness Systems (EFAS; GloFAS) provide complementary flood forecast information supporting flood risk management at all levels.

The users of the service include entities and organisations at regional, national, European and international level active in the field of emergency management. The EMS can be triggered only by or through an Authorised User (AU). Authorised Users include National Focal Points (NFPs) in the EU Member States and countries participating in the Copernicus programme, as well as European Commission services and the European External Action Service (EEAS).

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5.1.2 Copernicus EMS Rapid Mapping

In case of floods - or floods induced by storms or tsunamis – it is necessary to identify the water bodies on post-event images and compare them with the water extent before the event. This goal can be successfully achieved if multi temporal images (SAR or optical) acquired before and after the event are available or, as an alternative, if reliable and updated reference water body cartographic data are available (exploiting the availability of the Internal SDI). In this regard, the availability of a large worldwide archive data from the Sentinel-1 mission enables the extraction if necessary of the extent of the reference water based on a recent pre-event SAR image.

The special characteristics of SAR satellites, such as the ability to acquire an image of the Earth's surface whatever the light and weather conditions and their peculiar interaction with water surfaces, enables the fast and accurate detection of flooded areas. Optical satellites generally suffer from the presence of clouds when acquiring images over an area affected by floods, as generally there are persistent bad weather conditions over the area itself. Nevertheless, satellite optical images are strongly recommended to detect flooded areas over urban areas and forested areas, in which the results of the analysis based on the SAR images have a low accuracy due to the limitations of SAR imaging. These optical images often enable the mapping of flood impacts and traces only once the weather has improved and flooding is often gone.

Most flood or water extraction methods used in Copernicus EMS RM fall into a semi-automated classification technique category. An initial classification using samples combined with image bands and/or chosen indexes if the imagery is optical is applied followed by an operator validation phase to remove commission and add omission. Moreover, optical spectral responses or SAR surface responses of water targets being quite characteristic enable a fast and accurate automated detection of flooded areas from SAR and optical images.

The classification is based on the same principles: all the pixels of the same class are characterized and regrouped according to similar spectral signatures or surface characteristics for SAR. The signatures of the classes should be well distinct from each other. It must be said that a manual capture by photo-interpretation of the samples for the classification can take time in complex settings. An alternative solution involves using external data references, if available during Copernicus EMS Rapid Mapping service activation, to automatically generate classification samples. This method will be described below.

The automated flood extraction pipeline makes it possible to take full advantage of advanced machine learning algorithms in a short timeframe and leave enough time for an expert operator to validate the result and correct any unmanaged detection errors. Although automated algorithms are not flawless, they greatly facilitate and accelerate the detection and mapping of crisis information, especially for the very frequent flood and fire activations.

Three machine learning algorithms are identified for their robustness and performance in classification procedures: Support-Vector Machine (SVM), Random Forest (RF), and Artificial Neural Network (ANN).

- Support-Vector Machine: SVM is a powerful machine learning procedure created by Vapnik (1995) and is useful because of applicability in a large range of applications (Vapnik 1998, Cherkassky and Mulier 1998). The power of SVMs relies on the kernel function which can adapt dimension function compared to the mapping input (Cortes and Vapnik 1995). In addition, the kernel can adapt itself into a matrix kernel instead of high dimensional space if the classes are linearly separable in the input space.

- Random Forest: The random forest algorithm is part of the ensemble classifiers family. This technique is popular within the remote sensing community due to the accuracy of its classifications. It was first introduced by Tin Kam Ho (1995). The method was extended by Breiman (2001) highlighting important concepts like bagging (bootstrap aggregating) and Out-of-bag error (OBB). The bootstrap sampling allows for the decorrelation of the trees and therefore improves the results and the robustness of the model. The OBB error can be used to determine the importance of features used for the training.

- Artificial Neural Network: Multilayer perceptions (MLP) are a class of feed forward artificial neural network, referred to as ANN in Orfeo Toolbox. At the heart of this model is the perceptron (aka neuron)

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which produces a nonlinear activation of a linear combination of inputs. These perceptions are then arranged in a layered fashion giving the name multilayer perceptron. They are trained iteratively using at each step the partial derivatives of a loss function with respect to the model parameters. This machine learning model leads to approximate solutions for extremely complex problems. Its strengths include a capability to learn non-linear relations, a capacity to handle large amounts of data, and a very fast inference time … Its main downsides include a requirement to tune a number of hyper-parameters (e.g. the number of hidden neurons) and a sensitivity to the quality of input training data.

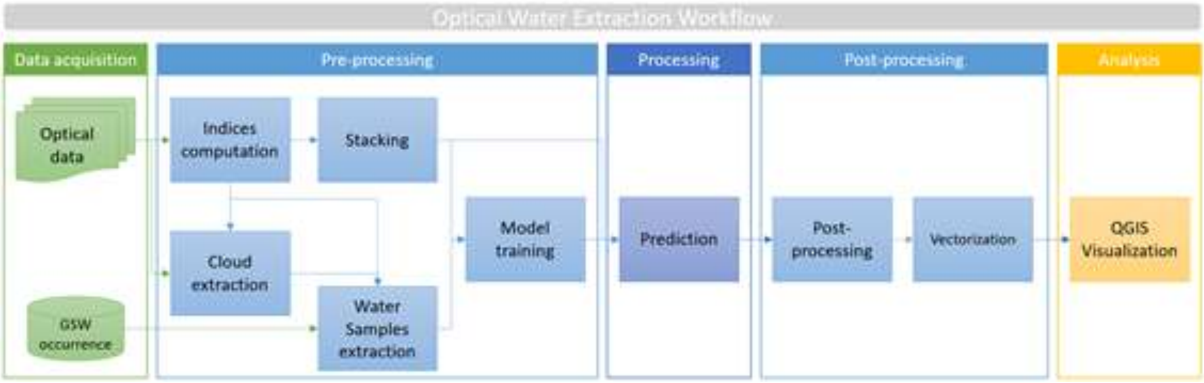

Figure 37: Water extraction workflow based on optical imagery

The optical workflow illustrated by Figure 37 presents the different steps further described below:

1. Global Surface Water (GSW) occurrence product download on the area covered by the optical data;

2. Spectral index computation derived from the optical data: MNDWI, AWEInsh, AWEIsh, WI;

3. Stack relevant spectral indices and bands for training;

4. Cloud extraction from the optical data;

5. Water sample generation from GSW using an occurrence value (relatively low for flood mapping and high for water body mapping) and reference hydrology if available;

6. Water sample filtering using the cloud mask generated and the indices computed to remove outliers and filter the training samples to the hydrological reality of the image (water extent, resolution);

7. Training using the Multi-Layer Perceptron classifier. The training method can be chosen among other classifiers that are implemented such as Random Forest or Support Vector Machine;

8. Prediction of a trained model over a stacked image;

9. Slope and hill shade thresholds derived from HR DEM are applied to refine the water extraction (post-processing);

10. Mosaicking of the results coming from several tiles with the same date and projection;

11. Minimum mapping unit (MMU) sieving to remove small features and fill holes;

12. Vectorisation step in all classic formats including GeoJSON, ESRI Shapefile or Keyhole Markup Language (KML);

13. A second stack may be included in the output folder with a different pile of bands/indices, with a different resolution than the training/predicted stack, and this time only for visualization purposes. This step is relevant when large areas area covered with the need for instance to decrease the resolution in order to display and navigate quickly with the optical data as a background.

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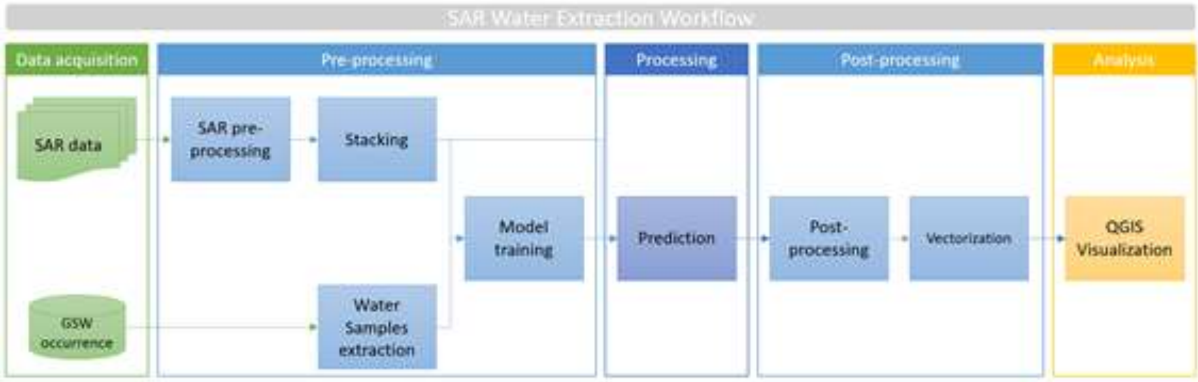

Figure 38: Water extraction workflow based on SAR imagery

As illustrated in Figure 38, the SAR workflow is very similar to the optical workflow. The default training stack includes either the raw amplitude, and the output of a de-speckle process. The water sample filtering step is not included in the SAR workflow. There is an additional post-processing step removing features not connected to the hydrology network (beyond slope breaks). The preferred machine learning method is Random Forest, as it has been proven more robust on thin stacks and SAR offers less usable bands.

The objective is that automated flood chains should produce delineation masks almost ready to be published. A perfect chain that produces 100% reliable and complete delineation masks and that would remove the human validation is the final goal. However, the algorithms are not infallible and the natural environment changes greatly meaning that validation by an expert is still necessary. Indeed, the expected quality of the delineation maps from the CEMS users is very high and goes well beyond the 80% threshold of computed thematic accuracies. Only a few wrongly classified pixels may discredit an entire rapid mapping service or activation.

After operator validation of commissions and omissions, these classification methods generally obtain general accuracy levels of 85-90%. Results are present in the thematic quality section 1.1.4.

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5.1.3 Copernicus EMS Risk & Recovery

In this section, Copernicus Emergency Management Service the Risk & Recovery Mapping – Standard (here to be referred as RRM-STANDARD) portfolio limitations in urban flood mapping are addressed. In order to pursue this aim, a general analysis of the RRM-STANDARD operations has been conducted and following a review of the past activations, four of the latest and significant of them have been selected to better understand and highlight the urban flood criticalities belonging to the RRM-STANDARD framework. Benefitting from the operational experience and events covered in EMS RRM flood events in urban contexts, including different types of urban morphology, the main limitation in terms of coverage, delivery times, and production strategies are reviewed.

Risk & Recovery is one of the Copernicus Emergency Management Service's on-demand modules that provide value-added geospatial information to support decision-making related to emergency management activities not inherent to the crisis response phase. It covers the activities related to the prevention, preparedness, reconstruction, and recovery phases in the Disaster Risk Reduction cycle. Risk & Recovery is of STANDARD and FLEX components: STANDARD offers a portfolio with a pre-defined set of twenty products with each of proper sphere and specifications; on the contrary, FLEX can manage non-standard and customizable user requests operating independently from a standard portfolio. Within the aim of the CENTAUR project, as one of the sub-tasks under Task1.1, the review of Risk & Recovery Mapping operations for urban flood detection is performed from a critical point of view and the key findings are summarized in this section. It is noteworthy to specify that only the RRM-STANDARD is considered for the analysis based on the product portfolio and available past-products, whereas the RRM-FLEX is disregarded for the scope of this study as the requests are formed ad-hoc out of a standard portfolio and the ease of access to the past products are quite limited with respect to the RRM-STANDARD due to the presence of a number of sensitive cases related to the flood context.

Out of twenty products offered in the RRM-STANDARD portfolio, there are only three flood-related products with a focus on flood analysis:

- P04 – Flood delineation (which is the only EO-strict dependent product and thus it is detailed in the next sections and took and referred for the current analysis).
- P05 – Modelled flood extent for major events.
- P06 – Temporal analyses of occurred flood events.

The principal specifications of these three products are presented in the following table below:

Table 11: The product specifications for P04, P05 and P06

CEMS RRM standard flood products	Input data	Output	Delivery time	AOI size [Km2]	Image resolution class / sensor type	Output scale	MMU [m2]
P04: Flood delineation	EO data (satellite imagery), hydrography vector data, Digital Elevation Model (DEM) - Data preferably sourced from national dataset if available.	Flood delineation Water depth	5-10 days	25–500	VHR-SAR, HR-SAR (and optical data in some cases as further support)	1:25 000	2,500
P05:	Obligatory: Digital Terrain Model (high	- Modelled flood extent	5-10 days	25 – 500	VHR-SAR, HR-SAR (and optical	1: 25 000	2,500

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CEMS RRM standard flood products	Input data	Output	Delivery time	AOI size [Km2]	Image resolution class / sensor type	Output scale	MMU [m2]
Modelled flood extent for major events	resolution, 5 m or better), geometry of the riverbed, land use data, historical precipitation data, river level measurement DEM data preferably sourced from national dataset if available Optional: P04	- Max water depth			data in some cases as further support)		
P06: Temporal analyses of occurred flood events	Obligatory: P04, digital terrain model (high resolution, 5 m or better), discharge information, land use data, river level measurement DEM data preferably sourced from national dataset if available Optional: historical precipitation data.	- Max flood extent -Flood temporal evolution -Max flood depth	2-5 days	25 – 500	None	1: 25 000	2,500

The table below sums up the RRM-STANDARD past activations selected for this analysis and the related input data exploited for each case.

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Table 12: RRM-STANDARD activations selected for review and the corresponding input data

Activation Name	EO data source (pre-event and post-event)	Post-event EO - SAR data spatial resolution (GSD)	DEM source and spatial resolution	Use of optical EO-data as support	Date of the Event	Products	Activation Name
EMSN140: Flood in Chad	PRE: Sentinel-1 (10/10/2022) POST: Sentinel-1 (22/10/2022)	10 m	FABDEM 30m	-	15/10/2022	P04, P05 (non standard)	EMSN140: Flood in Chad
EMSN139: Retrospective flood analysis in Luxembourg	PRE: Sentinel-1 (12/07/2021); POST: Sentinel1 (15/07/2021, 16/07/2021)	10 m	DTM 1m Luxembourg data platform (nationally sourced)	-	15/07/2021	P04, P06	EMSN139: Retrospective flood analysis in Luxembourg
EMSN105: Floods in Solingen, Germany	PRE: Sentinel-1 (06/07/2021); POST: Sentinel-1 (15/07/2021 and 16/07/2021)	10 m	GeoBasis-DE/ BKG 1 m (nationally sourced)	-	13/07/2021	P04, P06	EMSN105: Floods in Solingen, Germany
EMSN086: Tropical Cyclone Eloise in Mozambique	PRE: Sentinel-1 (14/01/2021); POST: Radarsat-2 22/01/2021, Sentinel-1 (25/01/2021 and 26/01/2021)	10 m with Sentinel-1, 5 m with Radarsat-2	SRTM 30 m	-	22/01/2021	P04	EMSN086: Tropical Cyclone Eloise in Mozambique

It should be noted that EMSN105 - Floods in Germany and EMSN086 - Tropical Cyclone Eloise in Mozambique are particularly important to review as they are to be addressed also as case studies / demonstrators in the next phases of the project.

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P04 is the flood delineation product of RRM-STANDARD portfolio, providing the flood extent and an estimate of the associated water depth value. In P04, the flood extent is directly derived from the available SAR (VHR and HR) and optical imagery (HR or VHR if available) acquired during the post-disaster phase and the flood depth estimation integrates the digital elevation model data. Reference hydrography from a reference dataset is required to distinguish the permanent inland water extent from the flooded area. The methodology to generate the flood delineation product (P04) is summarised below:

Required input data: As input data, a reference set of optical or SAR images capturing the situation before the flood event and a crisis set of SAR and optical images (if available) capturing the situation during the flood event are required.

SAR data pre-processing: The SAR pre-processing is the first essential step to achieve an improved image visualization in order to extract the value-added crisis information in a later stage. The present standard workflow has been developed for the P04 specific purpose:

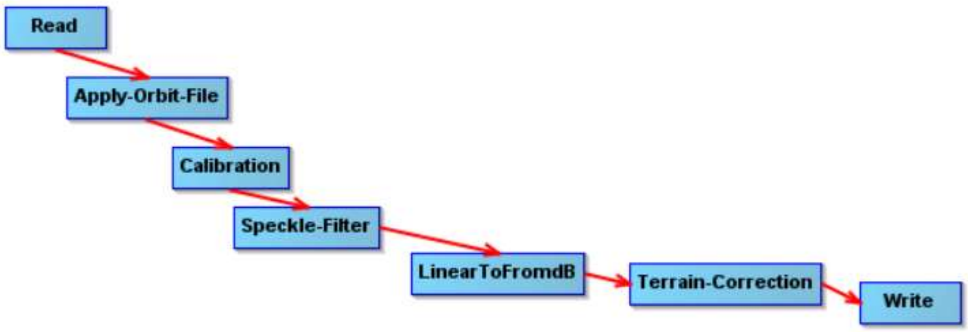

Figure 39: SAR data pre-processing workflow

The fundamental steps are described hereafter:

- Radiometric calibration: it's the first standard radiometric correction and it is necessary to be able to compare several SAR acquisitions, it transforms the digital number of each pixel into backscattering coefficient. It has been decided to select the VV co-polarization here (considered slightly more suitable than VH cross-polarization for flood detection).
- Speckle filtering: SAR imagery is subjected to speckle phenomenon - resulting in a coarse and very granular texture. This affects the quality of the interpretation and classification by impacting the backscattering coefficient values. This is a fundamental step to improve significantly the radiometric quality of the image.
- Terrain Correction: it is the geometric correction that leads to the conversion of SAR images – either slant range or ground range geometries – into a cartographic reference system. It use the satellite orbital parameters (state vectors) and a DEM data to correct topographic distortions in SAR imagery.

Once a superior-quality image is obtained applying the pre-processing steps, a supervised classification is executed as a first step to achieve the flood extent.

The algorithm used for the classification is the Random Forest. Training samples are collected by the operator in a radiometrically homogeneous area, both inside the flooded areas and outside. The training samples are merged in the two homogeneous classes (as water / no water) and the supervised classification is applied. The result is erased by the Reference hydrology layer. The vector data is filtered according to area filters to remove false alarms due to SAR shadowing and to remove / fill small patches / gaps below the MMU. The final result for flood delineation layer is verified and manually refined by an expert operator by Computer-Aided Photo Interpretation (CAPI).

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Water depth estimation

The estimation of water depth is dependent to the delineation of flooded areas. As input data, the flooded area extraction and a DEM are required. Two different approaches are foreseen for the generation of the water depth:

- For large flooded area linked to a river overflowing, the HAND[194] (Height Above the Nearest Drainage) methodology is applied.
- For small, isolated flooded areas with no connection to the nearest river, a second method directly based on the DEM is to be applied.

Quality assessment of P04 products

The thematic validation procedure defined for P04 Flood products is described herebelow.

The flood delineation can be considered as a layer representing two classes: flooded and non-flooded areas. As reported by Congalton, Russell G. and Kass Green (2002) for change/no change map, a binomial class distribution is appropriate for assessing the sample size; for instance, for a 90% accuracy and a confidence level of 95%, a sample size of 298 is required. The thematic accuracy required for P04 is 85% and is tested with high confidence level by using 400 samples. To increase the number of samples in the areas surrounding the flood-polygons; “flooded”, “interface”, “non-flooded” classes are defined, each will host at least 50 validation points. For each sample point, the operator verifies the correctness of the classification and compiles a confusion matrix. The rest of the points are dispersed proportionally to the size of the three areas. The accuracy of the delineation product is assessed through Producer’s, User’s accuracies and the Overall accuracy. The Overall accuracy of the product must be over 85%. If not, the flood delineation has to be verified and new samples have to be taken in order to assess the accuracy again.

Regarding the validation of Water Depth raster, it has not been possible to develop any rigorous method and thus it is limited to a superficial thematic accuracy in case geolocated social media images / information are available.

[194] Nobre, A.D., Cuartas, L.A., Hodnett, M., Rennó, C.D., Rodrigues, G., Silveira, A., Waterloo, M., Saleska, S., 2011. Height Above the Nearest Drainage – a hydrologically relevant new terrain model. Journal of Hydrology 404, 13–29. https://doi.org/10.1016/j.jhydrol.2011.03.05

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5.1.4 Copernicus Global Flood Monitoring

The CEMS launched a new operational product: the Global Flood Monitoring (GFM). This is yet again a ground-breaking and unique CEMS tool: as part of flood early warning and monitoring component of CEMS, it consists in a fully automated tool that processes the entire influx (and past archive) of Copernicus Sentinel-1 radar imagery to extract ongoing (and past for the archive re-processing) flooding episodes on a global scale. It is designed to fully exploit the unique capabilities of the Copernicus Sentinel-1 (S-1) satellite mission, which is capable of all-weather and day/night imagery acquisition with a radar whose characteristics are ideally suited to discriminate water from bare soil, thus providing a monitoring of all land surface areas to detect flood events.

The GFM product is specifically designed to address three additional critical user requirements, namely:

- Significantly enhancing the timeliness of flood maps for emergency response,
- Enabling a global, large-scale monitoring of floods
- Improving the effectiveness of activation requests of the CEMS Rapid Mapping component, through a better identification of the areas of interest.

As a consequence of its timeliness, GFM is a truly operational service for decision makers. Key users include national and regional water authorities, civil protection and first line responders, insurance companies, international humanitarian aid organisations and the EU's Emergency Response Coordination Centre (ERCC).

The GFM product output layer "S-1 observed flood extent" shows the flooded areas which are mapped in near real-time from Sentinel-1 (S-1) satellite imagery, as the difference between the GFM output layers "S-1 observed water extent" and "S-1 reference water mask". The three flood mapping algorithms which are used by the GFM product to generate the output layer "S-1 observed flood extent" are described below, and correspond to the algorithms provided by LIST, DLR and TU Wien.

More details can be found at the following link:

https://extwiki.eodc.eu/GFM/PDD/GFMoutputLayers

Flood mapping algorithm 1 (LIST)

The LIST algorithm is a change detection algorithm. It aims at detecting and mapping all increases and decreases of floodwater extent with respect to a reference one. A change detection approach is adopted because it allows to differentiate floodwater from permanent water bodies and, at the same time, filter out classes having water-like backscattering values such as shadows or smooth surfaces. Moreover, in order to reduce false alarms caused by different types of unrelated changes (e.g. vegetation growth), a reference image acquired close in time is used. Sentinel-1 fulfils this latter requirement since it has a repeat cycle of 6 days. Moreover, to reduce false alarms and to speed-up the analysis, it uses as optional input data the exclusion mask and the HAND (Height Above Nearest Drainage) map.

As in all statistical floodwater or change detection mapping algorithms, the parameterization of the distributions of "water" and "change" classes is conditioned by the identifiability of the respective classes. This depends on the shape of the histogram. More explicitly, some classes may not be easily identifiable on the histogram typically when flooded or changed areas represent only a small percentage of the total image.

Considering an image, it is hypothesised that two classes are present. It is further assumed that both distributions can be approximated by Gaussian curves. Finally, it is hypothesised that the prior probabilities of the two classes are strongly unbalanced. This last assumption is usually verified when processing images that cover large areas and where changes only impact a small part of the image. When this happens, the smallest class is dominated by the other class and its distribution is practically indistinguishable in the global histogram, thereby causing the classification problem to be ill-posed and the selection of the threshold highly uncertain. Hence, in order to cope with this ill-posed problem of unbalanced populations, areas where the two classes are more balanced are identified. The adopted hierarchical split based approach (HSBA) consists of two main steps. First, the image X is

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split into separate sub-regions (i.e. tiles) using a quad-three decomposition. Next, the tiles showing a clear bimodal behaviour with two Gaussian balanced populations are selected. From these populations, statistical "seeds" are created to sprawl regions until stop values are encountered.

The exclusion layer, the HAND mask and the ocean mask from the Copernicus DEM are applied to mask out all pixels which are not part of flood prone areas.

Flood mapping algorithm 2 (DLR)

GFM flood mapping algorithm 2 requires a full Sentinel-1 scene as the main input and further exploits three ancillary raster datasets: a digital elevation model (DEM), areas not prone to flooding and reference water. Initial descriptions of the algorithm were published by Martinis et al. (2015) and Twele et al. (2016).

The algorithm applies a parametric tile-based thresholding procedure by labelling all pixels with a backscatter value lower than a threshold to the class water. The threshold is computed on a smaller, limited number of subsets of the SAR scene and applied to the entire scene. Subsets used to define the threshold are selected based on their backscatter values compared to the global scenes, and which should consist of both low backscatter and a strong variation therein.

After this selection process, the five final parent tiles should have a bimodal backscatter distribution, which is likely to contain a valid water-land-boundary. They then apply the thresholding algorithm of Kittler & Illingworth (1986) to each of the five parent tiles. The algorithm is an iterative, cost-minimization approach, where the histogram is split into two classes with a threshold that identifies the class boundary. The optimal threshold τ for a tile separates both classes with minimum effort. The final threshold separating the water and land classes is the mean of the thresholds of the parent tiles.

An average of all "water class centers" μwater is also computed with the same method as the mean threshold τ for the entire SAR scene. Applying this threshold to the entire SAR scene returns an initial basis for water detection.

Flood mapping algorithm 3 (TUW)

GFM flood mapping algorithm 3 (Bauer-Marschallinger et al. 2021) requires three inputs: the SAR scene to be processed, a projected local incidence (PLIA) layer, and the corresponding parameters of the harmonic model. Based on these inputs, the probability of a pixel belonging to the flood or non-flood class is defined. For this purpose the a-priori flood and non-flood probability density function (PDF) is required. For the values of an incoming Sentinel-1 image, the most likely class is selected by the use of the Bayes decision rule. The algorithm's output consists of a flood extent map and the corresponding estimation of the classification's uncertainty.

Flood backscatter probability density function

The proposed concept is the definition of the flood backscatter probability density function $p(\sigma0|F)$ for any given incidence angle θ. It is assumed that the function is a normal distribution and can be parametrized by the statistical value-pair of mean and a standard deviation. Therefore, various backscatter observations (further referred to as $\sigma(W,\theta)$ and their respective incidence angles were collected over oceans and inland waters from the Sentinel-1 datacube. By sorting the water backscatter collection $\sigma(W,\theta)$ along the incidence angle, the expected indirect relation of water backscatter values and incidence angles can be confirmed.

Non-flood probability density function

In order to model the normal, non-flooded circumstances, we propose the use of the harmonic model (details given in Section 0). The harmonic model allows retrieving an expected backscatter value for any day of the year and a specific relative orbit. Therefore, the backscatter's seasonality is modelled by defining the pixel's harmonic parameters based on its backscatter time-series. Furthermore, this model is taken as the base of the non-flood probability density function, which is assumed to be a normal distribution. The mean backscatter value is set to the expected backscatter of the harmonic model. In addition to the harmonic parameters the standard deviation s of the harmonic model is used as an input for the algorithm and standard deviation of the PDF.

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Bayesian Decision

With the per-pixel knowledge of the relative orbit, the day of year and the incidence angle, one is able to define the flood backscatter probability density function and the non-flood probability density function for each pixel. By using these PDF the belonging of the incoming Sentinel-1 image to either the flood or non-flood class can be determined on a pixel-level.

Uncertainty Values

The algorithm provides the ability to quantify the uncertainty of the classification by the use of the conditional error. This measure is the posterior probability of the less probable class (i.e. the class not selected as flood), is defined between 0.0 and 0.5, and directly quantifies the uncertainty of the classification decision.

Low-Sensitivity Masking

For improving the reliability of Algorithm 3 in (non-supervised) operations, TUW introduced a set of routines to exclude locations where our statistical model does not allow a robust decision between flood and non-flood condition. Consequently, the following masks (PLIA, distributions conflicts, outlier, and high uncertainty) are applied on the preliminary flood extent map obtained from the Bayes decision

Morphological post-processing

Due to the coherent nature of the radar signal, a single-time Sentinel-1 observation is in general affected by multiplicative noise (known as speckle). The random signal variation could lead to single pixels that feature a lower backscatter and could be confused with flood conditions. In order to reduce the influence of noise on the final flood extent map, a median filter of kernel size 5 is applied. This constitutes the final step and the result represents the flood extent and uncertainty output of algorithm 3.

Ensemble flood mapping algorithm

The GFM ensemble flood mapping algorithm combines the flood and likelihood results produced with all three individual flood mapping algorithms. The output is entirely pixel-based. A consensus decision of all algorithms, based on majority voting, determines if a pixel is marked as flooded or as non-flooded. To generate the combined product, each pixel is attributed with the ratio of the number of classifications as flooded to the number of algorithms that were applied. A value of 1.0 means that all three algorithms agreed on its classification as being flooded. A pixel is classified as flooded if it was classified as flooded by at least two algorithms.

In the end, the three algorithms rely strongly on discriminating flooded areas through adaptive thresholds applied on the whole or parts of the observed Sentinel-1 scene. Nevertheless, GFM only takes as input Sentinel-1 data and is not suited (by design) for other SAR data. But more important to our matter, the pipelines would not detect vegetated or urban floods, as thresholding is not enough to detect these kind of flooded areas as mentioned previously.

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5.2 GAP IDENTIFICATION

5.2.1 Copernicus EMS Rapid Mapping

Current practices, methods and results in CEMS RM with respect to coverage, delivery times, production strategies and user feedback.

Current practice is to use a supervised classification like random forest or manually train a machine learning method in order to get quick and efficient results. Those practices are providing good results on simple extractions. The main limits are those with respect to mapping floods in urban areas be that with SAR data or optical data.

There are currently no automated extraction techniques for urban flood extraction, whatever the sensor's type, either SAR or optical. This is due to the different phenomena which contribute to the complexity of the data interpretation in cities.

With respect to optical data, weather is the biggest issue. It is rare to obtain a cloud-free or even exploitable image at a floods peak in order to map floods in urban areas, because flooding is generally accompanied by cloudy, rainy weather. Other issues include shadowing, building masking flooded areas and sometimes mixed pixels due to coarse resolution. All of these limit flood extent mapping from optical data.

For SAR data, dihedral phenomena cumulated to multi bounce, orbital direction influence and speckle effects are known issues for flooded urban areas. This leads to high backscattering in urban areas. Also, much confusion can be caused between flat artificial surfaces found on roofs and road infrastructure as low backscattering, a signature of water, often occur from these surfaces. Airport runways are quite a specific case here. Even smooth grass surface can lead to confusion. Hence, most SAR-based mapping of flood events are restricted to rural areas as the following examples illustrate. There is a big gap in mapping urban areas, the areas users are most interested in.

Mahajanga, Madagascar, Case Study

The work carried out over [EMSR645] Mahajanga: Grading map EMSR64, AOI 05 MAHAJANGA illustrates this point well. For this illustration we will use a Sentinel-1 SAR image taken the 27 January 2023 and an optical Pléiades image taken the 28/01/2023 further described in Table 13. The activation had been triggered for flooding the 25 January 2023.

Table 13: Description of satellite data used in the Mahajanga example

Sensors	Pixel size [m]	Acquisition date and time (UTC	Spatial resolution [m]
Sentinel-1	10	27/01/2023 02:26	27/01/2023 02:26
Pléiades	0.50	Sentinel-1A/B (2023) provided under COPERNICUS by the European Union and ESA	Sentinel-1A/B (2023) provided under COPERNICUS by the European Union and ESA

In the Sentinel-1 image acquired the 27/01/2023, the dense urban area comprising the south-west of the blue outlined AOI seems water-free, observed through low backscattering which in this illustration translates to dark pixels, and, in fact, conversely extremely high backscattering is emanating from the city centre (Fig. HH).

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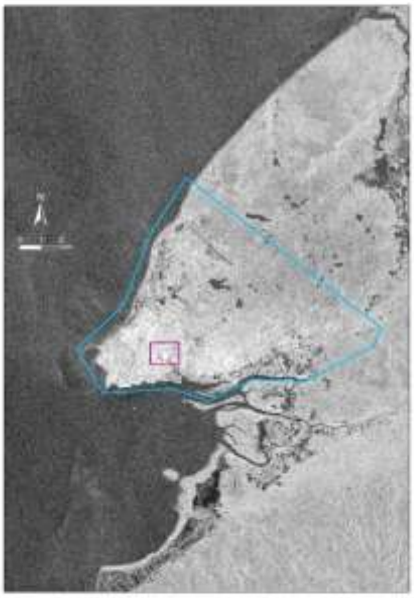

Figure 40: Sentinel-1 data acquired the 27/01/2023 at 02:26, provided under COPERNICUS by the European Union and ESA. The main urban centre in the south-west of the AOI in blue shows very high backscattering. The purple rectangle represents an extensively flooded area observed 1 day later and depicted in Figure 41.

In the figure below (Fig. TT) extensive flooding can be observed within a relatively dense urban area of Mahajanga.

Figure 41: Extensive flooding found in a dense urban area of Mahajanga as seen in Pleiades data, © CNES (2023), distributed by Airbus DS (acquired on 28/01/2023 at 07:02 UTC, GSD 0.5m, approx. 22% cloud coverage in AOI, 26.8° off-nadir angle), provided by international Charter (call ID 917), all rights reserved

This is not the only area observed as affected by flooding and in fact thanks to this Pléiades image a comprehensive urban flood and damage mapping of this city area was elaborated manually, presented in Figure DD. The orange dots on the map represent flooded buildings; the yellow dots represent buildings lying within areas where flood traces are found. The flood traces of course represent areas where previous flooding had left damage of some type. This means that when the Sentinel-1 image had been taken a day earlier the flooding most likely was larger.

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In the section concerning up and coming methods, an InSAR based method is proposed to infer flooding in urban areas from a phenomenon seen in double SAR-pairs acquired across flood events, whereby an increased backscattering and lowering of coherence is observed moving from pre to crisis event Sentinel-1 imagery. This exceptional case will form part of the tests before the user cases

Figure 42: Detail map over the city centre of Mahajanga, EMSR645 AOI05, comprising of a damage grading assessment

Aberdeen, Scotland, Case Study

Another potential example of SAR potentially missing urban flooding can be observed in the case of flooding in and around Aberdeen. Activation EMSR640 was triggered on the 18 November 2022 at 21:46 UTC with AOI 02 covering Aberdeen and surroundings. A flood event was declared the 19th of November 2022. On the 19 November 2022, the flood event was described as follows in the on-line Independent Newspaper 'Danger to life' floods overwhelm homes, railways and roads in Scotland after 140mm of rain falls overnight Saturday". SAR data acquisitions often miss what are often very ephemeral flood events, but here acquisitions were taken on the 18 November and the 20 November 2022 close to the flood peak. Given the large amount of plain flooding detected upstream of Aberdeen on the 18th and 20th of November concerning two rivers, the Dee and Don, pouring into the Aberdeen city area, and social media photos on the 18th of November (Figure 43), it is more than possible that urban flooding continued until the 20th of November. This is highlighted in the River Don and Dee discharge hydrographs taken little upriver from Aberdeen. The discharge peaks were on the 18th of November but remained high until the 19-20th of November. Of course, water discharge isn't flood extent but it means a lot of water was most likely still around in the flat area on the 20th of November, were the Sentinel-1 show the highest flood extent.

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Figure 43: Homes in Aboyne were badly hit when the River Dee burst its banks. Picture: Kami Thomson/DC Thomson

Nonetheless, using conventional methods no flooding was detectable in the city centre and seen in the EMSR640 activation mapping (Figure 44).

Figure 44: Hydrograph of the “Don at Parkhill” gauge station on the Don River upriver of Aberdeen for the November 2022 flood event

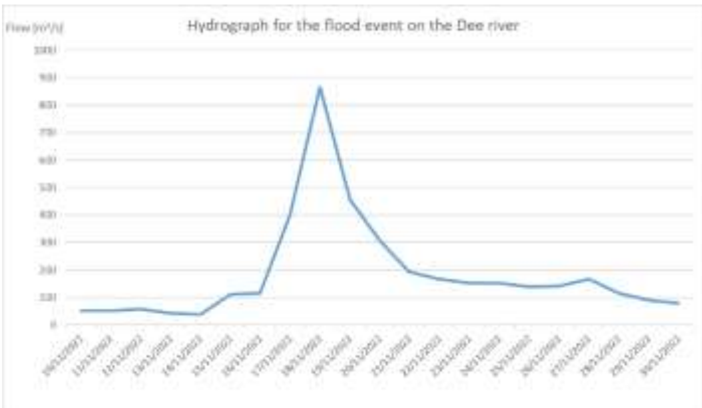

Figure 45: Hydrograph of the “Dee at Park” gauge station on the Dee River upriver of Aberdeen for the November 2022 flood event

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Table 14: Description of satellite data used to map flooding in the Aberdeen area for the November 2022 flood episode (EMSR640)

Sensors	Pixel size [m]	Acquisition date and time (UTC	Spatial resolution [m]
Sentinel-1	10	18/11/2022 17:59	18/11/2022 17:59
Sentinel-1	10	Sentinel-1A/B (2023) provided under COPERNICUS by the European Union and ESA	Sentinel-1A/B (2023) provided under COPERNICUS by the European Union and ESA

Figure 46: Delineation Monitoring 01 flood extent map over the AOI02 Aberdeen area on the 20th November 2022. Both the 18th and 20th flood extent mapping are shown in the map here

Tabasco, Mexico, Case Study

The case of the flood occurred in November 2020 in Mexico represents another activation (EMSR479) in which the limitations of SAR imagery are manifest. In Figure 47 one can observe how the analysis of the flood extension performed with the image Sentinel-1 acquired on the 09/11/2020, no flood delineation is found in the urban areas of Villahermosa.

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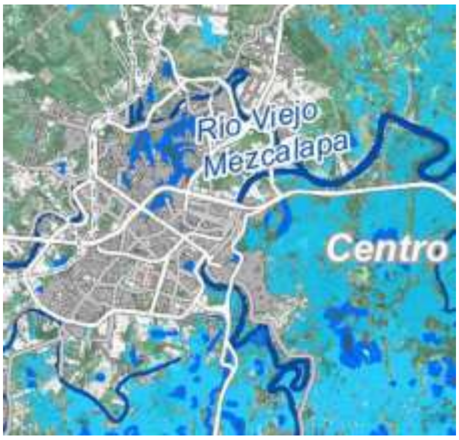

Figure 47: Delineation Monitoring 01 flood extent map over the AOI02 Villahermosa area on the 9th November 2020 – zoom on the town of Villahermosa. Flood delineation using Sentinel-1 imagery acquired the 09/11/2020 at 12:01, © European Union

The activation was triggered for flooding on the 08 November 2020 and, after the first delineation map produced on the 9th November, a grading product was delivered using a Pléiades image, acquired on the 10th November 2020. More details about the images used in this activation are available in Table 15:

Table 15: Description of satellite data used in the Villahermosa example

Sensors	Pixel size [m]	Acquisition date and time (UTC	Spatial resolution [m]
Sentinel-1	10	18/11/2022 17:59	18/11/2022 17:59
Sentinel-1	10	Sentinel-1A/B (2023) provided under COPERNICUS by the European Union and ESA	Sentinel-1A/B (2023) provided under COPERNICUS by the European Union and ESA

Focusing on the South-East area of the town, a comparison between the Sentinel-1 (left) and the Pléiades (right) shows how the inundation in the urban area cannot be described by the processing of the image from the SAR satellite (Figure 48, left). The flooding is clear in the Pléiades image.

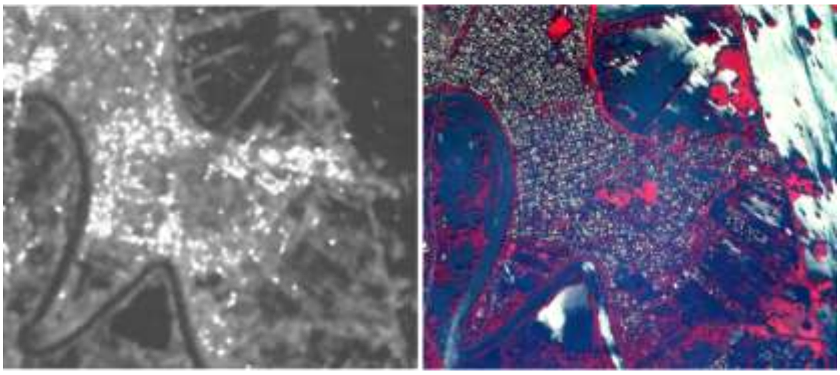

Figure 48: Zoom on the inundated area in Villahermosa; comparison between the Sentinel-1 image - 09/11/2020 (on the left) and the Pléiades - 10/11/2020 (on the right)

Thanks to the Pléiades image, it was possible to manually elaborated a more accurate urban flood and damage mapping of this city area, as it can be seen in Figure 11.

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Figure 49: Detail map over the South-East area of Villahermosa, comprising a damage grading assessment, Copernicus Emergency Management Service (© 2020 European Union), [EMSR479] AOI02 Villahermosa: Grading

5.2.2 Copernicus Risk&Recovery

An evident constraint of the RRM-STANDARD service is the lack of a specific cartographic product developed to detect floods within urban areas. As Baghermenash et al. (2022)[195] reported, SAR-based flood detection in urban areas is challenging due to various complex urban backscatter patterns, including double bounce, shadow, and layover, which cause misclassification and increase false alarms. Due to this issue, the majority of SAR-based studies in the literature have focused on rural flood detection and left urban flood detection largely unexplored.

Indeed, the flood detection procedure developed in P04 is generally applied to any type of land cover present within the area of interest; as a result, the total flood extent in the urban area retrieved from SAR image is very likely to be underestimated.

Another limitation linked to the abovementioned drawback, is the lack of diversified approaches in product strategy to extract flood information from SAR imagery. The P04 is exclusively only based on the SAR intensity processing domain (applying a supervised classification of the back-scatter values).

Other methodologies[196] or production strategies[197][198] based on different SAR processing domains such as radar interferometry (InSAR), radar polarimetry (POLSAR) or InSAR polarimetry (POLInSAR) are not yet considered in the current portfolio.

Being dedicated to the non-crisis response activities, normally, the Risk & Recovery Mapping service is activated several days/weeks after the event. Following the service activation request and the reception of the input data, the production timeline for the provision of cartographic outputs is extended to several days – allowing for a very detailed analysis of the user's request without time pressure for delivery unlike the Rapid Mapping service. In terms of delivery time, the performance of the RRM-STANDARD could be surely improved. In terms of delivery

[195] Baghermanesh SS, Jabari S, McGrath H. Urban Flood Detection Using TerraSAR-X and SAR Simulated Reflectivity Maps. Remote Sensing. 2022; 14(23):6154. https://doi.org/10.3390/rs14236154

[196] Md Tazmul Islam, Qingmin Meng,
An exploratory study of Sentinel-1 SAR for rapid urban flood mapping on Google Earth Engine,
International Journal of Applied Earth Observation and Geoinformation, Volume 113,2022, 103002, ISSN 1569-8432, https://doi.org/10.1016/j.jag.2022.103002

[197] Zhang, H.; Qi, Z.; Li, X.; Chen, Y.; Wang, X.; He, Y. An Urban Flooding Index for Unsupervised Inundated Urban Area Detection Using Sentinel-1 Polarimetric SAR Images. Remote Sens. 2021, 13, 4511. https://doi.org/10.3390/rs13224511.

[198] Jo, Min-jeong & Osmanoglu, Batuhan & Zhang, Boya & Wdowinski, Shimon. (2018). FLOOD EXTENT MAPPING USING DUAL-POLARIMETRIC SENTINEL-1 SYNTHETIC APERTURE RADAR IMAGERY. ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. XLII-3. 711-713. 10.5194/isprs-archives-XLII-3-711-2018.

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time, the performance of the RRM could be surely improved. As reported in the table below, for the average of the production time (the time elapsed between the activation date and the delivery of the products) is around 32 days for the past activations selected for this review.

Table 16: The production delivery timing of the RRM-STANDARD activations selected for review

CEMS RRM standard flood products	Input data	Output	Delivery time	AOI size [Km2]	Image resolution class / sensor type	Output scale	MMU [m2]
EMSN140: Flood in Chad	15/10/2022	21/12/2022	02/02/2023	43	P04, P05 (non standard)	EMSN140: Flood in Chad	15/10/2022
EMSN139: Retrospective flood analysis in Luxembourg	15/07/2021	11/10/2022	16/11/2022	36	P04, P06	EMSN139: Retrospective flood analysis in Luxembourg	15/07/2021
EMSN105: Floods in Solingen, Germany	13/07/2021	16/08/2021	15/09/2021	30	P04, P06	EMSN105: Floods in Solingen, Germany	13/07/2021

Another point worth mentioning is that the Service Provider Consortium for Risk & Recovery Mapping does not have direct the access to the user feedback forms compiled after the closure of the activation that could provide precious feedback on the overall accuracy of the flood extent delineation with respect to the ground validation.

Limitations in P04 Flood Delineation

A main limitation of P04 is the poor use of optical post-images that could compensate / integrate the well-known limitations of the interpretability of the SAR data over the urban areas. It is self-evident that SAR data are the most widely used EO sources in flood mapping due to their all-weather and day-night imaging capability; however, the spatial resolution, the complex scattering mechanisms and SAR geometric effects occurring in an urban environment, may not always allow detecting the entire flood extent accurately. Thus, the integration of optical images when available and captured as cloud-free should be default over the urban areas. The following figures depict zoom-ins of the urbanized areas within the areas of interests of the the past activation analysed with limited flood detection.

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Figure 50: EMSN086 - P04 Flood Delineation with a zoom on Beira City

The zoom is extracted from the EMSN086-P04 Flood Delineation product with the flood mask retrieved from the SAR image (Radarsat, 5m resolution) acquired on the 22th January 2021. While the map did not specifically identify affected areas, the traditional media uncovered urban districts that were hit particularly hard, as shown in Figure 51.

Figure 51: Left: Photo released by European Pressphoto Agency on 23th January 2021 with flooded areas in residential areas in the city of Beira. Upper right: Photo released by TRT World Agency on 23th January 2021 in the city of Beira with submerged vehicles in the transportation network. Bottom right: Photo released by UNICEF (distributed by VoaNews) on 23th January 2021 in the city of Beira, mentioning the observations of U.N. Resident Coordinator in Mozambique regarding the widespread floods.

The zoom was extracted from the EMSN105-P04 Flood Delineation product with the flood mask retrieved from the SAR image (Sentinel-1, 10m resolution) captured on 15th July 2021. While the map indicates that Solingen's urban area has not been affected by the flood, some images circulating in the media suggested otherwise. (see Figure 52).

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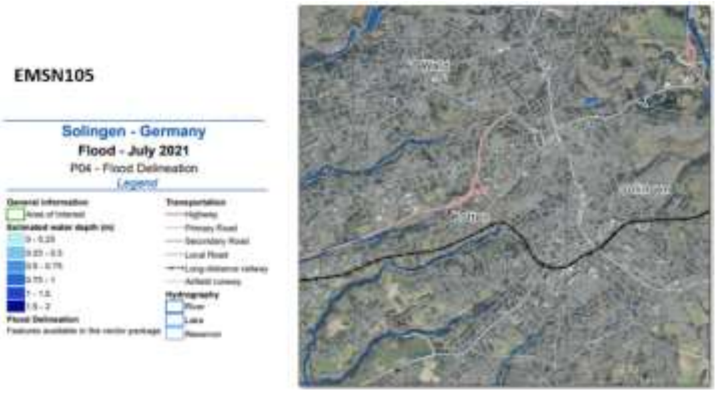

Figure 52: EMSN105 - P04 Flood Delineation with a zoom on Solingen city

Figure 53: Photo distributed by [The Local](#) with rescue workers surveying the flooded area in Solingen on 15th July 2021

Figure 54: EMSN139 - P04 Flood Delineation with zoom on Mersch city

The detail zoom above in Figure 54 was extracted from the EMSN139-P04 Flood Delineation product with the flood mask d from the SAR image (Sentinel-1, 10m resolution) acquired on the 15th July 2021 (the peak day of rainfall event). While the flood event has been referred to as "catastrophic", the limitations of interpreting the SAR acquisition used in this product must be considered. Due to the complex scattering mechanisms, SAR geometric effects, and spatial resolution issues inherent in urban environments, flood detection is challenging. Consequently, the total flood extent derived from the Sentinel-1 image is likely to have been underestimated.

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Figure 55: On July 15th, 2021, the photo posted on social media depicts a fully flooded street in the center of Mersch

The following zoom over Tandal city was extracted from EMSN140-P04 Flood Delineation product with the flood mask derived from SAR (Sentinel-1, 10m resolution) acquired on 22th October 2022. The map indicates that there is no flooding in the urban area of Tandal. However, without additional images or documentation, it is impossible to determine if there is any potential underestimation of the extracted flood area over Tandal city.

Figure 56: EMSN140 - P04 Flood Delineation with zoom on Tandal

Another intrinsic limitation of P04 product is its being stringent in terms of product specifications as the output scale must be 1:25 000 with a standard Minimum Mapping Unit (MMU) of 2500 m2 to be applied for any type of EO-data (both HR and VHR resolution classes; both optical and SAR images). In the narrow spaces of urban blocks, a flooded area of 2500 square meters, if detected, could have some relevance.

The RRM-STANDARD activations review reveals also a poor use of VHR (Very-High-Resolution) SAR data that, given the architectural nature of cities, where open spaces are reduced, would be the proper resolution class to try to extract information within the urban areas. But actually, the HR SAR data is primarily used in this product, especially Sentinel-1 (Level-1, Ground Range Detected, Interferometric Wide Swat, with a declared resolutions of approximately 20 m and a pixel spacing of 10 m). Only in very few cases, VHR SAR commercial data is exploited. This is a criticality especially considering also the recent advances in the satellite SAR constellations with high revisit time.

<u>Limitations in P04 Water Depth Estimation</u>

The main critical point identified for the Water Depth definition regards the limited availability of a high-resolution DEM as input data. Indeed, the quality and the accuracy of the water depth is strictly dependent to the quality of the input DEM. In most of the cases, especially outside Europe, it is very difficult to retrieve VHR quality (or even HR data). For example, in EMSN140 Flood in Chad, the DEM used for the analysis was FABDEM, derived by

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Copernicus DEM, with a quite coarse resolution of 30 m. Another similar case is EMSN086 Tropical Cyclone in Mozambique, where SRTM DEM-30m (NASA/USGS) was exploited for P04.

P05 & P06 – Flood delineation

P05 and P06 are Risk&Recovery products in which hydraulic modelling executions are required for product generation.

P05 aims to provide modelled and simulated flood extent information based on discharges and estimated water levels using statistical methods or hydrological cycle models (runoff models). P05, through statistical analysis, allows the reconstruction of future flood scenarios for different return times. Return time is an estimated mean time or mean time between the occurrence of events such as floods or river flows. It is a statistical measurement typically based on historical data over a long period and is usually used for risk analysis.

The outputs of the P05 are the main inputs for the hydraulic modelling such as the rivers discharge present in the area of interest.

P06 aims to provide temporal analysis of a flood event that occurred in the past within a defined area of interest. The P06 consists of two sub-products: a) reproduction of the flood from the point of view of the maximum extension and depth; and b) temporal evolution of floods. The first provides information on the past flood event, in terms of extent and maximum depth that occurred during the extreme flood event. The second, the temporal evolution of the flood, provides information on the flooded area for defined time intervals modelled (e.g. extension of the flooded area every 12 hours, every day at 12:00, every two days) and allows the persistence of the flood to be reconstructed over the various days/hours of interest.

The outputs of P06 refer to the maximum flood extension, the maximum flood depth and the temporal evolution of the flood in terms of flood extension. This product, in general, can be used in the recovery phase of the disaster management cycle.

P05 & P06 limitations observed in the past activations

P05 and P06 have several limitations closely related to the quality of the input data used for hydraulic modelling.

Hydraulic modelling requires the following inputs:

- Digital Terrain Model (DTM).
- hydrological data of the event of interest (e.g. rainfall).
- hydraulic data of the event of interest (e.g. water levels, water flow rates, sea level, etc.).
- precipitation history dataset (only for P05).
- data of river and lake bathymetries.
- geometry and hydraulic info of hydraulic structures (e.g. volume of reservoir, flow discharge, etc..).
- land use and land cover.
- P04, the satellite flood delineation (useful for the calibration of the hydraulic model).
- geolocated social media markers.

When one of these data presents low accuracy, it will affect the goodness of the output.

Of all the input listed above, the one that has the greatest impact on output accuracy is lack of the digital terrain model (DTM) with acceptable spatial resolution, hydrological and hydraulic data and robust P04 product. Below are some pictures of floods simulated with low spatial resolution terrain models.

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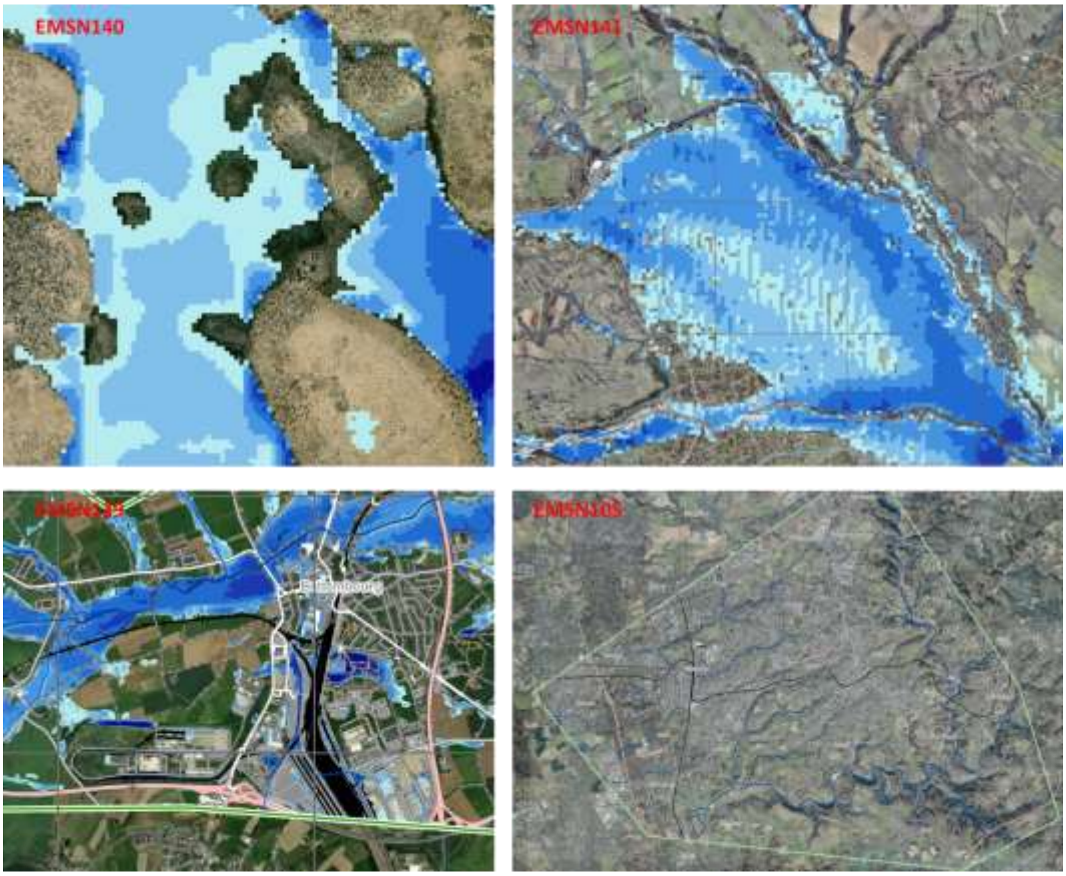

Figure 57: P05 and P06 accuracy limitations

In the Figure 57 above, the images referring to EMSN 140, 141 and 139 show typical issues due to the use as input data of a DTM with low spatial resolution and satellite estimated precipitation. For all the proposed cases a FABDEM Copernicus with a spatial resolution of 30 m and precipitation of the event of interest deriving from the Global Precipitation Measurement (GPM) constellation was used.

The main issues that occurred while using these inputs were: a) incorrect localization of the flooded areas; b) overestimation and/or underestimation of the entity of the floods; c) overestimation and/or underestimation of the flooding depth d) “step effect of depth calculation”.

The digital model of the terrain, being an approximate representation of the area of the terrain in which the flood of interest occurred, if it does not exactly reproduce the environment for which flooding assessments must be carried out, reproduces errors in terms of flooding location. Furthermore, the DTM does not faithfully represent the reality of the flooded environment and presents errors related to poor vertical resolution, generating overestimates and/or underestimates of the calculated flooding depth and the error called "step effect". The latter error, is a problem identifiable as a variation in calculated flooding depth, even of several meters, between neighbouring pixels. The following figure clarifies the concept related to this type of error.

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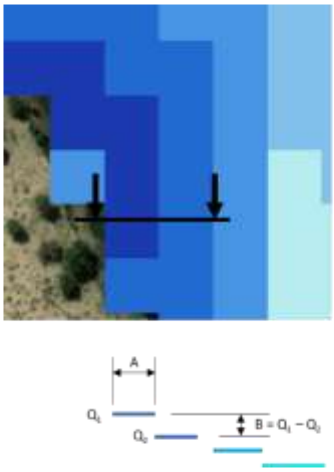

Figure 58: Step effect depth error

A is the pixel size of the DTM used as input of the hydraulic simulation, Q1 and Q2 are the calculated flooding depths and B is their difference. B in most cases could be variable from 0.50 to 2 meters.

The estimate of rainfall in GPM, as evidenced by the literature (Weng et al., 2023, Wang et al, 2023, Zouh et al., 2023, Guo et al., 2023)[199][200][201], heavily underestimates the measurements of rainfall especially in correspondence with the peaks. This very important problem is due to the saturation of the signal, during heavy rainfall, in the measurement of the brightness temperature. The brightness temperature is the main parameter through which the precipitation measure is estimated.

The precipitation peaks, in several cases, are underestimated even by 200 mm.

Another important limitation is the scarce presence of polygons identifying the flooded areas seen from the satellite in P04. P04 is essential for the generation of P05 and P06, because it allows the calibration of the hydraulic modelling results in terms of flood extent. When you have a situation like the one shown in Figure 58, as for EMSN105 where there are very few flood polygons in P04, a hydraulic modelling calibration is impossible. This means that the flood extent obtained from hydraulic modelling could be larger or smaller than what actually happened.

[199] Weng, P., Tian, Y., Jiang, Y., Chen, D., & Kang, J. (2023). Assessment of GPM IMERG and GSMaP daily precipitation products and their utility in droughts and floods monitoring across Xijiang River Basin. Atmospheric Research, 106673.
[200] Wang, Y., Miao, C., Zhao, X., Zhang, Q., & Su, J. (2023). Evaluation of the GPM IMERG product at the hourly timescale over China. Atmospheric Research, 106656.
[201] Zhou, Z., Lu, D., Yong, B., Shen, Z., Wu, H., & Yu, L. (2023). Evaluation of GPM-IMERG Precipitation Product at Multiple Spatial and Sub-Daily Temporal Scales over Mainland China. Remote Sensing, 15(5), 1237.
Guo, Binbin, Tingbao Xu, Qin Yang, Jing Zhang, Zhong Dai, Yunyuan Deng, and Jun Zou. "Multiple Spatial and Temporal Scales Evaluation of Eight Satellite Precipitation Products in a Mountainous Catchment of South China." Remote Sensing 15, no. 5 (2023): 1373.

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5.3 GAP PRIORITISATION

Table 17: Gaps identification and prioritization in the framework of CEMS RM and RRM services

CEMS services	Gap Identification	Gap Prioritization
CEMS RM	Current SAR data processing does not enable urban flood mapping. Optical data need clear skies to map urban floods. Neither SAR nor optical data acquisitions are frequent enough nor throughout the day (optical), leading to difficulties to catch the flood peak and flash floods. No automated extraction techniques for urban flood mapping.	1 – Automated urban flood mapping using all-weather InSAR imagery 2 – Hydro-geomorphological urban flood modelling using EO inputs and ancillary data (VHR DTMs, social media, gauges, precipitation...) Another one we have no influence on, is higher frequency InSAR compatible acquisitions
CEMS RRM	The main limitation of CEMS RRM product portfolio is not having a dedicated product focusing on urban flood detection. SAR - HR spatial resolution, rigid production scale and a single predefined type of production strategy (supervised classification based on back-scatter values for water mask extraction) limit the urban flood delineation capabilities. The unavailability of in-situ data and low-resolution DTMs in poorly instrumented areas limit the flood detection capabilities both on the spatial extent and the water depth estimation.	1 – VHR DTMs for hydraulic modelling

Table 18: Gap identification and prioritization in terms of relevant data for Urban Flood detection and monitoring

Relevant data	Gap Identification	Gap Prioritization
Topographic data	Free available DTM data useful for flood index calculation have a low spatial resolution not adapted to the generation of accurate flood maps. VHR DTM data not always available (in particular in poor areas such Africa, South America …). VHR DTM and Lidar data need to be pre-processed to speed-up usage in CEMS RM.	VHR DRMs derived from InSAR compatible coverages and/or optical 3D compatible coverages (CO3D, Pléiades...)
Weather and flood forecast system	Intense and localised precipitation forecast still a challenge for urban applications. Hydrologic forecast cannot resolve the scale at which urban floods happen.	1 – reception of high spatial and temporal resolution flood forecasts and potential flood modelling

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Relevant data	Gap Identification	Gap Prioritization
Socio-economic and demographic data	Data on socio-economic vulnerability are usually relatively coarse in terms of spatial and temporal coverage. They may also be expensive to collect (particularly for survey data), difficult to scale up, and limited in availability, particularly in the context of developing countries. Even when EO data such as night-time light emissions are used as proxy measures for socio-economic vulnerabilities, they may suffer from validity and interpretability issues. In this case, data from traditional and social media sources can help address this gap.	Use of traditional and social media sources (as proxies) to infer and validate socio-economic indicators Develop a principled approach to integrate several platforms and fuse traditional and social media-based indicators with non-media ones

With regard to CEMS Rapid Mapping, flooding maps obtained using existing satellite data do not allow to delineate floods in urban areas nor to catch the peaks of the flood event. This is mainly due to both optical and SAR sensors limitations, in terms of spatial and temporal resolution.

The main limitations of Standard CEMS Risk and Recovery Mapping, on the other hand, lie behind the fact it is a flood delineation product without urban focus. In fact, the existing P04 for flood delineation is rigid in terms of product specifications with SAR HR EO data domination. Furthermore, P05 and P06 may not be always regarded as feasible for generation or yield accurate outputs due to the unavailability of high resolution DTM and additional input data needed for hydraulic modelling.

To date, free available DTM data useful for flooding index definition are characterized by low spatial resolution. VHR DTM data are not always available especially for poor areas or developing countries (i.e. South America, Africa, etc.).

Lastly, the main limitation of the current weather and flood forecast system is still related to the spatial resolution of the DTM used for the modelling.

Regarding the use of traditional and social media to infer socio-economic indicators, little work seems to have been carried out to date. The authors[202] employ advertising data from Facebook as a proxy to infer socioeconomic indicators for a small selection of countries. Amroush and Hababou[203] likewise examine Facebook and investigate its penetration in a specific population as a proxy for socio-economic factors. In both cases, only Facebook is considered and statistics on the platform rather than contents and use by the population is focussed on. Furthermore, no other platforms nor traditional media are taken into account. The use of social and traditional media (as proxies) to infer socio-economic indicators as well as a principled approach to integrate several platforms and fuse such indicators with non-media ones thus seems to provide a genuinely novel approach to be investigated within CENTAUR.

[202] Fatehkia et al. EPJ Data Science (2020) 9:22, Mapping socioeconomic indicators using social media advertising data, https://epjdatascience.springeropen.com/articles/10.1140/epjds/s13688-020-00235-w
[203] Role of Social Media in Socioeconomic Development: Case of Facebook, Review of Economic Analysis, Vol14.No3, 2022

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6 CSS-SEA OPERATIONS GAP ANALYSIS

6.1 REVIEW OF CURRENT CSS-SEA SERVICE PORTFOLIO AND PAST PRODUCTION

6.1.1 Copernicus Service for Security applications

The Copernicus service for Security applications aims to support European Union policies by providing information in response to Europe's security challenges. It improves crisis prevention, preparedness, and response in three key areas:

- Border surveillance. In the area of border surveillance, the main objectives are to reduce the death toll of illegal immigrants at sea, to increase the internal security of the European Union and to fight against cross-border crime.
  With an agreement signed on 10 November 2015, the European Commission entrusted FRONTEX with the border surveillance component of the Copernicus Security Service. The objective is to support the EU's external border surveillance information exchange framework (EUROSUR) by providing near real time data on what is happening on land and at sea around the EU's borders.
- Maritime surveillance. In the area of maritime surveillance, the overall objective of the European Union is to support Europe's maritime security objectives and related activities in the maritime domain. The corresponding challenges mainly relate to safety of navigation, support to fisheries control, combatting marine pollution, and law enforcement at sea.
  With an agreement signed on 3 December 2015, the European Commission entrusted EMSA with the operation of the maritime surveillance component of the Copernicus Security Service. Under the agreement, EMSA uses space data from Copernicus Sentinel 1 and other satellites combined with other sources of maritime information to effectively monitor maritime areas of interest.
- Support to EU External Action. As a global actor, Europe has a responsibility in promoting stable conditions for human and economic development, human rights, democracy, and fundamental freedoms. In this context, EU can provide assistance to third countries in a situation of crisis or emerging crisis and help prevent global and trans-regional threats having a destabilising effect.
  With an agreement signed on 6 October 2016, the European Commission entrusted SatCen with the operations of the Copernicus Security Service - Support to EU External Action with the signature of a Delegation Agreement by Lowri EVANS, Director-General DG Internal Market, Industry, Entrepreneurship and SMEs (GROW) at that time and Pascal Legai, SatCen Director at that time in order to support EU External Action with state-of-the art satellite data and technologies in a secure mode and environment. The Copernicus Service in Support to EU External Action became operational in May 2017.
  SatCen is thereby tasked with the operational management of the service, the issuing of industrial service contracts, and monitoring the quality of the service. SatCen also remains the focal point for service's Authorised Users.

6.1.2 CSS-SEA current service portfolio

6.1.2.1 About the service

The Copernicus Security Service - Support to EU External Action (CSS-SEA) is an operational European geospatial intelligence service relying on the analysis of satellite imagery, which assists the EU and its Member. It is designed to support European actors dealing with crisis management and security abroad, such as those involved in EU Common Security and Defence Policy (CSDP) Missions and Operations as well as Member State Ministries of Defence or Foreign Affairs and intelligence centres. The information provided contributes to improving European

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capacities in crisis prevention, preparedness and response. It also aims to assist in situations of crisis or emerging crisis and in preventing global and trans-regional threats with a potentially destabilising effect on societies and economies.

The Copernicus Security Service - Support to EU External Action can be activated only by Authorised Users. These include the European Commission services, the European Union's External Action Service, CSDP Missions and Operations, Member States (e.g. Ministries of Defence or Foreign Affairs and intelligence centres), and international organisations (the United Nations' Department of Field Support or Department of Peace-Keeping Operations). As this list makes clear, the service is mainly oriented towards European users, but can also be activated, under specific conditions, by key international organisations under cooperation agreements with the European Union.

The service can provide users with rapid, on-demand geospatial information for the detection and monitoring of events or activities that may have implications for European and global security. The service delivers various Product Types (section 6.1.2.5) based on the analysis of satellite imagery, taking the form of a range of printable and digital maps and reports, which fulfil user needs for information in a wide range of Application Areas (section 6.1.2.3). It is particularly valuable for remote areas, which are difficult to access, and where security issues are at stake.

Several Use Case Examples (Section 6.1.2.6) have been presented to demonstrate how the CSS-SEA can be used in specific situations to support the EU by improving the situational awareness of European Commission, European External Action Service and CSDP and other EU policies stakeholders. They have to be considered only as examples as they represent a small subset of possible cases.

6.1.2.2 Key features

The Copernicus Security Service - Support to EU External Action main key features include:

- Flexibility, responsiveness and custom-designed geospatial intelligence service. CSS-SEA service is designed to flexibly satisfy the information needs of users. Responses to user requests are individually tailored, taking advantage of a variety of Earth Observation techniques. The categories of products presented in this portfolio provide examples of the most common use cases, and they have been designed for broad adaptability. CSS-SEA experts assess user needs and translate them into a customised service offer which best suits the challenges presented.
- Detailed, rapid and high-quality information on remote or inaccessible areas. Making use of the fleet of available satellites through the Copernicus programme, the CSS-SEA service is capable of providing intelligence on any location on Earth – in some cases within a day or two of the request[204]. This allows remote, dangerous or inaccessible areas to be monitored, enabling informed planning of potential interventions in the field – or providing valuable insights for policy or planning purposes.
- Specialised space and terrestrial data processing technologies. The service makes extensive use of innovative data sources and processing techniques which exploit the unique properties of the available satellite sensors, placing a set of specialised capabilities at the disposal of the expert analysts. Examples include detecting surface changes corresponding to vehicle tracks in desert sand, identifying temperature differences in buildings, or satellites whose radar sensors can acquire imagery through clouds or at night.
- Insights and expert interpretation by experienced geospatial imagery analysts. Teams of imagery analysts within the CSS-SEA service comb through satellite imagery, processing results and terrestrial data sources seeking to

[204] Dependent on a range of conditions including weather, satellite overpass timing, and the complexity of the processing.

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extract insights in response to the questions posed by the user. The analysis is delivered by means of a set of products, with detailed annotations, interpretation and comments on the features or phenomena identified.

- Time-sensitive delivery. The service can be activated to respond within very short timescales, as is necessary in cases of responses to crises such as political or armed conflicts. The service can equally carry out monitoring campaigns over longer periods of time in order to provide an understanding of how phenomena are changing.
- Mission-ready products. The service supports a range of tasks, from operational to strategic planning and decision-making through its extensive offer of products: from First Impression Reports (FIR) for rapid insights, to comprehensive Briefing Notes (BN) covering multiple complex locations.
- Expert knowledge. Identifying the footprint of a wide variety of human activities in an area not only requires access to all available imagery and processing techniques, but also experience and knowledge to accurately spot and identify meaningful indicators of human activity. The Copernicus Service in Support to EU External Action relies on a pool of imagery analysts with different backgrounds, whose specialised knowledge underpins the quality and usability of the final products.

6.1.2.3 Application areas

The service finds application in a number of application areas related to European policies in the external action field. These domains provide the context for specific Use Cases showing how the products can be used at various institutional levels to support strategic decision-making and planning, as well as operations and intervention.

The service is currently operating in a wide range of domains:

- Crisis and Conflict. The CSS-SEA supports EU actors in the planning, intervention and operations phases providing various types of analysis for early warning, monitoring and situational awareness in areas of conflict and crisis.
- Humanitarian Aid. The CSS-SEA supports EU actors and international organisations in providing detailed information on emergencies, impact and a priori assessment, and a foundation for humanitarian support and response planning.
- Rule of Law. The CSS-SEA provides support to EU actors involved in the promotion of the rule of law outside the EU, delivering to users an analysis of human activities and enabling the monitoring of potentially illegal activities in a range of contexts. The service can support early warning, monitoring and situational awareness in unstable areas where maintaining the rule of law is a subject of concern.
- Security of EU Citizens. The CSS-SEA supports the EU and its Member States in providing detailed information for increasing situational awareness and preparing contingency plans.
- Stability and Resilience for Development. The CSS-SEA provides support to EU development actors involved in fostering stability, security and prosperity with neighbouring states. The Copernicus SEA enables efficient mechanisms to plan and monitor the implementation of development interventions linked to reinforcing stability and resilience, thus supporting informed decision-making and policy implementation.
- Transport Safety and Security. The CSS-SEA supports the EU and its Member States in providing detailed information on transportation infrastructures.

Within Service Evolution activities, CSS-SEA developed a strategy to identify and implement solutions aimed at optimising, improving, and enlarging the service. As an example, the identification of new application areas, such as:

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- Cultural Heritage. The CSS-SEA provides support to EU actors involved in monitoring damages to world cultural heritage in areas affected by armed conflicts. The service can assess potential damage to cultural heritage sites over areas of conflict inaccessible to the international community and offers supplemental information when access is possible.
- Environmental Compliance. The CSS-SEA supports EU actors and public authorities in monitoring situations of infringement of EU regulations and assessing the derived impact on the environment and society.

In addition, there is a perspective to further increase the catalogue with additional application areas, such as:

- Climate Security. The CSS-SEA supports EU decision-makers with detailed information on areas where climate change-induced effects exacerbate crises and conflict situations or raise possible security issues.
- Health Security. The CSS-SEA supports EU actors and public authorities in providing actionable geospatial information for rapid situational awareness and adequate response planning.
- International Trade and Economic Diplomacy. The CSS-SEA supports EU actors and international organisations in providing information on supply chains, goods storage and critical infrastructures status to anticipate potential disruptions and anomalous fluctuations directly affecting the EU trade and economic indicators.

Figure 59. Current Service, Evolution and Perspective of CSS-SEA Application Areas.

6.1.2.4 Information content

The products of the CSS-SEA service contain layers of information, which may be extracted from satellite imagery (e.g. a transportation network), carry the results of analysis (e.g. a damage assessment) or be externally acquired (e.g. from open sources).

The information contained in the products can be grouped as follows:

Table 19. Information content.

Icon	Topic - Description
	Transport Transportation networks, comprising either basic or detailed feature classification. Includes specific layers for features of special interest such as roadblocks or bridges.
	Populated Area and Demography Populated areas (urban or rural), optionally including trends in population change.

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Icon	Topic - Description
	Administrative Units Boundaries delineating units of administrative control at local or regional levels.
	Points of Interest Locations of special interest such as healthrelated, diplomatic and administrative buildings and facilities.
	Terrain A range of features and properties associated with terrain, including land use and land cover, topography and hydrography.
	Place Name Standard labelling of places, including with multilingual support.
	Impact Special category denoting phenomena of interest such as damage, detected changes and flooding.
	Critical Infrastructure Critical infrastructures such as power generation facilities and major transportation hubs (harbours or airports) as well as (optionally) their operational status.
	Analysis Special category denoting analytical outputs, including a range of features or phenomena of interest, such as enclosures and security measures, evacuation routes, helicopter landing areas, gathering points, areas under construction and indicators of activity.
	Settlements Areas of temporary human settlement, namely camp dwellings and other buildings, as well as (optionally) changes to these structures.

6.1.2.5 Product types

A number of different products are available in order to satisfy a wide range of user needs. The selection of the appropriate product takes into account constraints such as timely responsiveness and accuracy. The user's request is evaluated with respect to the nature of the analysis required, the deadline and the temporal validity of the information to be provided. Products can be provided in printed or digital format, according to the operational needs of the user.

The Quick Report (QR) is the fastest analytical product available (1 day). It is focused on providing specific answers to a user request within a tight deadline. It gives a quasi near-real-time analysis of satellite imagery, delivering a first look and concise assessment over the specified AOI. The QR may contain: *Satellite imagery; Focused Imagery Intelligence Analysis (included in the product as features and annotations); Critical Actionable Intelligence (in the form of descriptive and interpretative text)*. Based on a reference resolution of < 1m and a coverage area of 50-100 km², the estimated production time is 1 day.

The First Impression Report (FIR) is a very fast reporting and analysis product (1-4 days), providing the results of an analysis of the Area of Interest (AOI) in response to a user's request. The purpose of the product is timely analysis over an AOI to identify ongoing activities, confirm events and information and detect relevant changes on the

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specific LOIs. The FIR is more exhaustive than the QR. It comprises the information extracted from the analysis of satellite imagery (vectors and annotations), supported by a descriptive text based on the results of the imagery analysis and other collateral sources (geospatial and non-geospatial open data sources), making it a timely source of actionable intelligence for decision-makers. The FIR may contain: *Satellite imagery; Vector layers identifying the primary reference and topographic features; Comprehensive and contextual Imagery Intelligence Analysis (included in the product as features and annotations); Actionable Intelligence (in the form of descriptive and interpretative text)*. Based on a reference resolution of < 1m and a coverage area of 50-200 km², the estimated production time is between 1-4 days.

Figure 60. Extract of a First Impression Report (FIR) Product Type.

The Briefing Note (BN) is a relatively fast reporting and analysis product (1-4 weeks). This product is developed using information extracted from the analysis of satellite imagery and other collateral sources (geospatial and non-geospatial open data sources), as well as aggregated findings from previous analysis in the area. The product includes description and analysis of the geographical and political context of one or more AOIs. Feature extraction is required, being complemented by the inclusion of annotations identifying the features of interest, occurred changes, etc. This way, this product provides more insights and a deeper contextual analysis on the evolution of activities, changes to infrastructure, trends or potentially emerging events. The BN may contain: *Satellite imagery; Vector layers identifying the primary reference and topographic features; Comprehensive and contextual imagery intelligence analysis (included in the product as features and annotations); Actionable Intelligence (in the form of complete descriptive and interpretative text); Collateral information (in the form of charts and tables)*. Based on a reference resolution of < 1m and a coverage area of 50-800 km², the estimated production time is between 1-4 weeks.

The Digital Geographic Information (DGI) is a product that provides relevant and up-to-date cartographic and thematic information over a specific AOI. It includes necessary geographic information (e.g. hydrology, transport, land coverage, hypsography, toponyms, etc.), socio-economic factors (populated-related features, location of public services) and other relevant features requested by the user (e.g. embassies, military facilities, religious buildings) to determine the key characteristics of an AOI. One product could contain several detailed maps (a "map series") to represent the area at the reference scale of 1:10.000, depending on the area and the distribution of data. It also includes overview maps to provide an integrated vision of the area. The DGI may contain: *Satellite imagery; Complete vector dataset with an exhaustive representation of existing features; Close-ups of key areas with annotations and indications on relevant features; Collateral information (in the form of pictures, charts and*

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tables). Based on a reference resolution of < 1m and a coverage area of 200-1000 km², the estimated production time is between 1-4 weeks.

Figure 61. Extract of a Digital Geographic Information (DGI) Product Type.

The Mapbook (MB) is a product combining cartographic information with activity analysis. The Mapbook may be complemented with thematic maps (e.g. population, socio-economic factors, terrain analysis, location of public services) based on Geographic Information System (GIS) analysis and open source data. This product type is useful for regional analysis, border monitoring or the design of security plans over a city, facility or event location. It includes basic vector data, mainly focused on the transport network, hydrology and hypsography. The imagery intelligence analysis will focus on the detailed description of relevant places or event located within the AOI. This extensive product combines overview and thematic maps together with detailed reference map series and activity intelligence analysis. The MB may contain: *Descriptive introduction; Satellite imagery; Vector layers identifying the primary reference and topographic features; Close-ups of key areas with annotations and indications on relevant features; Comprehensive and contextual imagery intelligence analysis (included in the product as features and annotations); Actionable Intelligence (in the form of complete descriptive and interpretative text); Collateral information (in the form of pictures, charts and tables)*. Based on a reference resolution of < 1m and a coverage area of 400-1500 km², the estimated production time is between 4-8 weeks.

The Country Map Coverage (CMC) is a single thematic map covering a region or a country. The purpose of the product is to quickly inform about the administrative organisation, the main transportation network and the socio-economic context of the area. The CMC may contain: *Descriptive introduction; Satellite imagery; Fundamental thematic information (e.g. administrative units, population-related features, elevation, major cities, main airports and harbours, etc.); Close-ups of key areas with annotations and indications on relevant features; and Collateral information (in the form of pictures, charts and/or tables)*.

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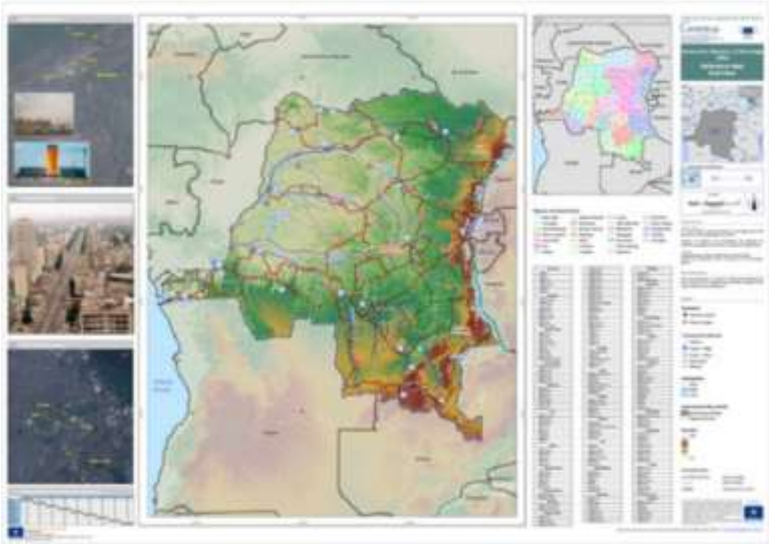

Figure 62. Example of Country Map Coverage (CMC) Product Type.

This Country Map Coverage product provides an overview of a country and its immediate surroundings. Key topographic and infrastructural features such as the road network, airports, elevation and hydrography are depicted, and detail of key administrative boundaries (regions and departments) is supplied.

The table below summarises the SEA products and indicates the formats in which they are available (printable paper documents, geo-referenced maps and layer groups) as well as the associated file types.

Table 20. Summary of CSS-SEA products and formats.

PRODUCTS		FORMATS				
		PRINTABLE		GEO-REFERENCED MAP		LAYER GROUP
		PDF	GEOPDF	TIFF	JP2	GDB
REPORTS	Quick Report	✓				
	First Impression Report	✓			✓	✓
	Briefing Note	✓			✓	✓
CARTOGRAPHIC	Digital Geographic Information - Image Map		✓	✓	✓	✓
	Digital Geographic Information - City Map		✓	✓	✓	✓
	MapBook		✓	✓	✓	✓
	Country Map Coverage		✓	✓	✓	✓

6.1.2.6 Use case examples

The following use cases examples demonstrate how the service supports its set of Authorised Users. It is worth to note that the CSS-SEA is designed to flexibly satisfy the information needs of users. Responses to user requests are individually tailored, taking advantage of a variety of Earth Observation techniques. The Use Cases presented

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in this section have been designed for broad adaptability. CSS-SEA experts assess user needs and translate them into a customised service offer which best suits the challenges presented.

Activity Report. All human activity leaves a trace or a footprint and, in many cases, this footprint may be observed using satellite imagery. Therefore, it is possible to confirm intelligence about a given location or to monitor an area in which activities of interest are suspected of taking place. A multi-purpose solution can be used to audit development projects of the EU abroad, assess whether an illegal activity is taking place in a given location, or identify suspicious locations matching the user request based on patterns of activity.

Figure 63. Example of Activity Report.

Support to Evacuation Plan. EU citizens living abroad enjoy the protection of EU Member States and the EU as a whole. Individuals responsible for the protection and security of these citizens need to be able to anticipate crisis situations and create contingency plans to prepare for them. In this context, CSS-SEA provides a powerful multi-layered solution supporting the development of evacuation plans in urban areas. The solution is built on a base layer comprising an accurate and up-to-date mapping of the road network. Using this base layer as a reference, the optimal routes between key origins (such as diplomatic facilities) and destinations (such as airports) are calculated. Furthermore, an analysis of the distances and projected travel times is carried out and presented in a separate information layer. This provides decision-makers with ample data to design their evacuation plans.

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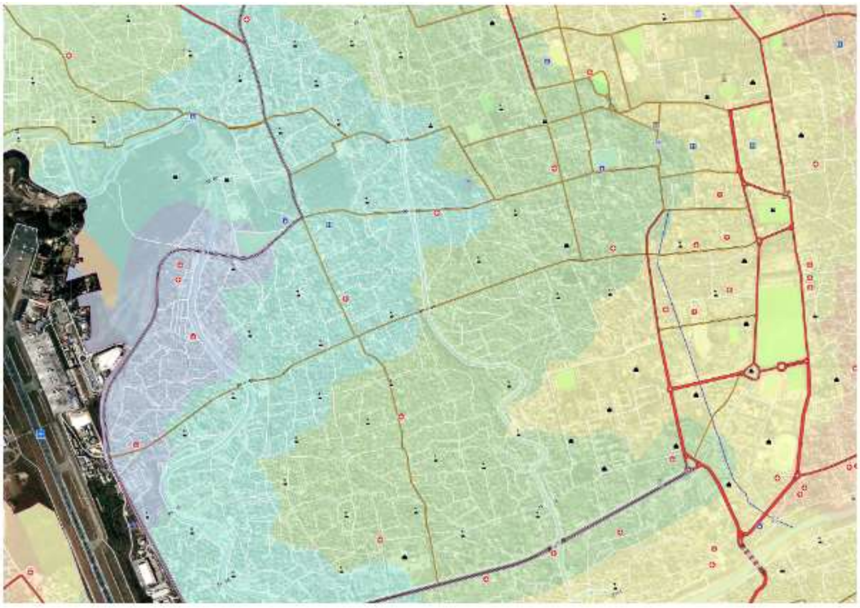

Figure 64. Example of Support to Evacuation Plan.

Road Network Status Assessment. CSDP missions and operations usually require the movement of assets across a territory outside the European Union. This can be particularly hazardous, for example, in countries exposed to heavy seasonal rains, in combination with a large, unpaved road network. These hazards could potentially jeopardise the mandate of the operations, and it is therefore important to be able to plan for effective alternative routing of vehicles. CSS-SEA can help to identify and assess the impact of the rainy season on the transport network, assisting in identifying feasible routes through a flooded area. The analysis of long time series of multispectral imagery allows to measure the level of surface moisture. The impact on the existing road network can then be assessed by comparison with the flooded state.

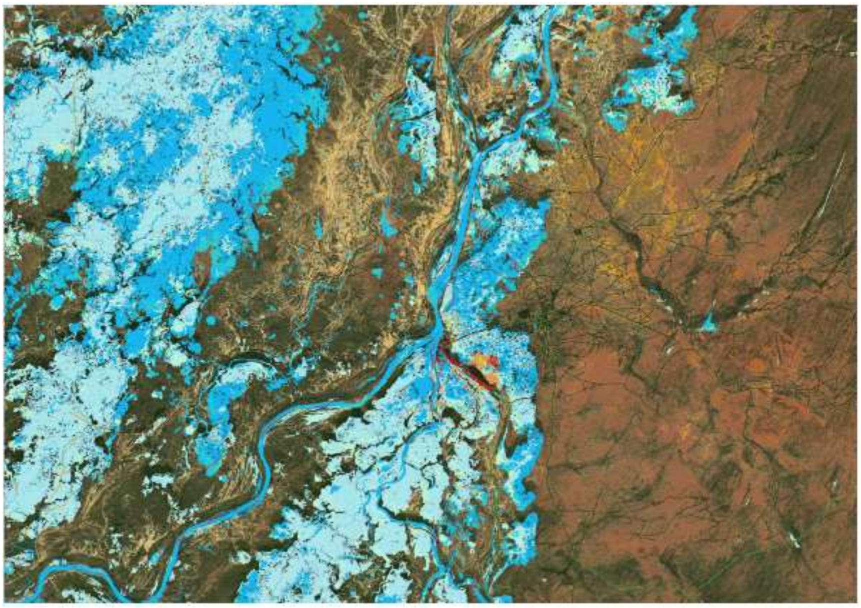

Figure 65. Example of Road Network Status Assessment.

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Camp Analysis. As a major international humanitarian actor, the EU monitors, funds and coordinates responses to refugee (or Internally Displaced Persons – IDP) crises, providing aid and support to many individuals in dire situations at IDP or refugee camps. In this context, EU humanitarian responders face the challenge of managing material, resource and personnel requirements in a constantly evolving situation. A combination of new and previous satellite imagery is used to measure and monitor the changes in the size and distribution of IDP or refugee camps. The main aim is to support accurate assessments of needs, in order to enable a proportional and sufficient humanitarian response, but alternatively, questions such as assessing the security, safety and morphology of the camp, can also be addressed.

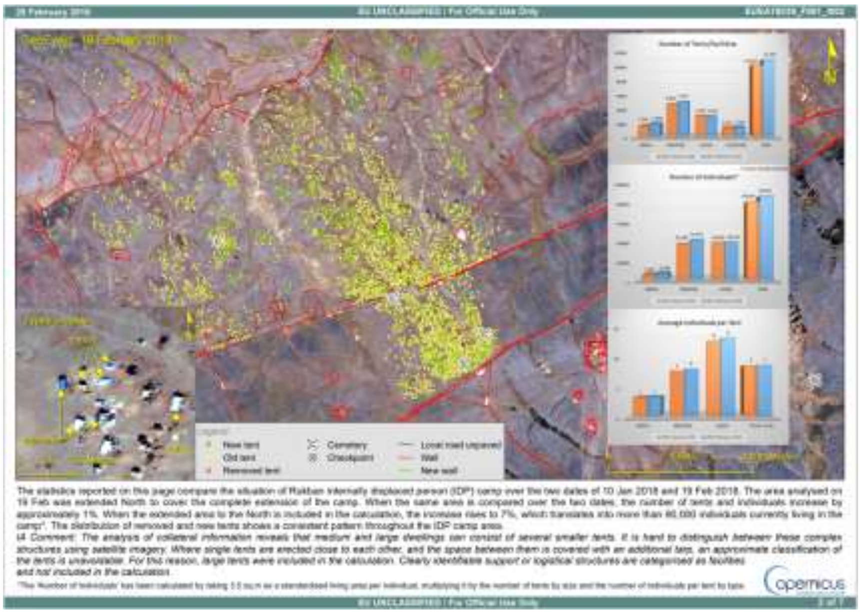

Figure 66. Example of Camp Analysis.

Critical Infrastructure Analysis. Critical infrastructures are assets of which the operational status is critical to the functioning of systems whose failure could seriously disrupt EU interests and impact ongoing EU policy activities. Transportation and industrial infrastructure are typical examples. Using one or more satellite images, analysts create products in which they assess the operational status of the facility. Multiple images are used for longer-term monitoring of activities in and around the infrastructure of interest. The analysis can determine whether an airfield is operational and usable for logistical deployment, the progress in the construction of a dam or whether an oil refinery is performing normally.

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Figure 67. Example of Critical Infrastructure Analysis.

Non-EU Border Map. As a global actor, the EU is party to numerous bilateral agreements between countries. These agreements (as well as other circumstances) may give rise to the need for information on non-EU borders - a need to which this product directly responds. A combination of satellite imagery at different resolutions with other sources of geographic information is used to generate relevant multi-layered products along a selected border or segment. Through this product category, users can obtain an overview of the complete border area, allowing informed decision-making on questions such as at which points it is easier to hide vehicles or goods, or the border is more permeable or harder to patrol. The analysis is based on the location of natural features such as rivers, mountains or foliage, as well as assessments of distance to infrastructure (such as jetties and roads) or settlements.

Figure 68. Example of Non-EU Border Map.

Conflict Damage Assessment. Assessment of damage to human-made structures is possible thanks to the availability of satellite imagery. Satellite imagery acquired immediately after destructive events can be used in

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combination with images taken prior to the event, to assess the extent and type of damage in the area. In the case of damage linked to conflict, specific analytic skills are required in order to identify the type of damage caused by different types of ammunition and weaponry. CSS-SEA provides users with a trustworthy source of information diagnosing the extent and type of damage over an area, including its impact on the operational status of local infrastructure (such as runways).

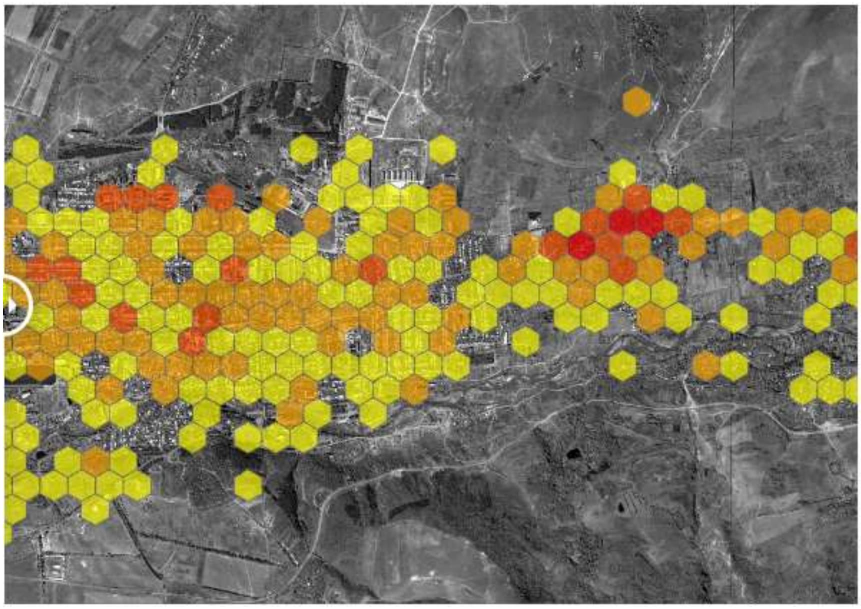

Figure 69. Example of Conflict Damage Assessment.

Crisis Situation Picture. Situational awareness is a primary concern for involved international actors during the development of a crisis. Political decision-makers are in need of a strategic overview of the area in order to support proportionate and effective intervention. The result is formed by combining underlying geographic data with multiple open sources of information. Variables with a geographic dimension, such as the distribution of ethnicities or religions and the locations of the most recent violent episodes are put together in the form of a map or a report to support informed political decision-making.

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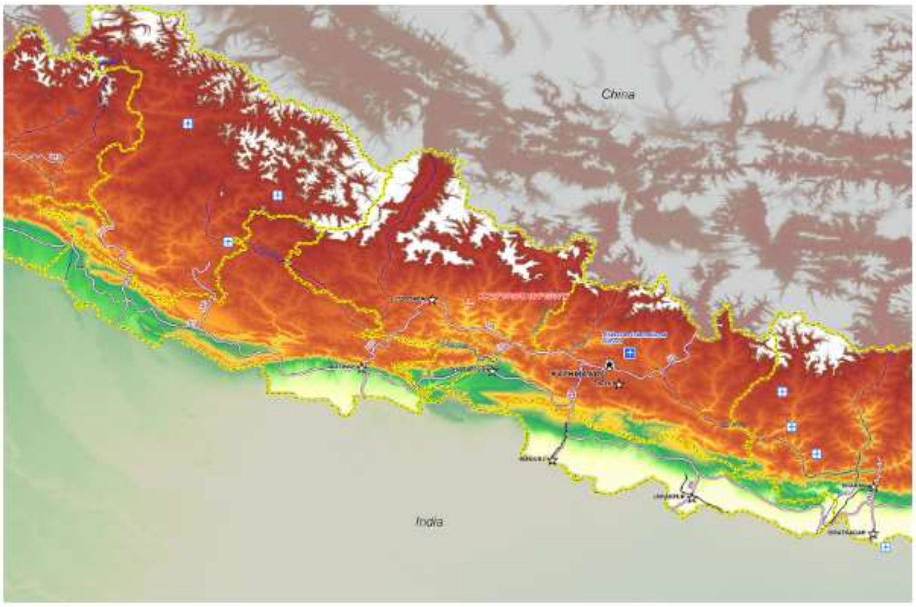

Figure 70. Example of Crisis Situation Picture.

Reference Map. Reference Maps bring the capabilities of Earth Observation data into the world of cartography. In response to a user need for up-to-date information, imagery is acquired over the Area of Interest (AOI) and detailed extraction of information is performed by imagery analysts and cartographic specialists. The result is a map, containing a combination of layers specifically aimed at satisfying the user need. Map layers are extracted from recent imagery and render an up-to-date view on the location, which is essential for educated decision-making. This multi-purpose product category can help the user in a wide variety of scenarios.

Figure 71. Example of Reference Map.

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6.1.3 CSS-SEA past production

6.1.3.1 Activations

Since the service became operational in May 2017, CSS-SEA has assisted its users in 532 activations until February 2023 with the following breakdown: 31.4% for the European External Action Service (EEAS), 17.1% for EU Missions and Operations, 5.8% for the European Commission (EC), 6.6% for International Organizations, and 39.1% for Member States. This distribution highlights the diverse range of authorised users groups that CSS-SEA is supporting and underscores its importance in providing tailored solutions to satisfy a wide range of user needs.

Table 21. Percentage of activations by authorised user group, May 2017-Feb 2023.

Authorised User Group	% Activations
European External Action Service	31.4
EU Missions and Operations	17.1
European Commission	5.8
International Organizations	6.6
Member States	39.1

The CSS-SEA is designed as a responsive and customizable service, where user needs are evaluated by an expert team that recommends solutions based on geoinformation products. Categorising the activations based on user needs provides insights into the diverse range of requirements that CSS-SEA is addressing. See Table 22.

Table 22. Percentage of activations by user need, May 2017-Feb 2023.

User Need	% Activations
Activity Report	22.7
Support to Evacuation Plan	13.5
Road Network Status Assessment	0.8
Camp Analysis	10.0
Critical Infrastructure Analysis	2.6
Non-EU Border Map	1.3
Conflict Damage Assessment	2.3
Reference Map	46.8

To gain a better understanding of the spatial distribution of activations, we have broken down the total number by continental region. The results are as follows: Africa accounts for 58.2%, the Americas for 4.1%, Asia for 26.8%, and Europe for 10.9%. For a more detailed breakdown at the sub-regional level, please refer to Table 23 and Figure 72. These resources provide further insights into the regional distribution of activations.

Table 23 . Percentage of activations by geographic region, May 2017-Feb 2023.

Geographic Regions (sub-regions)	% Activations
Northern Africa	12.0
Eastern Africa	16.9

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Geographic Regions (sub-regions)	% Activations
Middle Africa	12.2
Western Africa	17.1
Caribbean	1.5
Central America	1.5
South America	1.1
Central Asia	0.2
Eastern Asia	0.8
South-eastern Asia	1.5
Southern Asia	4.9
Western Asia	19.4
Eastern Europe	4.9
Southern Europe	6.0

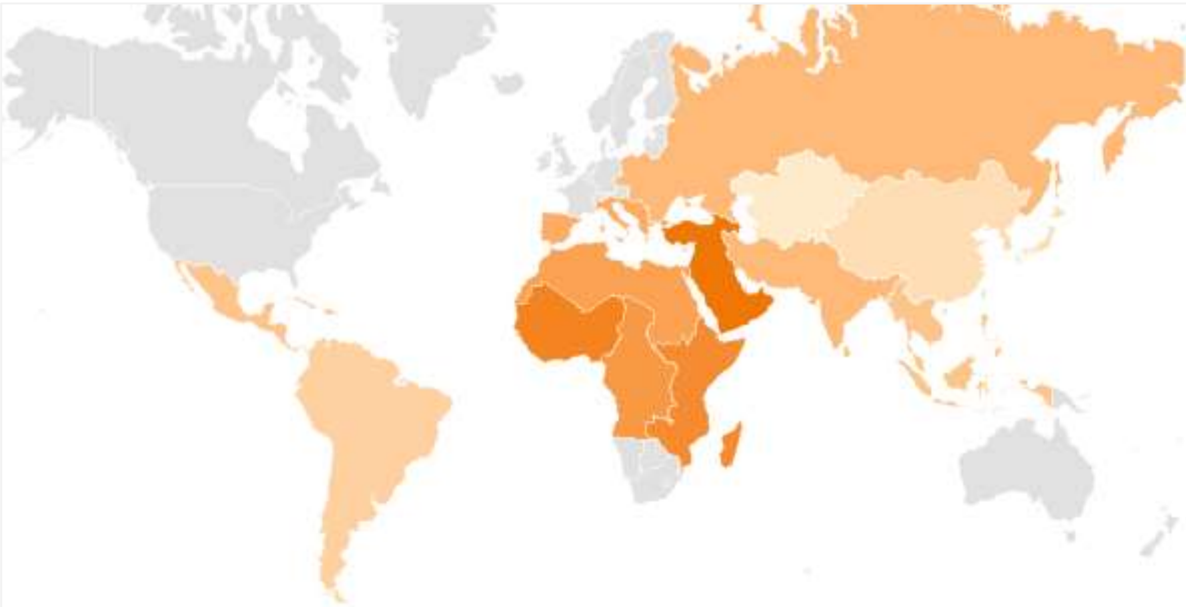

Figure 72. Number of activations aggregated by Geographic Regions (sub-regions), May 2017-Feb 2023.

6.1.3.2 Products delivered

Since the service became operational in May 2017, CSS-SEA has delivered 1,115 products until February 2023 with the following breakdown: 3.8% for Quick Report (QR), 5.3% for First Impression Report (FIR), 1.4 for Briefing Note (BN), 36.1% for Digital Geographic Information (DGI), 2.6% for Mapbook (MB), and 2.8% for a Country Map Coverage (CMC). This means that the ratio of products delivered to activations is 2.1.

Table 24. Percentage of products delivered by type, May 2017-December 2023.

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User Need	% Activations
Quick Report	3.8%
First Impression Report	53.3%
Briefing Note	1.4%
Digital Geographic Information	36.1%
Mapbook	2.6%
Country Map Coverage	2.8%

On one side, it is important to underline that FIRs (e.g. activity reports) are linked to more targeted and faster products, where areas of interest of 100 km2 are the most produced since the beginning of operations. On the other side, DGIs (e.g. reference map, evacuation plans) are linked to products built on a base layer comprising accurate and up-to-date mapping information, that need to be regularly updated.

6.1.3.3 Current Input Data

Regarding satellite data, the CSS-SEA mostly relies by the Copernicus Contributing Missions that play a vital role in Earth observation, providing Very High Resolution 1 (where resolution <=1m) imagery to the service, both new acquisition and archive.

Figure 73. Copernicus Contributing Missions.

To better explain the service from a data usage perspective, the following figures should be considered:

- Over 95% of the products delivered by the service use satellite imagery from the Copernicus Contributing Missions as their baseline data. Skilled imagery analysts then extract detailed insights in response to the user's questions.
- The Very High Resolution 1 (VHR1) dataset, where resolution <=1m, is by far the most frequently used dataset within the Copernicus Contributing Missions.

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- This fact is directly related to the sizes of the areas of interest, as over 90% of the products delivered by the service have an area of interest (AOI) smaller than 1,000 km².
- Over 95% of the orders placed to the Copernicus Contributing Missions are optical.

In addition, the large amount of High Resolution (where 4m <resolution<=30m) freely available data (e.g. Sentinel-1 and Sentinel-2) allows to explore innovative approaches to monitor large areas. The use of high-resolution data can bring new insights (e.g. identification of hotspots) into the development of solutions to enhance early warning and risk assessment capabilities at regional level, complementing the detailed geospatial intelligence analysis that CSS-SEA already provides. Some relevant examples are:

- Wide area activity report. Use of Sentinel-1 SM for the generation of MTC and CCD products to monitor activity in a wide area (e.g. 20,000 km2), with a particular focus on infrastructure changes, movements of people or vehicle convoys, the presence of temporary stopovers or camps, and the most frequently used tracks.
- Crop Monitoring and Damage Assessment. Use of Sentinel-2 multispectral capabilities for the evaluation of the changes in cropland and burnt areas at regional level.

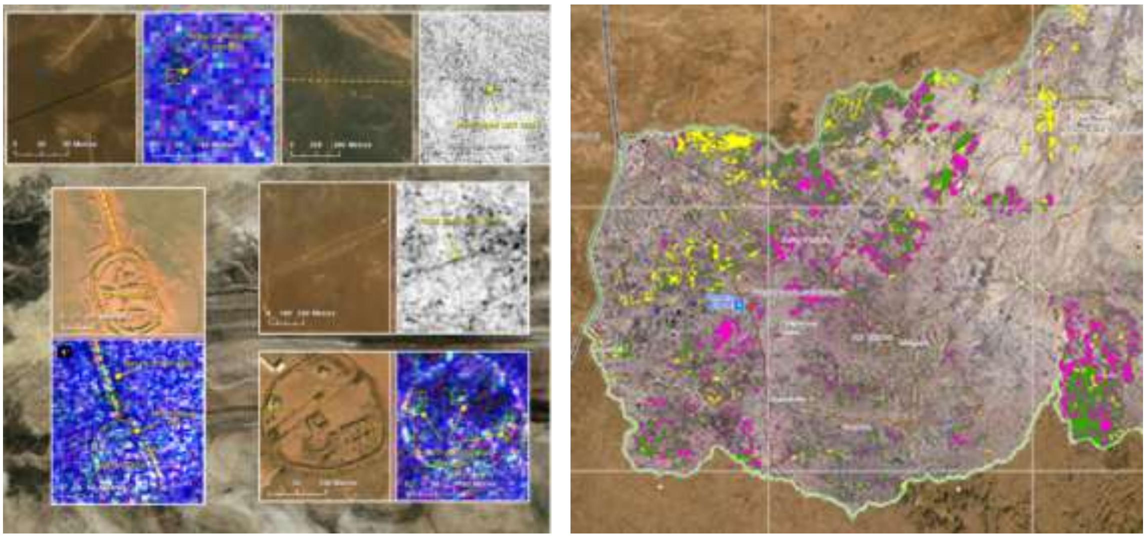

Figure 74. Wide area activity report using Sentinel-1 SM (left) and Crop Monitoring and Damage Assessment using Sentinel-2 (right).

It is important to underline the value for CSS-SEA to be able to access on-demand ad-hoc requirements for security purpose of Sentinel-1 emergency observations, fulfilled by very high-resolution observations (typically less than 5 meters).

Collateral Data is essential to the operations of CSS-SEA. Currently, the service primarily focuses on geographic areas outside of Europe, where local datasets are often unavailable. The most commonly used In Situ Data includes administrative units, critical infrastructures, transportation networks, place names, points of interest (such as reference buildings), populated areas, demography, settlements, and terrain features like hydrography, topography, and land use/land cover.

Currently, crowdsourcing/social media data is not used in a structured way. This information is consulted and used for specific products (i.e. briefing notes) on ad-hoc basis considering that one of the most critical issues of the use of OSINT data is their validation that is a crucial step for the security domain before their introduction in a product/analysis. Therefore, the benefits of crowdsourcing/social media data used within the CSS-SEA are

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minimum, considering that this type of data is used only for very specific products that represent a small percentage of the overall production.

6.2 GAP IDENTIFICATION

6.2.1 CSS-SEA New Application Areas: Climate security

As presented in section 6.1.2.3, there is a perspective to increase the service catalogue with additional application areas, including Climate Security.

The EU's 2022 Strategic Compass states, "Climate change, environmental degradation and natural disasters will also impact our security landscape over the next decades and are proven drivers for instability and conflict around the globe – from the Sahel to the Amazon and the Arctic region".

In this context, CSS-SEA will support EU decision-makers with detailed information on areas where climate change-induced effects exacerbate crises and conflict situations or raise possible security issues.

Some use case examples are:

1. Identify possible conflict zones between communities sharing resources under stress.
2. Assess food security issues as a precursor of conflict in support of policy and humanitarian response.
3. Support for planning and deployment of M&O.
4. Detect uncontrolled natural resource extraction that could cause severe environmental and social damage.
5. Monitor the Arctic to detect activity patterns related to potential security issues induced by uncurbed warming scenarios in the region.

Figure 75. New CSS-SEA application area: Climate Security.

CENTAUR will contribute to enlarge the thematic scope of the service, by reinforcing the new Climate Security application area. CENTAUR will address water & food insecurity by defining and measuring indicators and crisis indexes that are sensitive to increased water/food insecurity and model subsequent risks political instability, conflicts, and displacements risks in developing and fragile countries.

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6.2.2 CSS-SEA On-demand Component

The new service portfolio will transition from a product-oriented approach to a service-oriented approach.

The CSS-SEA will present a portfolio of services customisable by design, offering tailor-made solutions that best address each individual activation. It will offer a reference catalogue of services, available for a variety of applications across its application areas.

The portfolio of CSS-SEA delivers digital value-added products and information. The on-demand component provided by CSS-SEA will be associated to three services:

Geospatial Analysis

The service will be used to confirm any information requested by the user. The resulting information will support decision-making processes. Additionally, it can provide monitoring capabilities based on EO data, allowing to regularly observe areas of interest, to exploit long-term datasets and to detect changes when comparing the ground situation in different moments in time. The service allows to detect changes (if any) and to determine the causes of a particular event.

This multi-purpose service can be used to audit development projects of the EU abroad, assess whether an illegal activity is taking place in a given location, or identify suspicious locations matching the user request, based on patterns of activity.

Mapping for Situational Awareness

The service will provide up-to-date cartographic and thematic information, based on recent satellite imagery data in response to user needs. Teams of experts composed by imagery analysts and cartographic specialists perform detailed extraction of information. The result of this service is a set of products, containing a combination of layers especially aimed at satisfying the user need, essential for making informed decision-making or to draw a common operational picture on different scenarios.

Support to Planning

The service will be conceived to be used in the preparatory phase of a mission or event. It usually provides elaborated products in complex scenarios, with several sets of information and layers, requiring long processing time.

Among others, it might provide assessment of the road network status for deployment or identification of optimal routes to support evacuations. It can be also used to detect possible helicopter landing areas and best location for logistic facilities. The service is based on the use of accurate and up-to-date information as a reference.

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Figure 76. The three services of the CSS-SEA on-demand component.

Each service represents a specific functionality within the CSS-SEA offer, providing customized solutions that best address each individual activation. These three services will provide solutions to issues in the areas of application of SEA, raised at various institutional levels, to support strategic decision-making and planning, as well as operations and intervention.

In this context, CENTAUR can enhance the on-demand component of CSS-SEA service portfolio to better respond to climate security risks and effects. The analysis of social, economic & political indicators together with environmental degradation related indicators, can provide timely information about how inequality, poverty and institutions are or risk to be affected by extreme climatic events. These new layers of information can enrich the current product portfolio (such as IDP Camp or Critical Infrastructure Analysis) by integrating new vulnerability and fragility indicators and forecasts.

6.2.3 CSS-SEA Proactive Component

As stated in the Disaster Risk Reduction in EU external action - Council conclusions (28 November 2022): *"[…] In this context, the Council calls on the Commission, the EEAS and the Member States to: […] Shift from reactive crisis response to more proactive, forward-looking and anticipatory action, financing and risk management and, while respecting humanitarian principles and international humanitarian law (IHL), […]"*.

In this context, to complement the on-demand component that is reactive to the requests of the users, CSS-SEA seeks to develop a proactive component providing anticipatory services at an early phase of the intelligence chain, by anticipating and guiding the user to the location where crisis events are expected to take place. Therefore, it is expected that the service will proactively produce information at regional level in the form of indicators, derived indexes and early alerts that improve situational awareness, foresight, and early response capabilities, with a focus on security challenges in connection with climate change and environmental degradation.

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It is therefore foreseen the development of anticipative and operational capabilities to assess climate change effects on security issues, such as:

Improved understanding of climate security implications

The development of CENTAUR encompasses anticipative and operational capabilities that assess the effects of climate change on security issues. One primary objective is to enhance the understanding of climate security implications by examining the intricate connections between climate change, political instability, and the occurrence of violent events. Through comprehensive analysis and validation of datasets and indicators, CSS-SEA aspires to establish a robust catalogue that encompasses a wide range of information related to water and food insecurity, political instability, and conflict. This baseline resource consolidates datasets and indicators covering various aspects such as biophysical parameters, agriculture monitoring, water resources, meteorological variables, fine-scale population data and exposure to security risks, as well as demographic and socioeconomic stress and vulnerability. By integrating and analysing these datasets and indicators, the proactive component of CENTAUR significantly enhances the understanding of the complex interplay between water and food security and their implications for societal stability.

Risk assessment and early-warning system

CENTAUR envisions the development of a comprehensive risk assessment and early-warning system that plays a vital role in supporting decision-making processes. Through systematic gathering and analysis of information from diverse sources, this system enhances situational awareness and keeps stakeholders well-informed about emerging threats and evolving crisis situations. By providing valuable insights into the security challenges associated with climate change and environmental degradation, CENTAUR enables timely and well-informed decision-making. The cornerstone of this system is an early-warning mechanism specifically designed to promptly alert users when specific triggers and drivers for crises and fragility related to water and food insecurity are detected. Leveraging advanced monitoring techniques, as well as advanced visualization and statistical analysis, this mechanism identifies critical thresholds or patterns that indicate the likelihood of crisis events. By leveraging these tools, the system facilitates the early identification of potential crises, allowing for timely response and effective mitigation efforts.

Foresight capabilities

CENTAUR also recognizes the importance of foresight capabilities in anticipating and preparing for future security challenges related to climate change. The project will focus on developing anticipative and operational capabilities to assess the risk of food crises escalating into broader crises with conflict and fragility dimensions, as well as the dimension of displacement. This will involve utilizing modelling and scenario analysis techniques to gain insights into potential future impacts, vulnerabilities, and risks, including conducting "what if" analyses. By employing foresight approaches, stakeholders will engage in strategic planning, allocate resources effectively, and formulate proactive policies to address climate-related security challenges. The foresight component of CSS-SEA significantly contributes to mid-term resilience-building and adaptation efforts, ensuring that the Copernicus Security Service in Support to EU External Action remains at the forefront of addressing evolving climate-related security challenges.

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Figure 77. CENTAUR CSS-SEA Value Proposition - Food and water insecurity.

In summary, CSS-SEA's proactive component aligns with the Council's call for a shift towards proactive, forward-looking, and anticipatory action. By enhancing understanding, facilitating early-warning capabilities, and fostering foresight, CENTAUR strengthens the CSS-SEA's ability to proactively manage security challenges associated with water and food insecurity.

In order to the develop the proactive component for CSS-SEA in the frame of CENTAUR, the project can take advantage of the participation of several members of the consortium in the Horizon 2020 project that aimed to design and implement an early-warning system named ARCOS (ARCtic Observatory for Copernicus SEA Security Service) providing continuous monitoring of the Arctic Region[205].

6.2.4 CSS-SEA Potential Input Data

Common prerequisites for most of the new capabilities that the CENTAUR system will provide for the CSS-SEA component are:

- To establish continuous monitoring capabilities to enhance the understanding of how climate change and environmental degradation pose challenges to international peace and security.
- To improve temporal and spatial resolution, in particular to those indicators related to biophysical and socioeconomic data that require some improvements in temporal and spatial resolution to predict adverse events more accurately.
- To design and test actionable indicators and indexes automatically extracted by multiple sources of data, in line with the project expected outcomes of improving the integration of non-space data and finding new paradigms in data fusion, processing and automation.
- To cover large areas, considering that the spatial scale of the analysis should be focused at regional level (e.g. admin1, admin2).

On one side, the evolution of the CSS-SEA will have to consider the systematic use of high resolution EO data (e.g. Sentinel data) as a basis for the creation of new services and applications (e.g. indicators and crisis indexes). The availability of high-quality and free-of-charge data from Sentinel will enable the development of innovative and valuable solutions that contribute to a better understanding of the water and food insecurity domain.

[205] ARCOS (Arctic Observatory for Copernicus SEA) (arcos-project.eu)

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Figure 78. Sentinel-2 infographic.

Integrating non-EO data systematically (e.g., climate, socio-economic, crowdsourcing, and social media data) will enable improved detection, identification, and characterization of local crises or anomalies in human activity within areas identified by crisis indexes generated through multi-criteria analysis. These new capabilities complement existing services and provide additional insights for modelling and analysis in the context of water and food insecurity.

Figure 79. ACLED Data: Distribution of Political Violence Events in Sudan, 14 April 2022 - 14 April 2023.

Furthermore, the utilization of products from other Copernicus Services, such as the Climate Change Service, Atmosphere Service, and Land Monitoring Service, can provide valuable support for CSS-SEA activities related to crises triggered by climate change phenomena and extreme events.

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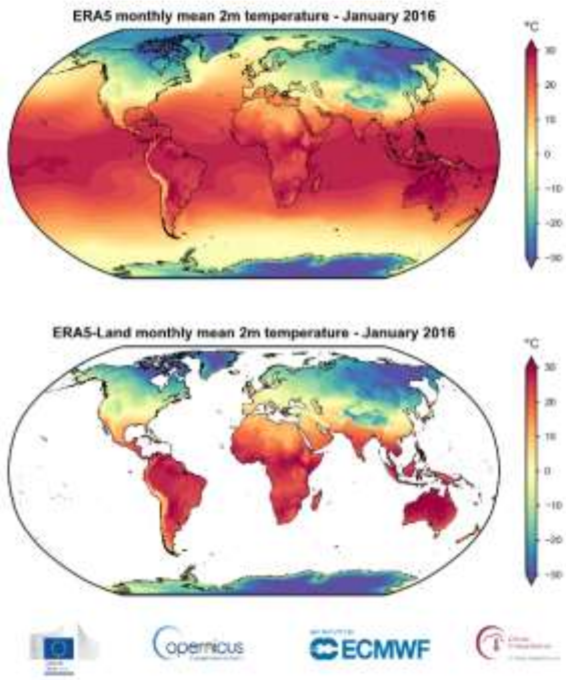

Figure 80. ERA5 climate reanalysis produced by ECMWF.

EO data as well as non-EO data (e.g. such as in situ data, geospatial databases) are the perfect match to improve situational awareness, early response and foresight capabilities. However, the effective management of this type of data presents several technological implications and challenges. The extensive coverage of geographical areas, the demand for real-time responsiveness, and the large volume of data pose significant obstacles. Consequently, it becomes imperative to implement automated data processing chains within the system to overcome these hurdles.

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6.3 GAP PRIORITISATION

To identify and prioritise gaps within the CSS-SEA, the following table has been created.

Figure 81. CSS-SEA gap identification and prioritization.

Topic	Gap Identification	Gap Prioritization
CSS-SEA on-demand component	The CSS-SEA uses up-to-date geospatial data (critical infrastructures, populated areas, demography and settlements) for its operations. They represent important and sensitive information and provide crucial support to strategic decision-making in humanitarian and/or conflict-related crisis situations. It is also important to underline that CSS - SEA mainly focuses on geographic areas outside Europe, where local datasets are not generally available. A huge amount of geospatial data (e.g. EO data, non EO data and data from other Copernicus Services) is used in the generation of situational awareness products of the CSS – SEA. Usually this data is gathered, processed, and integrated in the frame of ad-hoc products covering a limited area. Due to its specificity, most of these processes are very manual and do not worth to be automatized. Therefore, there is a need for a system capable of collecting, preparing and integrating systematically and automatically this type of information into CSS – SEA on-demand products and services, both at the local and regional levels. In this context, CENTAUR offers the potential to enhance the on-demand component of CSS-SEA's service portfolio, enabling a more robust response to climate security risks and their effects. The incorporation of new layers of information (e.g. social, economic & political indicators together with environmental degradation related indicators) can enrich the existing service by integrating new datasets, indexes and composite indicators.	1 – Automatic access, processing, fusion and integration of social, economic & political indicators together with environmental degradation related indicators at regional level (e.g. admin 1, admin 2). 2 – Automatic access, processing, fusion and integration of social, economic & political indicators together with environmental degradation related indicators at local level.
CSS-SEA proactive component	CSS-SEA currently could not rely in a proactive service to produce information in the form of indicators, derived indexes and early alerts that improve situational awareness, foresight, and early response capabilities, with a focus on	1 – Development of a service to proactively monitor security challenges, such as conflict and fragility, associated with water and food insecurity at regional level (e.g. admin 1, admin 2), including the three different

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Topic	Gap Identification	Gap Prioritization
	security implications of climate change and environmental degradation.	capabilities: improved understanding of climate security implications, risk assessment and early warning system, and foresight capabilities (e.g. “what if”). 2 - Development of a service to proactively monitor security challenges, such as migration flows and displacement, associated with water and food insecurity at regional level (e.g. admin 1, admin 2), including the three above-mentioned capabilities. 3 – Development of a social media automated crawling capability for decision support in security challenges associated water and food insecurity.

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7 IDENTIFICATION AND DEFINITION OF DATASETS AND INDICATORS

7.1 DATASETS AND INDICATORS TO SUPPORT EMERGENCY APPLICATIONS

7.1.1 EO data

In this section, an inventory description of the main existing radars and optical sensors used for flood mapping, particularly within the Copernicus EMS context, is provided. Moreover, an overview of the new EO data constellations is given.

7.1.1.1 Presently available and limitations

The Table below shows the main characteristics of radar sensors or constellations using InSAR technology. The most recent Capella (2020) and ICEYE (2019) have the highest spatial resolution with a maximum of 0.5 m, while PAZ (2018), Gaofen-3 (2016), ALOS-2 PALSAR-2 (2014), RADARSAT-2 (2008) and COSMO-SkyMed (2007) reach up to 1 m. To date, the most commonly used active sensors within a flood mapping context are ALOS PALSAR, RADARSAT-1/2, TerraSAR-X, Envisat ASAR, COSMO-SkyMed and Sentinel-1A.

Table 25: Characteristics of the most relevant satellite SAR sensors

Sensors/Constellation	Operational since	Wavelength class	Spatial resolution [m]	Revisit time	InSAR (Yes/No)
Capella constellation	2020	X	0.5-1.7m	Days	Yes
ICEYE constellation	2019	X	0.5-3m	Days	Yes
PAZ	2018	X	1-6m	11 days	Yes
SAOCOM-1A/B	2018	L	10-100m	8 days	Yes
Gaofen-3	2016	C	1-500m	29 days	Yes
ALOS-2 PALSAR-2	2014	L	1-100m	14 days	Yes
Sentinel-1A	2014	C	5-20m	6-12 days	Yes
KOMPSAT-5	2013	X	0.85-20m	28 days	Yes
RISAT	2012-2017	C	9-50m	12 days	Yes
RADARSAT-2	2008	C	1-100m	24 days	Yes
COSMO-SkyMed 1st & 2nd generation	2007	X	1-100m	16 days (per satellite) 1-8 days (constellation)	Yes
TerraSAR-X / TanDEM-X	2007	X	0.25-40m	11 days	Yes
ALOS-1 PALSAR	2006-2011	L	7-100m	46 days	Yes
Envisat ASAR	2002-2012	C	30m/150m	35 days	Yes
RADARSAT-1	1996 -2013	C	10-100m	24 days	Yes
ERS-2	1995-2011	C	25m	35 days	Yes
JERS-1	1992-1998	L	18m	44 days	Yes
ERS-1	1991-2000	C	25m	35 days	Yes

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On the other hand, passive Optical satellite sensors are characterized by a large variety of technical parameters, the most notable of which are the spatial, spectral and temporal resolutions. Both of these are crucial for monitoring the condition of embankments of rivers and forecasting the occurrence of flood events. In particular, the presence of SWIR spectral band which helps a lot in water and flood trace detection.

The following Table presents the characteristics of shows the main optical satellite sensors. The satellites with the highest resolutions are the most recent ones (e.g. EROS C (2022), SuperView NEO (2022), Pleiades Neo (2021), Cartosat-3 (2019) and Blacksky (2018)). Unfortunately, the most recent sensors and those with the highest resolutions do not have SWIR (except WorldView-3). With regards to the most commonly used optical sensors for flood mapping or flooding risk assessment at a global scale, they are AVHRR/3, SeaWiFS, MODIS (Chen and Zhang, 2004), Landsat, AWiFS and Sentinel-2A/2B.

Table 26: Characteristics of the most relevant satellite optical sensors

Sensors/Constellation	Operational since	Panchromatic resolution [m]	Multispectral resolution [m]	Wavebands
ALOS AVNIR-2	2006-2011	-	10m	VNIR
ALOS PRISM	2006-2011	2.5m	-	Pan
ALOS-2 CIRC	2014	-	<200m	TIR
ASTER	1999	-	15 m/60 m/90m	VNIR, SWIR, TIR
AVHRR	1978	-	1100m	R, NIR, MIR, LWIR, TIR
BKA	2012	2.1 m	10.5m	VNIR
Blacksky	2018	0.8–1.3 m	0.8–1.3m	Pan, V
Canopus-B	2012	2.1 m	10.5m	VNIR
Cartosat-1 (IRS-P5)	2005	2.5 m	-	Pan
Cartosat-2	2007	0.8m	-	Pan
Cartosat-3	2019	0.28m	1m	VNIR
CBERS-1/2/2B	1999	2.5 m/20 m	20–260m	Pan, VNIR, SWIR, TIR
Deimos-1	2009	-	22m	VNIR
Deimos-2	2014	0.75m	3m	Pan, VNIR
DMCii	2002	4m	22–32m	Pan, VNIR
DubaiSat-1	2009	2.5m	5m	Pan, VNIR
DubaiSat-2	2014	1 m	4m	Pan, VNIR
EO-1 ALI	2001–2017	10m	30m	Pan, VNIR, SWIR
EO-1 Hyperion	2001–2017	-	30m	VNIR
EROS A	2000–2016	1.9m	-	Pan
EROS B	2006	0.7m	-	Pan
EROS B (nighttime)	2006	1m	-	Pan
EROS C	2022	0.3m	0.6m	Pan, VNIR
Formosat-2 (Rocsat-2)	2004–2016	2m	8m	Pan, VNIR, SWIR
Gaofen-1 (GF-1)	2013	2m	8–16m	VNIR
Gaofen-2 (GF-2)	2014	0.8 m	3.2m	VNIR
Gaofen-4 (GF-4)	2015	50m	400m	VNIR
GeoEye-1	2008	0.4m	1.65m	Pan, VNIR
Ikonos	1999-2015	0.8m	3.6m	Pan, VNIR
IRS 1A/1B	1988	-	36/72m	VNIR
IRS 1C/1D	1995	5.8 m	23–188m	Pan, VNIR, SWIR
Jilin-1	2019	0.75m	3m	Pan, VNIR
Jilin-1	2015	0.72 m	2.88 m	Pan, VNIR

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Sensors/Constellation	Operational since	Panchromatic resolution [m]	Multispectral resolution [m]	Wavebands
Jilin-1 (nighttime & video)	2015	-	0.9m	V
KazEOSat-1	2014	1m	4m	Pan, VNIR
KazEOSat-2	2014	–	6.5m	VNIR
Kompsat-2	2006	1m	4m	Pan, VNIR
Kompsat-3	2012	0.7 m	2.8 m	Pan, VNIR
Kompsat-3A	2015	0.55 m	2.2 m/5.5 m	Pan, VNIR, TIR
Landsat (1,2,3,4,5) MSS	1972–1978	-	80m	VNIR
Landsat (4 and 5) TM	1982–1984	-	30 m/120 m	VNIR, SWIR, TIR
Landsat (7) ETM+	1999	15m	30 m/60m	Pan, VNIR, SWIR, TIR
Landsat 8	2013	15m	30 m/100m	Pan, VNIR, SWIR, TIR, Cirrus
MODIS	1999	-	250 m/500 m/1,000 m	VNIR, SWIR, MIR, LWIF, TIR
OrbView-3	2003-2017	1m	4m	Pan, VNIR
PlanetScope (Doves)	2014	–	3.7m	VNIR
Pleiades	2011	0.5 m	2 m	VNIR
Pleiades-NEO	2021	0.3m	1.2m	Pan, VNIR
Proba CHRIS	2001	-	18 m/36 m	VNIR
Quickbird	2001-2015	0.6m	2.4m	Pan, VNIR
RapidEye	2008	–	5m	VNIR
Resourcesat-1 (IRS-P6)	2003	5.8m	5.8–70m	VNIR, SWIR
Resourcesat-2	2011	5.8 m	5.8–70m	VNIR, SWIR
SeaWiFS	1957	-	1000m/4500m	VNIR
Sentinel-2A	2015	-	10-60m	VNIR, SWIR
SkySat-1, 2 (imagery)	2013	0.5m-0.9m	2m	Pan, VNIR
SkySat-1, 2 (video)	2013	1.1m	-	Pan
SPOT 1, 2, 3, 4	1986–2013	10m	10-20m	Pan, VNIR, SWIR
SPOT 5	2002–2015	2.5/5m	10–20m	Pan, VNIR, SWIR
SPOT 6, 7	2012	1.5m	6m	VNIR
SuperView NEO (1-2)	2022	0.3m	1.2m	Pan, VNIR
SuperView-1 (A-D)	2016	0.5m	2m	VNIR
TeLEOS-1	2015	1m	-	Pan
THEOS	2008	2m	15m	Pan, VNIR
Tianhui-1 (TH-1)	2012	2m pan / 5m tristereo	10m	Imagery: pan, VNIR Stereo: pan only
TripleSat (aka DMC3)	2015	1m	4m	VNIR
UrtheCast Theia	2013	-	1m video	V
Vision-1	2018	0.9m	3.5m	Pan, VNIR
WorldView-1	2007	0.5m	-	Pan
WorldView-2	2009	0.5m	2.0m	Pan, VNIR
WorldView-3	2014	0.3m	3.7m	Pan, VNIR, SWIR
WorldView-4	2017-2019	0.31m	1.23m	VNIR
Ziyuan III-01 (ZY3-1)	2012	2.1 m / 3.5 m stereo	5.8m	Imagery: pan, VNIR Stereo: pan only

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The main advantage of the SAR systems is that they operate in the micro-wave band, long waves that can penetrate through clouds, rain showers, fog, and snow (Anusha & Bharathi, 2019). For this reason, they can obtain information even during extreme events. Nevertheless, the presence of dense vegetation, buildings, shadows and rough terrain prevent the sensors to precisely detect and delineate the floodings. Furthermore, multitemporal and interferometric analyses are not always available and are often affected by errors.

Optical sensors, given the high resolutions that are provided in the latest missions launched in orbit (Sentinel 2, Landsat, Quickbird, Blacksky, etc.) and their excellent revisit time, are becoming increasingly crucial for those events which persist over time. It is possible, in fact, to detect and delineate flooding in an area where the water persists until the cloud coverage diminishes or vanishes. On the other hand, their main limitation is that it is possible to use optical data only in cloudless conditions or in between clouds. For this reason, optical data are widely used to evaluate the state of damage after a flooding event (post event phase), but not necessarily during an event.

Finally, the spatial and temporal resolutions of both active and passive satellite sensors are often not sufficient to monitor an extreme event while in progress. Indeed, the revisit capacity of the existing satellite sensors, even if increasing, still does not reach user expectations in terms of flood monitoring (up to near-real-time) and capturing the flood peak remains challenging.

7.1.1.2 New EO constellations and gaps filling

New satellite missions and spacecraft are scheduled to launch in the near future and could fit to the urban flood modelling requirements:

- IRIDE constellation
- CO3D constellation
- Capella Space
- Iceye
- NISAR
- Umbra
- ALOS-3 and ALOS-4
- Sentinel-1C and Sentinel 1-D

Because of the higher coverage, higher revisit time and higher spatial resolution of these new satellite sensors, it will be possible to overcome all the limitations of the current satellite sensors in the flood mapping context, stated in Section 1.1. In particular, the higher time and spatial resolutions will enable the monitoring of extreme flood events in progress.

Furthermore, the higher revisit time of these satellite sensors also may improve the detection of flash floods allowing to capture the peaks of the extreme events.

IRIDE constellation

The current composition of the whole IRIDE constellation for the first batch is provided below with preliminary information on launch dates:

- SAR mission A on PLATiNO platform (5 satellites) – Launch: December 2024
- SAR mission B on NIMBUS platform (6 satellites) – Launch: March 2025
- SAR mission C on ION platform (1 satellite) – Launch: December 2024
- HYPERSPECTRAL on PLATiNO platform (2 satellites) – Launch: July 2025

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- High Resolution Multispectral #1 on EAGLET-2 platform (12 satellites) – Launch: December 2024
- High Resolution Multispectral #2 on HAWK platform (10 satellites) – Launch: December 2024

Specifically, PLATiNO-1, PLATiNO-2, PLATiNO-3 and PLATiNO-4 will be launched in 2024 and 2025.

The PLATiNO-1 mission (2024), equipped with an innovative X-band synthetic aperture radar (SAR), will be able to operate in both passive and active modes, ensuring performance never before achieved in the mini SAR field. The spatial resolution will be 3 m.

The PLATiNO-2 mission (2024), equipped with a thermal infrared (TIR) optical sensor, will be operational within and in support of land monitoring and emergency management. The images produced will be used for tests in monitoring water, pollutants, crops and vegetation, energy consumption in urban areas, and in fire monitoring. PLATiNO-2 will be one of the first national missions to observe the Earth in the thermal channel from an orbit of less than 400 km, significantly improving the resolution of the images collected. It will have a spectral range of 8-12 micron, a spatial resolution of 40 m and a daily coverage of 170.000 km2.

The PLATiNO-3 mission (2024) will be a high resolution mission, with satellite sensors with a spectral range of 470-840 nm. The PLATiNO-4 mission (2025) will be a hyperspectral mission with satellite sensors with a spectral range of 400-1010 nm (VNIR) and 920-2025 nm (SWIR) and spectral resolution of 10 nm.

With regard to the 12 High Resolution Multispectral satellites which will be launched in 2024, they will have a revisit time of 30 minutes which will permit them to monitor the persistence of flood events and allow them to capture the peaks of the extreme events.

CO3D constellation

CO3D (Constellation 3D) is a constellation of a new generation of low-cost optical satellites, planned by the French Space Agency (CNES) and scheduled to be launched by 2024. The satellites will be produced and operated by Airbus Defence and Space (ADS). CO3D constellation will consist of four identical optical VHR satellites aiming at generating a DSM (Digital Surface Model) of the world, between S60° and N70°, with a 1 m spatial grid. In order to fulfil this production, each of these satellites will provide 0.5 m colour images in four bands (Blue, Green, Red and NIR) and with a field of view of 7 km.

The mission is expected to be concluded by 2026, with the realization of a DSM with an accuracy of 1 m and a 90% of surface covered (because of the persistent cloudiness of some regions).

Figure 82: Simulated CO3D DSM over Nice (downtown), France, based on Pleiades-HR data © CNES 2020

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Capella Space

The future Capella Space mission will introduce a third generation of SAR satellites, named Acadia, which will improve and expand the existing Capella constellation, with the aim of providing very high resolution images. New Capella Acadia satellites include a radar bandwidth of 700 MHz, a slant range resolution of 0.21 m and a ground spatial resolution of 0.31 m. The first satellites are scheduled to be launched in early 2023.

Iceye

The new Iceye mission, in partnership with BAESystems, will provide four advanced SAR satellites, in order to expand the existing BAESystems cluster, known as Azalea. These new satellites will produce very high resolution images in any weather condition, with persistent monitoring in order to quickly and accurately detect any physical change. The launch is scheduled by 2024.

NISAR

The NASA-ISRO SAR (NISAR) Mission will observe Earth’s land and ice-covered surfaces globally with 12-day regularity on ascending and descending passes, sampling Earth on average every 6 days for a baseline 3-year mission. It will operate at S- and L- bands, and map at a 3 to 10m resolution depending on the acquisition mode. The NISAR system comprises a dual frequency, fully polarimetric radar, with an imaging swath greater than 240 km. The launch is scheduled for 2024, and all NISAR science data, L-band and S-band, will be freely available and open to the public. The NISAR satellite weighs 2800kg.

Umbra

UMBRA is a new micro SAR generation, from a commercial company launching a constellation of SARs for land surface applications. The UMBRA-SAR sensor is imaging in X-Band with 1200 MHz bandwidth which can image down to 25 cm resolution. For a 12 satellite constellation, polar latitudes 15 min repeat, mid-latitudes 30 min repeat and tropical latitudes 45 min repeat. The micro satellites weigh 70kg.

Table 27: Characteristics of the most relevant satellite SAR sensors.

Provider	Iceye	Capella Space	CO3D (Airbus DS)	Umbra	NISAR
Webpage	https://www.iceye.com/	https://www.capellaspace.com/	https://co3d.cnes.fr/fr/	https://umbra.space/	https://nisar.jpl.nasa.gov/
Nb	18 satellites (when fully operational)	18 satellites (when fully operational)	18 satellites (when fully operational)	18 satellites (when fully operational)	18 satellites (when fully operational)
Current number	Current number	Current number	Current number	Current number	Current number
16	16	16	16	16	16
8	8	8	8	8	8
Resolution	Resolution	Resolution	Resolution	Resolution	Resolution
25 cm NEW	25 cm NEW	25 cm NEW	25 cm NEW	25 cm NEW	25 cm NEW
Frequency	Frequency	Frequency	Frequency	Frequency	Frequency
Every 3 hours (when fully operational)	Every 3 hours (when fully operational)	Every 3 hours (when fully operational)	Every 3 hours (when fully operational)	Every 3 hours (when fully operational)	Every 3 hours (when fully operational)

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Provider	Iceye	Capella Space	CO3D (Airbus DS)	Umbra	NISAR
Every hour (when fully operational)	Every hour (when fully operational)	Every hour (when fully operational)	Every hour (when fully operational)	Every hour (when fully operational)	Every hour (when fully operational)
Ordering procedure	Send an email with type of image + acquisition date + AoI.kml to customer@ICEYE.com (copie yvette.pearson@iceye.fi) Customer Success team available 9am-5pm CET Polish workdays. 24/7 call support.	Capella's automated scheduling system is done through imaging requests in an on-demand self-serve (Capella Console or Capella API) -> STAC	Not available	Web interface	No order
Delivery delay	Standard requests : - Order treated within 24h - Image acquired within 24h after approval - Delivery within 24h after acquisition Urgent requests : few hours (priority) 24/7 service end 2020	Order-tasking : 15 mn - Delivery within 24h after acquisition	Launch 2024 + 2 years of process before marketing	Not available	30-45 minutes of data downlink per orbit at 3.5 Gbit/s data rate through polar ground stations. 1 Gbit/s direct downlink to India over Indian ground stations
Delivery mode	sFTP	download from Capella online platform	/	Not available	
Catalogue	Not available	AWS	Not available	Maxar	
Prices	- Stripmap (3 m) 30*50 km : 800€. - Spotlight (1 m) 5*5 km : 1400€. - Xxxx (25 cm) X*X km : XXXX€.		Not available	-1m res, 4x4km: 500$ -0.5m res, 4x4km: 750$ -0.25m res, 4x4km: 3000$	Free

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Provider	Iceye	Capella Space	CO3D (Airbus DS)	Umbra	NISAR
	Price depends on the quantity. No emergency prices (not before end 2020).				
Licensing				Data is provided with a CC by 4.0 License	Open
Cancellation	Before scenario confirmation	Cancellation > 72 hours before first acquisition of order = cancellation available at no charge. Cancellation 12 - 72 hours before first acquisition of order = cancellation available at 25% charge of full order value < 12 hours before first acquisition of order = no cancellation allowed with 100% charge of full order value	Not available		

ALOS-3 and ALOS-4

On January 17, 2023, The European Commission announced a New Copernicus Cooperation Arrangement between the Commission and Japan to collaborate in the Earth Observation domain, facilitating reciprocal data sharing of EO data between the EU and Japan. In the light of this agreement, while the Japan will access the Copernicus Sentinel data through Tellus Data Hub, while The Copernicus ecosystem in Europe will get access to data from Japan's non-commercial Earth Observation satellites. Access to in-situ data from Japan will enhance the quality and precision of Copernicus services for the benefit of all users.

Based on this new Copernicus Cooperation Arrangement with Japan, disaster risk reduction and food security are among the common areas of interest; therefore, a review of the future non-commercial satellites will be presented in this section with a focus on ALOS-3 and ALOS-4 as being optical and radar sensors respectively.

Table 28: Review of ALOS-3 and ALOS-4 future non-commercial satellites: optical and radar respectively

	ALOS-3	ALOS-4
Webpage	https://www.eorc.jaxa.jp/ALOS/en/alos-3/a3_about_e.htm	https://www.eorc.jaxa.jp/ALOS/en/alos-4/a4_about_e.htm
Nb	1 satellite	1 satellite
Mission instrument	Wide-swath and high-resolution optical imager	PALSAR-3 (Phased Array type L-band Synthetic Aperture Radar-3)

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	ALOS-3	ALOS-4
		SPAISE3 (SPace based AIS Experiment 3)
Bands	Panchromatic: 520-760nm Multi-band: Band 1: 400-450nm (Coastal) Band 2: 450-500nm (Blue) Band 3: 520-600nm (Green) Band 4: 610-690nm (Red) Band 5: 690-740nm (Red Edge) Band 6: 760-890nm (NIR)	L Band (HH, VV, HV, VH)
Spatial Resolution	0.8 m Panchromatic 3.2 m Multispectral	3x1 m Spotlight 3-6-10 m Stripmap 25m ScanSAR
Extent	70 km Stripmap, 200x100 km Wide-ranging area mode	35 km Spotlight 100-200 km Stripmap 700 km ScanSAR
Revisit Frequency	35 days (Sub-cycle 3 days)	14 days
InSAR repeat-track	35 days (Sub-cycle 3 days)	14 days
Launch timeline	7th March 2023 with a launch failure Next attempt yet unannounced	March 2023
Design life	7 years	7 years

ALOS-3 (Advanced Land Observing Satellite-3) is a follow-on mission from the ALOS/Daichi program developed by the Japan Aerospace Exploration Agency (JAXA). Unfortunately, the launch scheduled on 7th March 2023 failed, and the satellite was unable to enter the Earth's orbit as planned. The H3 rocket was then destroyed with its payload ALOS-3. The JAXA is still investigating on the failure. ALOS-3 should complement observations of its predecessor, ALOS, providing supporting imagery for applications in environmental and disaster monitoring. ALOS-3 has an optical sensor which improves the ground resolution by about three times that of ALOS (2.5 to 0.8 m at nadir) remaining the wide-swath (70 km at nadir). ALOS-3 has also improved the frequency of observations by shortening the revisit to 35 days from 46 days of ALOS.

Sentinel-1C and Sentinel-1D as part of the Copernicus Sentinel-1 mission

Sentinel-1C and Sentinel-1D are parts of the Copernicus Sentinel-1 mission, the European Radar Observatory for the Copernicus joint initiative of the European Commission (EC) and the European Space Agency (ESA).

The Sentinel-1 mission is able to provide data for land and disaster monitoring, using radar technology.

Sentinel-1C and Sentinel-1D are to be launched in near future to provide the Copernicus Programme with operational continuity concerning radar data, all-weather and day and night.

Sentinel-1C will replace Sentinel-1B which is unavailable since December 2021 due to a technical anomaly related to the instrument electronics power supply provided by the satellite platform. In August 2022, ESA declared it irreparable and the end of mission life. Sentinel1-C is currently undergoing the last stage of its test campaign and the current plans target a launch in the second quarter of 2023. In April 2022 the European Space Agency (ESA) and Arianespace have signed a launch contract for Sentinel-1C on rocket Vega-C from the Guiana Space Center.

In addition, the functional Sentinel-1 satellite, Sentinel-1A, has already exceeded its design life of seven years (launched in 2014) with consumables for 12 years. Therefore, a new spacecraft Sentinel 1-D (currently under development) is expected to replace it by 2024.

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Another mission developed by JAXA is the Advanced Land Observing Satellite-4 (ALOS-4) which will replace ALOS-2. ALOS-4 uses L-band radar technology, and its aim is to observe and monitor natural disasters, forests, sea-ice and infrastructure displacement. Planned for launch by March 2023, ALOS-4 has an improved sensor (PALSAR-3), thanks to which it will achieve both higher resolution and a broader observation swath, compared to the previous ALOS-2

Potential use and suitability of new EO data for rapid mapping time constraints

Considering the limitations related to satellite sensors (for example, SAR cannot identify flooding in urban areas and optical sensors cannot be exploited during the night and in the presence of cloudy weather) and those related to spatial and temporal resolutions within the EMS Rapid Mapping Service, in many cases it is not possible to reconstruct accurate flood maps.

Thanks to the new sensors that will be present in orbit, equipped with much better spatial and temporal resolutions than the current one, it will be possible to have flooding maps able to better describe an extreme flood event. Better spatial resolution means better extreme flood event delineation and occurred damage assessments. Better temporal resolution, instead, allows covering a flood event of interest with more satellite acquisitions, allowing for a greater possibility of capturing the peak of the flood event and having more scenes showing the temporal evolution of the flooding.

The flooding map reconstruction in an urban area through modelling, can take place through the use of hydraulic and geomorphological models. These two models base their inputs and calibration on the use of EO data. Therefore, having these increasingly accurate and punctual data available, would allow flooding maps to be more precise in terms of flooding depth, extent and hazard mapping.

The InSAR technique is also strongly influenced by these improvements, as this technique relies directly on the data availability. To measure that urban flood phenomenon, it requires a pair of SAR pre-event and another during the event, thus 3 products are needed. The interferometric inSAR processing requires similar acquisition conditions for those 3 products.

InSAR urban flood detection is based on two physical facts while a flood is occurring on an urban area. Firstly, the double bounce of the backscattered signal is amplified by the water surface. This is due to the specular reflection property of the water that increase the double bounce effect compared to a standard road. Secondly, the interferometric coherence of a pre-event/crisis pair image is low. The interferometric coherence is the normalized cross-correlation of the signal between 2 images, it is usually high in urban areas as it's a stable scattered and the SNR (Signal-to-Noise Ratio) is high. But when the first image is normal and the second is flooded, the coherence drops off.

7.1.2 Topographic data

Elevation data can be used to derive water extent, depth and accumulation, in particular in an urban flood mapping context, but their resolution is a crucial parameter in the quality of the result.

7.1.2.1 Presently available and limitations

The following table provides an overview of the elevation data currently used during operations in the framework of the Copernicus Emergency Management Services.

Table 29: Topographic data used within Copernicus EMS

Coverage	Product Name	Fee-based	Used in EMS	Type	Producer	Resolution
Worldwide	COP-DEM_GLO-30	no	yes	DSM	ESA	30 m
Worldwide	FABDEM_2021	no	Yes (RRM only)	DTM	Fathom	30 m
Worldwide	SRTM 30	no	yes	DSM	NASA	30 m

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Coverage	Product Name	Fee-based	Used in EMS	Type	Producer	Resolution
Worldwide	SRTM 90	no	yes	DSM	NASA	90 m
Europe	COP-DEM_EEA-10-DGED	no	yes	DSM	ESA	10 m

SRTM DEM

The SRTM DEM is the oldest global elevation datasets used, and is based on the data collected during the Shuttle Radar Topography Mission (11 to 22 of February 2000) by the spaceborne radar sensors carried by the Endeavour space shuttle. The data was collected using single-pass interferometry. The project was led by the National Aeronautics and Space Administration (NASA) and the National Geospatial Intelligence Agency (NGA), with the support of the German and Italian space agencies, and resulted in a near-global digital elevation model covering latitudes below 60°.

Several versions were released, the current V3.0 (SRTM Plus) is available since 2015 and used the ASTER GDEM2 and USGS GMTED2010 elevation models to fill the voids in the dataset. The dataset is currently freely distributed since 2003-2004 for the 90m product and 2015 for the 30m product.

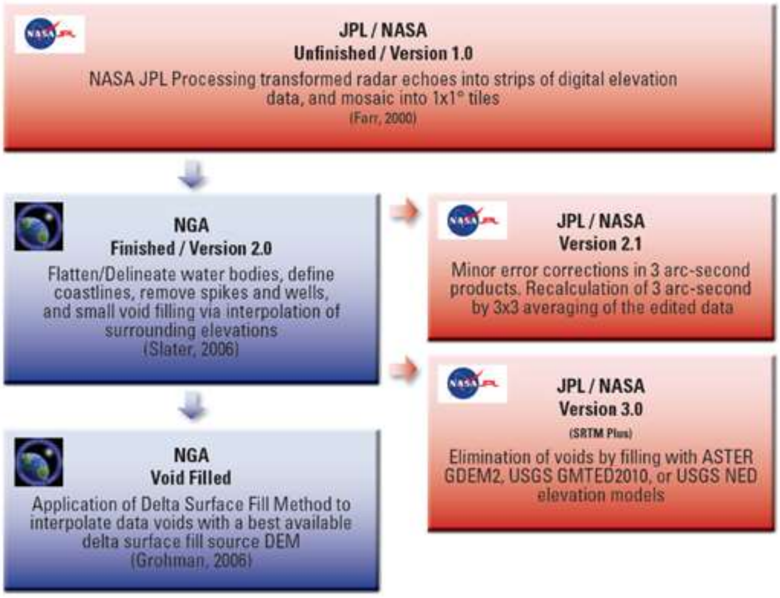

Figure 83: Genealogy of SRTM products, extracted from The Shuttle Radar topography Mission (SRTM) Collection User Guide, 2015.

The SRTM product targeted a vertical absolute error of maximum 16m, equivalent to a 9.73m RMSE, at 90% confidence level (Farr, 2007). (Rodriguez, 2006) estimated its accuracy as follows:

- Horizontal absolute geolocation error: 7.2 to 12.6m
- Absolute vertical error: 5.6 to 9.0m
- Relative vertical error: 4.7 to 9.8m

SRTM DEM has also shown increased bias in increasing slopes, as other global DEMs, and a positive bias in forested areas due to the multiple scattering reflected by the leaf cover (Uuemaa, 2020).

The SRTM datasets have been extensively used for the last 20 years to support geospatial analysis, including for flood modelling purposes. It can be classified as a Digital Surface Model (DSM), and as such should be used cautiously especially in urban and forested areas where the bare-earth surface can be significantly different. The

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age and geographical coverage of the SRTM also limit its use, especially in fast-evolving environments such as urban areas.

COP_DEM products

The Copernicus DEM is an elevation product funded by ESA and freely available since 2019. The GLO-30 and GLO-90 (respectively 30m and 90m horizontal resolution) are global instances of the product, while the EEA-10 product (10m horizontal resolution) covers only the EEA member states and cooperating countries (EEA39[206])

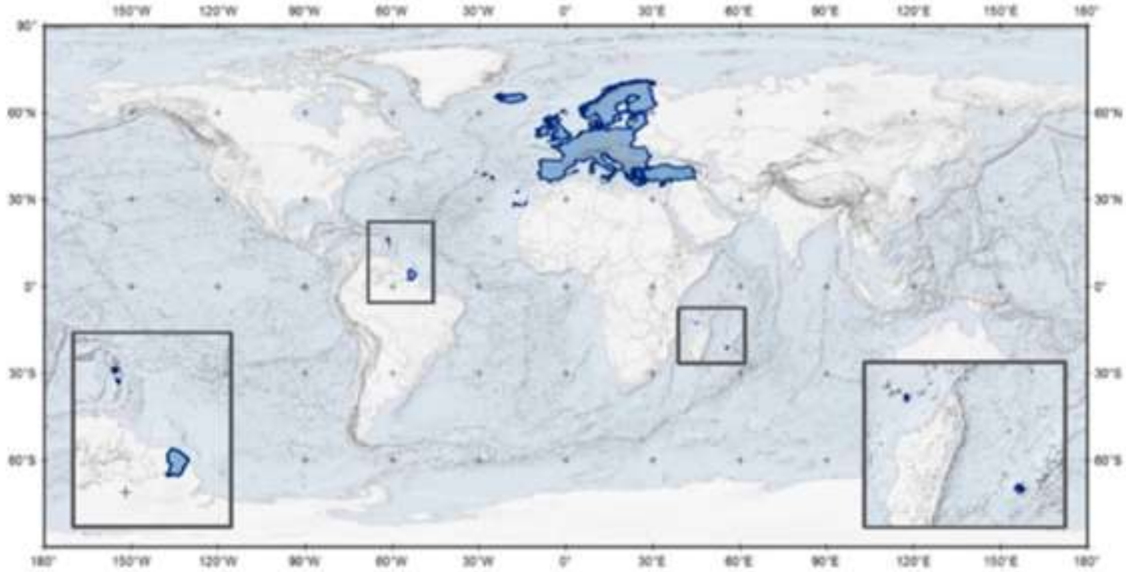

Figure 84: Land surface coverage within Copernicus DEM – EEA-10 (Source: ESA)

Copernicus DEM project was led by Airbus and DLR, and the product was derived from a commercial dataset named WorldDEMTM (10m horizontal resolution) that is based on the X-band interferometric radar data acquired by TanDEM-X and TerraSAR-X operated in very close orbit and in bistatic mode between 2011 and 2015 (TanDEM-X DEM).

[206] EEA-10 covers 39 European countries including all islands of those countries plus French Overseas Departments (excluding French Overseas Territories). Currently, there are 38 countries as part of the EEA network, with 32 member countries and 6 cooperating countries. The UK territory is covered by the EEA-10 product.

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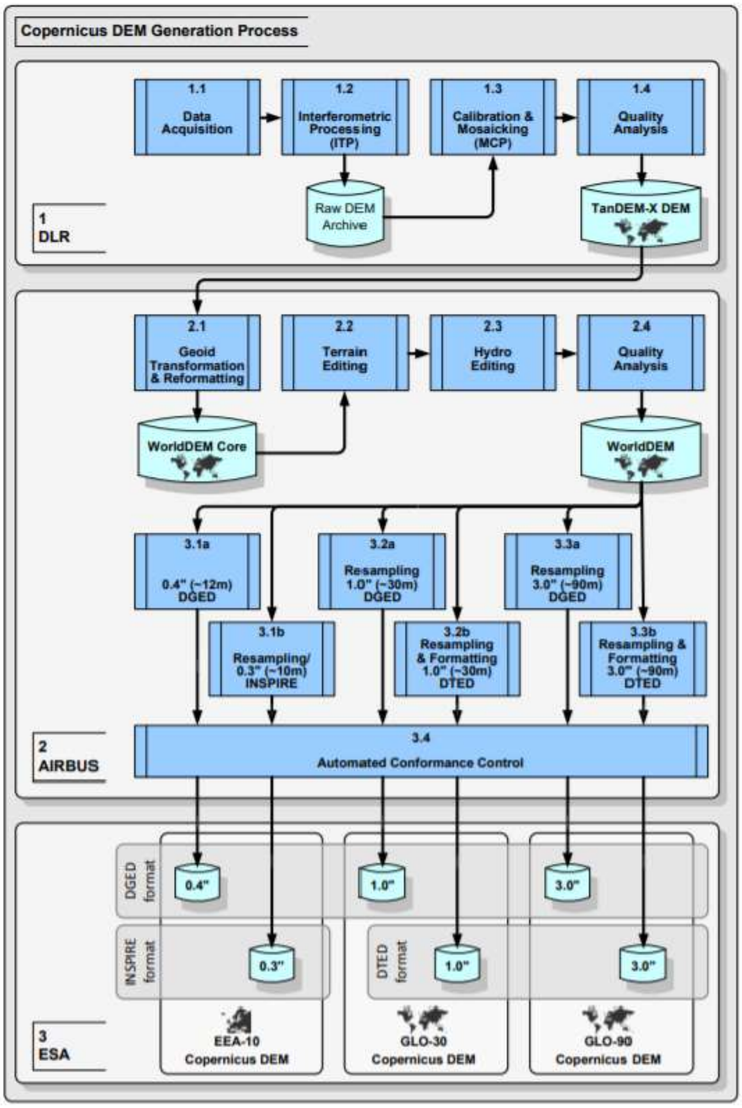

Figure 85: Copernicus DEMs Generation process chart from EDAP Copernicus DEMs Quality Assessment Summary, 2021

Copernicus DEM instances are digital surface models, and benefit from the editing process of the WorldDEMTM, including terrain implausible features removal and height editing of water bodies. The base elevation data was enhanced locally using other elevation datasets (ASTER GDEM, SRTM90, SRTM30, GMTED2010, SRTM30plus, TerraSAR-X Radargrammetric DEM, AW3D30, NorwayDEM, DSM05 Spain).

The Copernicus DEMs product Handbook (2021) describes the accuracy of the products:

- Absolute vertical accuracy: < 4m
- Relative vertical accuracy: < 2m for slopes ≤20%, < 4m for other slopes
- Absolute horizontal accuracy: < 6m

Validation studies led by the Earthnet Data Assessment Pilot, or EDAP, (2021) estimated a mean height error of 0.033m for GLO-30, with a RMSE of 0.628m, and 0.270m for EEA-10 with a RMSE of 1.415m. The study also concludes from comparison to other sources that the Copernicus DEMs are both above terrain and below surface, hence, neither a real DTM or DSM.

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FABDEM product

The Forest And Buildings removed DEM (FABDEM) was first published in 2021, and is based on the Copernicus GLO-30 DEM. Using two random forest algorithms, Hawker et al (2022) proposed to correct the GLO-30 surfaces bias in urban and forested areas, which are key areas for flood modelling. Additional predictors used for the processing include the Global Forest Height 2019, GEDI LIDAR data, tree fraction cover 2015 from Copernicus Land service, building footprints from World Settlement Footprint, population from WorldPop, or night-time lights.

The calibration sample is extracted from LIDAR data in 12 different countries, while the validation sample also includes ICESat-2 ground terrain estimates. The cell minimum elevation value of both corrected DEMs were selected to create the FABDEM product that also underwent additional steps of smoothing and pits removal.

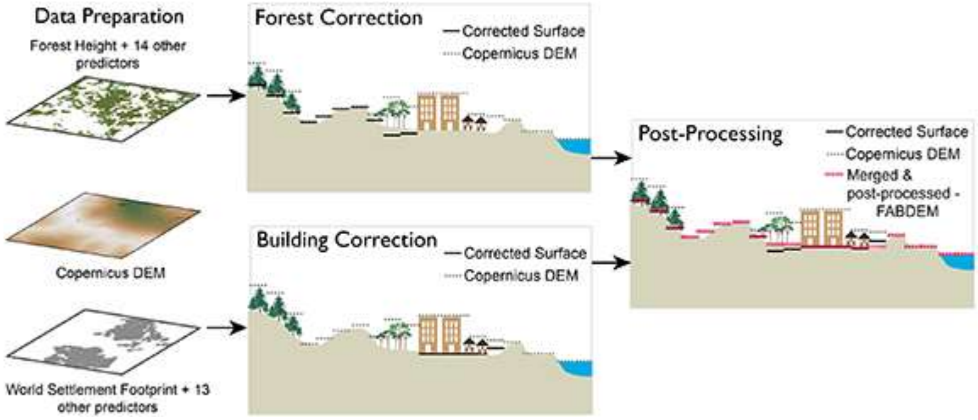

Figure 86: Schematic Workflow of FABDEM from Hawker et al (2022)

The current version of the FABDEM product (v1.2) is available since early 2023. The authors found the FABDEM product to be especially improved in densely populated urban areas larger than 5000 km² (median bias of 0.19m versus 1.90m for GLO-30), and forested areas with canopy coverage higher than 50% (median error of 0.45m versus 2.95m for GLO-30). Another validation study conducted with Ground Control Points (GCPs) in the Philippines[207] finds slightly higher accuracy values (1.44m mean vertical error versus -0.11m to 0.20m).

The elevation datasets used in CEMS Rapid Mapping and Risk and Recovery Mapping share many similarities and limitations. The first limit is inherited from the data used to produce the DEMs, that is both for the SRTM DEMs and the Copernicus DEMs acquired using SAR satellites in interferometric mode. SAR imagery presents the advantage of not being impacted by cloud cover and to use differences in the phase of the signal when acquired in interferometric mode to derive elevation information, thus allowing to map the surface of the Earth efficiently. However, the interferometric stereo restitution is based on the interaction of the SAR signal and the ground cover, which is different depending on the frequency of the signal emitted by the sensor.

SAR signal penetration into ground and objects increases as the signal wavelength increases. As shown by Figure 60 X-band signal is reflected in forested areas by the top of the canopy, whereas the C-band signals penetrates further into the vegetation. Similarly, the bare surface reflection is higher for the X-band signal than for the C-band signal. In terms of elevation datasets, this means that both the SRTM DEMs (C-band & X-band) and the Copernicus DEMs (X-band) suffer from this bias, and represent a surface that is not strictly a DSM nor a DTM.

[207] Santillan, J. R. "Vertical Accuracy Evaluation of the Forest and Buildings Removed Copernicus dem (fabdem) Over the Philippines." The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 48 (2023): 311-318.

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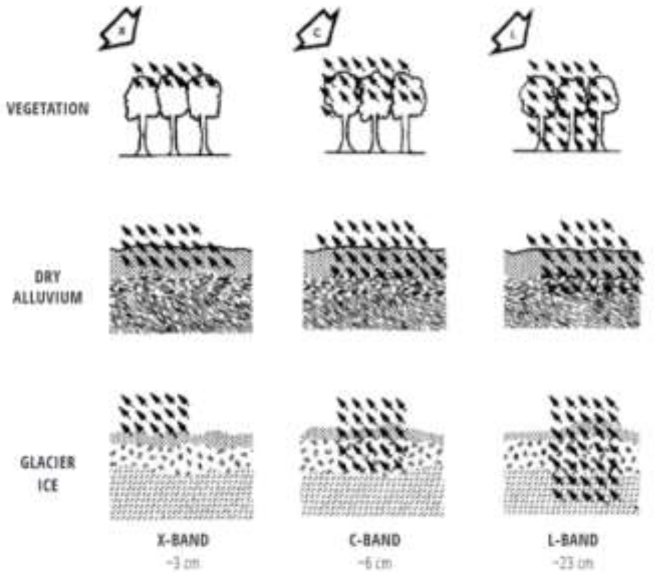

Figure 87: SAR signal penetration by sensor wavelength, from The SAR Handbook

The second limitation of these datasets for flood modelling applications is their respective resolution. At global scale both SRTM DEMs, Copernicus DEMs and FABDEM offer an accurate representation of the earth surface. On the other hand, at the local scale required for modelling flood in urban areas, the horizontal resolution of 30m (10m at best for COP-DEM_EEA-10-DGED) does not represent adequately the urban environment, where the size of the objects that affect the flood path (buildings, roads, infrastructures, riverbanks, transversal structures) is usually smaller than the 30m of the DEMs' pixel. If not properly described by the model (based on the DTM resolution), these could have an important effect on the reliability of the flood event description. Higher resolution DEMS are recommended when modelling in urban environments to capture buildings and finer terrain variations[208].

Similarly, the vertical accuracy of the SRTM DEMs and Copernicus DEMs in urban areas poses strong limitations, especially since a 4m vertical accuracy at best is a significant difference when the average building storey is generally between 3 and 4m high.

7.1.2.2 Proposal to fill-in CEMS limitations

The following table provides an overview of the currently available, but not used in CEMS RM&RRM, elevation data (LiDAR data and LiDAR-based VHR DTM datasets over Europe and satellite-based VHR DTMs outside Europe).

Only the datasets with a resolution equal or finer than 10 m have been considered relevant for the current study, since, from this type of data, the accuracy of some implemented indicators related to water extent, depth and accumulation is, in part, dependent.

[208] Hawker L, Bates P, Neal J and Rougier J (2018) Perspectives on Digital Elevation Model (DEM) Simulation for Flood Modeling in the Absence of a High-Accuracy Open Access Global DEM. Front. Earth Sci. 6:233. doi: 10.3389/feart.2018.00233

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Country	Coverage	Dataset	Fee	Producer/Provider	Period	Resolution	Format
World	Worldwide	GEBCO_2022	No	GEBCO	2022	15 arc-sec	-
	Worldwide	WorldDEM	Yes	AIRBUS	-	-	-
	Worldwide	CO3D	-	CNES, AIRBUS	2025	-	-
Albania	National	MDT 3D (Albania National Geoportal)	No	ASIG	2015 - 2017	2 m	GeoTIFF
Austria	National	Austrian Elevation Model	No	Geoland	2019	10 m	GRID
Bosnia Herzegovina	National	DTM - DSM	-	FGU	2023 - 2024	5 m	RASTER
Belgium	Regional - Flanders	DHM-Vlaanderen II	No	Flanders Region	2013 - 2015	1 m	.laz ; .tif
	Regional - Wallony	MNT 2013-2014	No	Wallony Region	2012 - 2014	1 m	.tif
Denmark	National	DHM - Terraen	No	ADSI	2018	0.4 m	.tif
	National	DHM - Overflade	No	ADSI	2018	0.4 m	.tif
England	National (not complete)	LIDAR Composite DTM	No	UK Environment Agency	2017 - 2022	0.25 m - 2 m	GRID ASCII
	National	OS (Ordnance Survey) Terrain 5	Yes	Ordnance Survey	2021	5 m	GML 3.2 and ASCII grid for DTM
Estonia	National	Elevation Data (RAW Lidar)	No	Estonian geoportal	2017 - 2020	1 m	.tif ; .asc
Finland	National	Laser scanning data 5 p	Yes	National Land Survey of Finland	2008 - 2019	2 m	.tif
	National	Laser scanning data 0,5 p	Yes	National Land Survey of Finland	2020 - present	0.4 m	.laz
France	National	RGE ALTI	No	IGN (Institut Geographique National)	2009	1 m	asc
	National	Lidar HD	No	IGN (Institut Geographique National)	2021 - 2025	10 poinst /m²	laz

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Country	Coverage	Dataset	Fee	Producer/Provider	Period	Resolution	Format
Germany	National	Digitale Geländemodelle (DGM5, DGM10)	Yes	BKG (Bundesamt für Kartographie und Geodäsie)	2016	5, 10 m	asc
Ireland	National (not complete)	Height Data: DTM	Yes	Ordnance Survey Ireland	2005 - 2014	2 m, 5 m	-
Italy	National	Tinitaly 1.1 DEM	No	INGV (Istituto Nazionale di Geofisica e Vulcanologia)	2023	10 m	Wms, wmts
	Regional - Piedmont (non-complete)	DTM LiDAR con Risoluzione a Terra 1 Metro - Regione Piemonte	No	Italian National Geoportal	2014	1 m	wms (can be downloaded upon formal request)
	Regional - Piedmont (complete)	Ripresa Aerea ICE 2009-2011 - DTM 5 - Regione Piemonte	No	-	2019	5 m	.tif
	Regional - Sicily (complete)	Modello digitale del terreno (MDT) LIDAR 2m Volo ATA 2012 2013 - Servizio di scaricamento	No	Italian National Geoportal	2013	2 m	wcs
	Regional - Sardinia (not complete)	Mosaico DTM 1m LIDAR - Sardegna - Altimetria	No	Italian National Geoportal	-	1 m	wms
	Regional - Sardinia (not complete)	Mosaico DTM 1m LIDAR - Sardegna - Ombre	No	Italian National Geoportal	-	1 m	wms
	Regional - Basilicata	Modello Digitale del Terreno (DTM) risoluzione 5m - Basilicata	No	Italian National Geoportal	2013	5 m	wms
	Regional - Basilicata	DTM LiDAR con Risoluzione a Terra 1 Metro - Regione Basilicata	No	Italian National Geoportal	2014	1 m	wms (can be downloaded upon formal request)
	Regional - Puglia	Modello Digitale del Terreno (DTM) e carte derivate - Puglia	No	Italian National Geoportal	-	-	wms

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Country	Coverage	Dataset	Fee	Producer/Provider	Period	Resolution	Format
	Regional - Puglia	DSM LiDAR con risoluzione a terra 1 metro - Regione Puglia	No	Italian National Geoportal	2014	1 m	wms (can be downloaded upon formal request)
	Regional - Campania	DTM LiDAR con risoluzione a terra 1 metro - Regione Campania	No	Italian National Geoportal	2014	1 m	wms (can be downloaded upon formal request)
	Regional - Calabria	DTM LiDAR con risoluzione a terra 1 metro - Regione Calabria	No	Italian National Geoportal	2014	1 m	wms (can be downloaded upon formal request)
	Regional - Abruzzo	DSM LiDAR con risoluzione a terra 1 metro - Regione Abruzzo	No	Italian National Geoportal	2014	1 m	wms (can be downloaded upon formal request)
	Regional - Emilia Romagna	DTM LiDAR con risoluzione a terra 1 metro - Regione Emilia Romagna	No	Italian National Geoportal	2014	1 m	wms (can be downloaded upon formal request)
	Regional - Lazio	DSM LiDAR con risoluzione a terra 1 metro - Regione Lazio	No	Italian National Geoportal	2014	1 m	wms (can be downloaded upon formal request)
	Regional - Liguria	DSM LiDAR con risoluzione a terra 1 metro - Regione Liguria	No	Italian National Geoportal	2014	1 m	wms (can be downloaded upon formal request)
	Regional - Lombardy	DSM LiDAR con risoluzione a terra 1 metro - Regione Lombardia	No	Italian National Geoportal	2014	1 m	wms (can be downloaded upon formal request)
	Regional - Marche	DSM LiDAR con risoluzione a terra 1 metro - Regione Marche	No	Italian National Geoportal	2014	1 m	wms (can be downloaded upon formal request)
	Regional - Dolomitic area	DTM LiDAR con Risoluzione a Terra 1 Metro - Area dolomitica	No	Italian National Geoportal	2014	1 m	wms (can be downloaded upon formal request)

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Country	Coverage	Dataset	Fee	Producer/Provider	Period	Resolution	Format
	Regional - Bolzano Province	DTM LiDAR con Risoluzione a Terra 1 Metro - Provincia Autonoma di Bolzano	No	Italian National Geoportal	2014	1 m	wms (can be downloaded upon formal request)
	Regional - Molise	DSM LiDAR con risoluzione a terra 1 metro - Regione Molise	No	Italian National Geoportal	2014	1 m	wms (can be downloaded upon formal request)
	Regional - Tuscany	DSM LiDAR con risoluzione a terra 1 metro - Regione Toscana	No	Italian National Geoportal	2014	1 m	wms (can be downloaded upon formal request)
	Regional - Umbria	DSM LiDAR con risoluzione a terra 1 metro - Regione Umbria	No	Italian National Geoportal	2014	1 m	wms (can be downloaded upon formal request)
	Regional - Valle D'Aosta	DSM LiDAR con risoluzione a terra 1 metro - Regione Valle D'Aosta	No	Italian National Geoportal	2014	1 m	wms (can be downloaded upon formal request)
	Regional - Veneto	DSM LiDAR con risoluzione a terra 1 metro - Regione Veneto	No	Italian National Geoportal	2014	1 m	wms (can be downloaded upon formal request)
Latvia	National	DHM Basic Data	No	LGIA	2019 - 2050	0.25 m	.lasnether
Luxembourg	National	BD-L-MNT5	No	ACT	2016	5 m	.tif
	National	LiDAR 2019	No	ACT	2019	0.5m	.jp2
Netherlands	National	AHN 3	No	National GeoRegister	2013 - 2018	0.5 m	.jp2, wms, wcs
	National	LiDAR dataset (Dutch National Spatial Data Infrastructure)	No	National GeoRegister	2014	0.5m	LAZ (vector)
Norway	National	Ardupilot and DTM10 Kartverket	No	geonorge.no	2019	10 m	.tif ; .laz
Poland	National	LIDAR (4p)	No	geoportal.gov.pl	2011 - 2020	0.5m	.laz

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Country	Coverage	Dataset	Fee	Producer/Provider	Period	Resolution	Format
	National	Digital Elevation model	No	geoportal.gov.pl	2000 - 2021	1m	.asc
	National	Digital Surface model	No	geoportal.gov.pl	2000 - 2021	0.5 - 1m	.asc
Scotland	National (not complete)	Light Detection And Ranging (LiDAR) - Phase 1,2,3,4,5,6	No	Scottish Remote Sensing Portal		0.5 m	WMS, GeoTIFF
Spain	National	Modelo Digital del Terreno de España	No	CNIG (Centro Nacional de Informaciòn Geografica)		5 m	
	National (not complete)	MDT02 - PNOA Lidar 2a cobertura	No	CNIG (Centro Nacional de Informaciòn Geografica)	2015 - 2021	2 m	.asc
	National (not complete)	Mapa LIDAR - PNOA Lidar 2a cobertura	No	CNIG (Centro Nacional de Informaciòn Geografica)	2015 - 2021	2.5 m	.ecw ; .jpg
Switzerland	National	SwissALTI3D	No	Swisstopo	2012 - 2021	0.5 m	.tif
	National (not complete)	SwissSURFACE3D	No	Swisstopo	2017 - 2023	0.2 m	.las
Slovakia	National (not complete)	DTM 5.0	No	ÚGKK SR	2017 - 2023	5 m	.tif
	National (not complete)	DSM 1.0	No	ÚGKK SR	2017 - 2023	1m	.tif
	National (not complete)	Classified Point Cloud	No	ÚGKK SR	2017 - 2023	1m	.laz
Sweden	National (complete)	LaserData Download, NH	Yes	Lantmäteriet	2009 - 2019	0.5m	.las

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7.1.3 Demographic and socio-economic indicators

7.1.3.1 Current practices in demographic and socio-economic indicators

This section is based on a brief review of studies assessing the socioeconomic vulnerability of people to urban floods, as well as tools/databases to assess the economic impact of and vulnerability to (urban) floods. It reviews popular indicators, discusses the limitations of commonly used data sources, and outlines the potential of employing traditional and social media as complementary and novel sources for indicator creation.

Indicators of socioeconomic vulnerability

A number of indicators or indicator groups appear rather consistently, with some deviations, across the reviewed studies[209]. For the purpose of this report they can be classified as follows:

- Robustness and quality of the built environment. This group includes indicators of fragile urban infrastructure (e.g. poor drainage network and pipelines etc.). It also includes indicators of uncontrolled urbanisation and settlement on marginalised land (e.g. slums in the context of developing countries; see Taylor et al. 2020), as well as different indicators of the quality of materials used to build houses. For example garbage, adobe, clay bricks, plastic etc. are considered as poor building materials that increase households' vulnerability to floods.[210]
- Assets and financial resources of affected households. Assets and financial resources are essential in determining the vulnerability and coping capacities of affected households in the wake of urban floods.[211] They also determine the extent to which households are able to prepare for future flood events. This group of indicators includes indicators of household wealth, often proxied by the assets and possessions of a household: e.g. household appliances, roofing material (common proxy in developing country context), household ownership, ownership of land etc.[212] It also includes indicators of access to insurance, credit, social safety nets (see Bigi et al. 2021). Furthermore, this group also includes aggregated measures of poverty, unemployment -e.g. for a census or administrative area.[213]
- Access to services and government support. This group includes indicators of access to basic health and other emergency response services: e.g. the percentage of the population with access to medical service,[214] the number of health staff/hospitals in an area, the number of local police stations, the number of firefighter stations, the number of hospital beds, the number of shelters/reception centres (schools can count) per inhabitants etc.[215] In the context of developing countries and for cases where high spatial precision is not required, this group can also include indicators of corruption and accountability of public officials in charge of disaster response and prevention.[216]
- Access to social networks and community support. Access to social networks and support by fellow community members are essential to effectively cope with- or prepare for urban flood events. In some

[209] Bigi, Velia, et al. "Flood vulnerability analysis in urban context: A socioeconomic sub-indicators overview." Climate 9.1 (2021): 12.

[210] See (1) Bigi et al. 2021; (2) Chi et al. 2022. Microestimates of wealth for all low-and middle-income countries. Proceedings of the National Academy of Sciences, 119(3); (3) Ghoneim et al. 2022. A GIS Vulnerability Assessment Tool to Support Strategic Planning of Cities Facing Flash Floods–Case Study of Nuweiba City–Egypt. Architecture, 10(5A), 288-312; (4) Leal et al. 2021. Physical vulnerability assessment to flash floods using an indicator-based methodology based on building properties and flow parameters. Journal of Flood Risk Management, 14(3); (5) Müller et al. 2011. Assessment of urban vulnerability towards floods using an indicator-based approach–a case study for Santiago de Chile. Natural Hazards and Earth System Sciences, 11(8), 2107-2123; (6) Nasiri et al. 2019. District flood vulnerability index: urban decision-making tool. International Journal of Environmental Science and Technology, 16, 2249-2258.

[211] Detges et al. 2022. A Conceptual Model of Climate Change and Human Mobility Interactions. HABITABLE research paper. Berlin: adelphi.

[212] See (1) Rasch 2016. Assessing urban vulnerability to flood hazard in Brazilian municipalities. Environment and urbanization, 28(1), 145-168; (2) Salazar-Briones et al. 2020. An integrated urban flood vulnerability index for sustainable planning in arid zones of developing countries. Water, 12(2).

[213] See (1) Ghoneim et al. 2022; (2) Salazar-Briones et al. 2020.

[214] Salazar-Briones et al. 2020.

[215] (1) Ghoneim et al. 2022; (2) Tascon-Gonzalez et al. 2020. Social vulnerability assessment for flood risk analysis. Water, 12(2).

[216] See (1) Müller et al. 2011; (2) Taylor et al. 2020. Messy maps: Qualitative GIS representations of resilience. Landscape and Urban Planning, 198.

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studies this is proxied by indicators for the percentage of foreign nationals living in an area, assuming that these groups will find it more difficult to count on the support of their neighbours.[217]

- **Knowledge and timely access to relevant information**. Information and know-how are important to quickly react and adequately prepare for urban flood risks. In reviewed vulnerability analyses they are often proxied by indicators like access to internet, wifi, and telephones; levels of education and literacy (e.g. what degree a person holds); and past experience with floods.[218]
- **Constraints to mobility**. People's vulnerability to urban floods is determined to a large extent by their ability to move out of harm's way. Studies usually capture this facet of vulnerability with indicators like the percentage of very young and elderly persons, as well as disabled persons in an area.[219] To these physical constraints to mobility one can also add social constraints, for example with regard to gender roles. For example, women are often expected to care for children and older relativism, which limits their mobility.[220]
- **Connectedness to the outside world**. Lastly, people's vulnerability to floods is partly determined by how well they are connected to the outside world - e.g. how easily they can be accessed by crisis responders, as well as how easily they can be evacuated. To capture this, reviewed studies use indicators like a household's distance to the next primary road/paved roads, the density of roads in an area, or more explicitly the presence of evacuation routes.[221]

7.1.3.2 Limitations in commonly used data sources

Data on socioeconomic vulnerability to urban floods

Reviewed studies on social vulnerability to urban flood mainly rely on household survey data - often collected through field work, which is time consuming and usually has limited spatial and temporal coverage. This data collection method is expensive and difficult to scale up. Where available, official statistics and census data are used - e.g. the Demographic and Health Surveys (DHS) in the context of developing countries.

Some studies are able to benefit from fine-grained geo-referenced cadastral data that can be joined with data on demographic and social indicators to improve the coverage and replicability of the analysis. For example, the Spanish Institute of Statistics and the Spanish Electronic Cadastral Service offer rich data that can be joined to create maps of socioeconomic vulnerability to urban floods. An example for this is provided by Tascon-Gonzales et al. (2020) who develop socio-economic flood vulnerability indicators at the urban parcel level for the city of Ponferrada. However, such data are not always readily available, especially in the context of developing countries where census data is scarcer.

Micro estimates for wealth and economic development

There are a number of projects that provide geo-referenced poverty or development estimates with global coverage. As poverty and human development can be considered proxy measures for socio-economic vulnerability (see section 7.1.3.1 above), they provide opportunities for overcoming the limitations of some of the datasets discussed above; especially when it comes to measuring vulnerability in developing countries where census data is more scarce. For example, Chi et al. (2021) have developed poverty micro estimates covering all low and middle income countries at 2.4 km resolution. The estimates are computed by applying machine learning algorithms to vast and heterogeneous data from satellites, mobile phone networks, topographic maps, as well as aggregated and de-identified connectivity data from Facebook. This is an improvement on earlier projects with global

[217] See (1) Bigi et al. 2021; (2) Tascon-Gonzalez et al. 2020.
[218] See (1) Bigi et al. 2021; (2) Ghoneim et al. 2022; (3) Tascon-Gonzalez et al. 2020.
[219] See (1) Bigi et al. 2021; (2) Salazar-Briones et al. 2020; (3) Tascon-Gonzalez et al. 2020.
[220] See Detges et al. 2022.
[221] (1) Bigi et al. 2021; (2) Chi et al. 2021; (3) Rasch 2015; (4) Tascon-Gonzalez et al. 2020.

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coverage that were measuring wealth at longer distances or at the level of administrative units like provinces and districts. Yet, these data are still coarse in comparison to other data discussed in this report.

When studying the spatial distribution of wealth (and climate resilience) in developing countries researchers have also frequently used raster data derived from night-time light emissions (NTL), that is how luminous places are at night when seen from space, which is assumed to capture local levels of economic development and wealth.[222] The spatial resolution of such datasets has considerably improved with, for example, the Suomi Visible Infrared Imaging Radiometer Suite (VIIRS) providing NTL data at 750m resolution on a monthly basis since 2011 or the Wuhan University's Luojia 1-01 satellite capturing NTL at 130 m resolution.

Yet, as highlighted by Bennett (2020), "Improved spatial resolution [...] does not necessarily clarify what increasing or decreasing lights reflect on the ground. A satellite image cannot explain whether brighter lights signal a growing population or the construction of new industrial facilities. Nor can it confirm whether dimmer lights indicate a declining population, a shrinking economy [...], or the ravages of war [...] or whether brighter lights actually do imply brighter futures for people on the ground." [223]

There remain thus important limitations with economic micro estimates and NLT data, not just in terms of spatial precision and temporal frequency, but also in terms of validity and interpretability.

Data on economic damages from (urban) floods

Databases used for economic assessments of flood damage draw on a range of different data sources: On-site expert surveys, telephone interviews of affected households, as well as data from insurance companies and local governments (e.g. HOWAS 21; FHRC database; NatCat Service). Some databases use data derived from (social) media (e.g. DamaGIS) or reports from UN organisations and NGOs in the context of developing countries (e.g. EMDAT).

Very often, these databases have national coverage (e.g. for Austria, France, Germany, or the United Kingdom). There are also databases with European (e.g. HANZE) and international coverage (e.g. NatCat Service; EMDAT), as well as databases covering only a city (e.g. MANDISA database of the Disaster Mitigation for Sustainable Livelihoods Programme at the university of Cape Town).

Our quick review shows that spatially more precise databases (e.g. at the level of affected buildings and objects) usually draw on expert assessments, on-site and telephone interviews (surveys), records of insurance companies and local governments, as well as internal incidents reports (e.g. the flood damage database of the Austrian railway company ÖBB). Those are expensive and time consuming to produce. On the other hand, less precise databases (e.g. at the level of administrative areas) use news sources and reports from humanitarian organisations that are less expensive to collect but often do not contain precise location information.

7.1.3.3 Socio-economic Indicators from traditional and social media sources

Media reports - on traditional as well as social media - provide a complementing source of information regarding the above factors. On the one hand, they may provide more immediate, on-the-ground information. On the other hand, they may serve to provide complementary information in case of limited or (highly) biased official information sources. Indicators based on media are envisioned to work as "sensors in the population", extending the more traditional indicators listed above. In this sense, they can be regarded to function as proxies for various phenomena covered by the media, which depends on a host of factors itself.

The use of social media in the context of crisis and disaster management has been studied extensively (e.g. by the Information Systems for Crisis Response and Management or ISCRAM). However, to date no systematic approach to how media-derived indicators can be fused with the traditional approaches outlined above has been taken. Furthermore, due to recent changes in the media landscape (e.g. the acquisition of Twitter by Elon Musk),

[222] Weidmann and Schutte 2017. Using night light emissions for the prediction of local wealth. Journal of Peace Research, 54(2), 125-140.
[223] Bennett (2020). Is a pixel worth 1000 words? Critical remote sensing and China's Belt and Road Initiative. Political Geography, 78, 102127.

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fundamental subsequent changes in the availability and hence in the use of such media may result. A robust approach, focussing on several sources and platforms (rather than focussing in single ones) thus needs to be defined in order to be as resilient as possible to such changes. The combination of traditional and social media - rather than only focussing on social media - is viewed as one pillar of such a more resilient approach. Within CENTAUR, only openly-accessible media are considered (even though we acknowledge the fact that closed media play an important role) due to privacy, ethical and legal reasons (i.e. only OSINT is considered).

Within the scope of an ongoing ESA/AID/GDA initiative, HENSOLDT has been working on developing a scheme to derive a set of socio-economic indicators from OSINT (the notion of “indicator” being a tentative one, applicable to this initiative but not generic yet and to be refined accordingly within CENTAUR). In several iterations, the scheme has been refined and currently addresses the following categories:

- natural disasters
- government and governance
- food security
- safety
- conflicts

Each category has been associated with an initial set of concepts which can be detected in traditional and social media in a multilingual manner. The resulting volumes of documents as well as their associated sentiment, concepts and co-occurrences of concepts have been interpreted by analysts and included into reports. Associated locations have been used to guide analysis towards certain regions.

The emphasis has been on producing aggregated and enriched data to allow analysts a broader and more profound interpretation in order to create reports. The emphasis has thus not been on the automation nor on the (principled) fusion of information (resp. indicators) which differentiates this work from the current project. CENTAUR, however, will build upon the developed methodology and place the emphasis on the principled generation of indicators, their fusion as well as on the automation of large stretches of the process.

7.1.4 Weather forecast systems for urban floods prediction

7.1.4.1 Present systems available

Urban flood prediction requires the forecast of extreme precipitation and the capability to anticipate the occurrence of inundation in urban areas. However, trust-worthy predictions of precipitation, at the local scale able to make sensible predictions of urban floods is a challenge. State of the art global operational weather forecast systems usually employed at the global and continental scale (e.g. forcing for EFAS/GLOFAS) have native resolutions in the 5-10 km scale which is clearly insufficient and has been so far used only to forecast flash flood events. The use of radar information can alleviate the inherent limitations of hydrological modelling and Initiatives and operational products coming from other European tools such as the Global Flood Monitoring might mitigate some limitations in the monitoring phase, but they won’t provide information at extended lead times. So while EFAS medium-range flood forecast provides an overview of upcoming flood events for the next 10 days, including possible flood impacts, they are not able to detect floods that occur at the much localized spatial scale. To partially fulfil these gaps In the last years EFAS have developed a series of indicators of flash floods based on high-resolution numerical weather predictions with up to 5 days lead-time as well as radar- based precipitation monitoring and “now casting” with up to 6 hours. While these indicators provide an advancement with respect to the hydrological chains when it comes to identifying impactful events produced by heavy precipitation, they are not specifically designed for urban areas and they are still based on the concept of a river network.

Recognising that an urban module is not available in the current EFAS system, in this section we review the present capabilities of the CEMS service on the products that are somehow related to the detection of floods due to heavy precipitation; ERIC and ERICHA. ERIC is a flash floods forecasting system-based on numerical weather prediction

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precipitation while ERICHA provides flash floods monitoring systems based on radar adjusted precipitation estimates.

ERIC

The ERIC flash flood forecasting is done by comparing the forecasted surface runoff accumulated over the upstream catchment with a reference threshold. It is based on the 20-member COSMO-LEPS ensemble precipitation and soil moisture forecasts from the LISFLOOD hydrological model and provides indicators for the next 5 days for catchments smaller than 2,000 km^2.

Figure 88: The ERIC flash flood forecasting modelling chain

Firstly Surface runoff is calculated by combining the 6 hourly COSMO-LEPS precipitation forecasts with the soil moisture forecasts produced by the LISFLOOD hydrological model when forced with COSMO-LEPS. Firstly both datasets are downscaled to 1 km using nearest neighbour. Next snow is removed from the COSMO-LEPS precipitation forecasts by removing all precipitation where the temperature is less than or equal to 0 degrees. Surface runoff is then calculated

The 6 hourly surface runoff time series are accumulated on the 1 km channel network for all cells with an upstream area less than or equal to 2000km2. This means that for each 6 hourly time-step, at each 1 km channel cell, the total surface runoff which occurs upstream of the cell is calculated. These 6 hourly accumulations are then further accumulated over time periods of 12 and 24 hours. The accumulated surface runoff at 6, 12 and 24 hour time periods are divided by the mean annual maximum surface runoff at each respective time period to compute the ERIC index value at each 1 km channel cell. If the accumulated surface runoff for a given time period exceeds the mean annual maximum, then the ERIC index will be greater than 1. The mean annual maximum values are derived from a 19 year COSMO-LEPS reforecast series. At each 1 km channel cell for each 6 hourly time-step, the maximum ERIC index value across the three time periods is then selected. Then the maximum ERIC index value across all the 6 hour time-steps in the 5 day forecast period is selected. The above three steps are repeated for all 20 COSMO-LEPS ensemble members. The next step calculates the exceedance probability of ERIC Index = 1 i.e. the probability of being above the mean annual maximum which is equivalent to the bank full height of the river channel. Only 1 km channel cells where at least 4 ensemble members have an ERIC index >= 1.0 are retained. The retained cells are clumped together, the most downstream cell in each clump is chosen as the location for where the ERIC reporting point is generated. At these reporting point locations the ERIC index for each ensemble member at each 6 hourly time step is converted into a return period using Gumbel parameters obtained from a 19 year COSMO-LEPS forecast series. Then the maximum exceedance probability of the 2, 5 and 20 year return periods are computed across the 5 day forecast period. This information is then used to generate the ERIC Reporting Points and ERIC Affected Area layers shown on the EFAS website (Figure 88).

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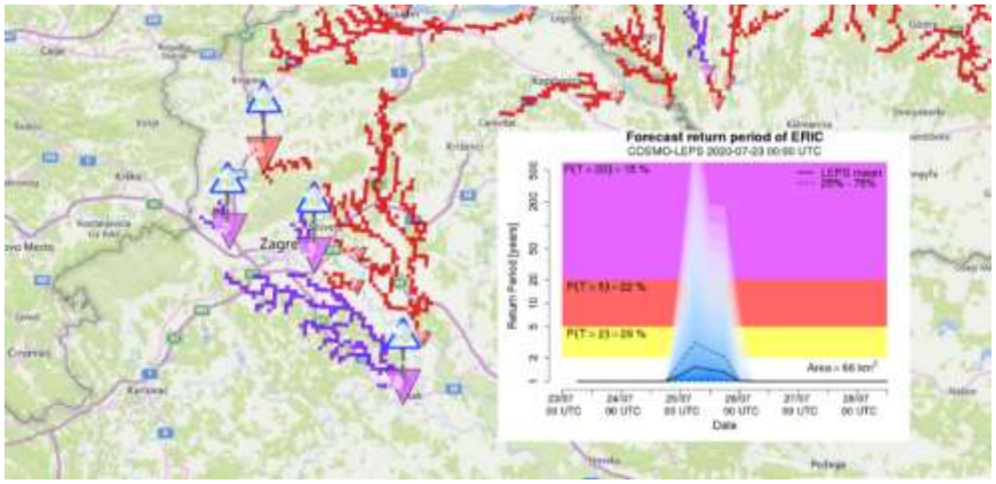

Figure 89: Example of the ERIC flash flood products available on the EFAS website.

ERICHA

The European Rainfall-InduCed Hazard Assessment (ERICHA) system for real-time flash flood monitoring and now casting (heather after ERICHA system). ERICHA system provides nowcasts of both precipitation and flash flood hazard (by means of a simple traffic-light indicator) in the range 0- 6 hours (a simplified scheme is shown in Fig. 1). The driving variable is the basin-aggregated rainfall estimated from radar-based observations adjusted with a rain gauge correction factor. In EFAS, the European radar composites (with a spatial grid resolution of 2 km) provided by the EUMETNET project OPERA are used to calculate the basin-aggregated rainfall over the drainage network with a grid resolution of 1-km. The output is ERICHA flash flood hazard indicator for basins up to 5000 Km^2.

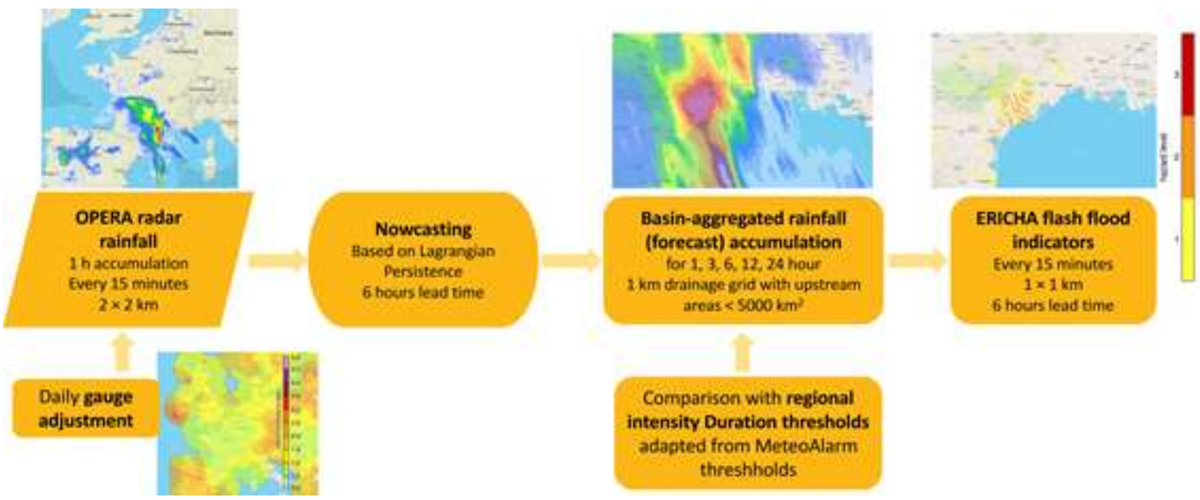

Figure 90: The chain of the updated ERICHA system producing precipitation and flash flood hazard nowcasts

The ERICHA-FF hazard assessment is solely based on radar rainfall inputs, assuming that the basin response will be strongly dominated by the basin-aggregated rainfall. Therefore, the quality of the rainfall inputs is critical to the resulting hazard indicator.

An adjustment technique is applied to the radar composite. The adjustment factor map is updated once a day (after the arrival of the gauge datasets from the previous day) and is applied to the 15-min radar precipitation

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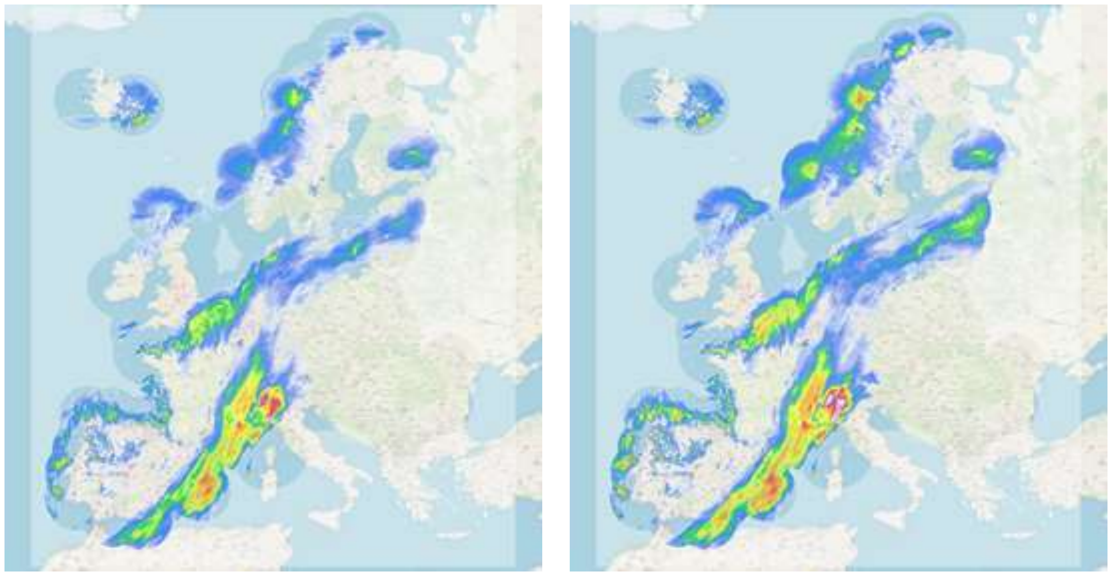
accumulations. As a result, radar underestimation can be partly improved, which has a clear effect on the estimated hazard level and location of flash floods.



(a) Before the adjustment (b) After the adjustment

Figure 91: Rain accumulation and estimated hazard level for 21 October 2019 at 1700 UTC (a) before and (b) after applying the adjustment factor

The list of products available from these two systems is reported in Table 30.

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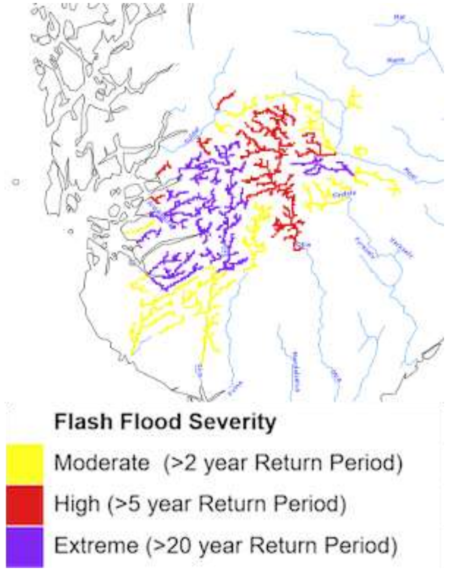
Table 30: List of weather forecast products available.

	Product name	Description (established over forecast horizon)	Outputs	Forecast horizon	Forecast Model (# of forecast)	Gaps for urban applications
Short range	Eric Affected Area	Drainage area affected by the forecasted heavy precipitation and potential flash floods. Yellow/Red/Purple = drainage area affected with a high probability to exceed a 2/5/20 year return period magnitude.	Map 	5 days	COSMO (20)	Resolution inadequate for urban areas
Short range	ERIC Reporting Points	Reporting points showing the furthest downstream locations where the forecasted	Map	5 days	COSMO (20)	Resolution inadequate for urban areas

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	Product name	Description (established over forecast horizon)	Outputs	Forecast horizon	Forecast Model (# of forecast)	Gaps for urban applications
		probability (%) of extreme runoff accumulations exceeds a 2 (yellow), 5 (red), or 20 (purple) year return period magnitude. Enlarged triangles represent the most flash flood prone location within each administration unit where the forecasted probability is >= 10% of the 5 year return period and the lead time to the runoff peak is <= 60 hours. Persistence shows the number of prior				

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	Product name	Description (established over forecast horizon)	Outputs	Forecast horizon	Forecast Model (# of forecast)	Gaps for urban applications
		forecasts, including the current one, where at least one reporting point in each administration region has a forecasted probability >=10% of the 5 year return period.				
Short range	ERICHA - FF hazard levels forecasts	Using the gauge-adjusted precipitation estimates and nowcasts, the flash flood hazard level is estimated by first computing the upstream basin-aggregated rainfall over the drainage network	Map	6 hours	NOWCAST (1)	Inadequate time span to be used as early warning system

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	Product name	Description (established over forecast horizon)	Outputs	Forecast horizon	Forecast Model (# of forecast)	Gaps for urban applications
		(resolution: 1km) and then comparing the observed values with a set of reference thresholds to determine the flash flood hazard level (yellow - low; orange - medium; red - high). The ERICHA FF hazard level is displayed in a loop with 15-minute time interval. It shows the estimated flash flood hazard level for several hours in the past up to current time and nowcasts up to 6 hours (when the				

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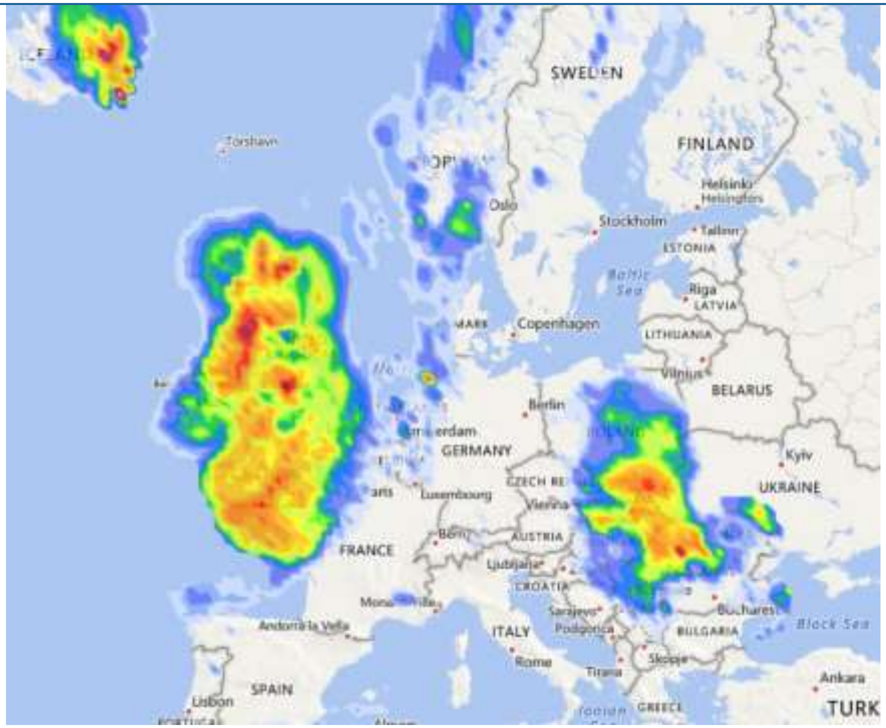
	Product name	Description (established over forecast horizon)	Outputs	Forecast horizon	Forecast Model (# of forecast)	Gaps for urban applications
		loop bar turns red). T				
Long range	ERICHA 24-h accumulations	Daily gauge-adjusted radar rainfall accumulation is estimated for the last 24 hours finishing at the selected time stamp (00:00, 12:00 UTC). In EFAS this product is only available for the past 7 days.			NOWCAST (1)	Inadequate time span to be used as early warning system

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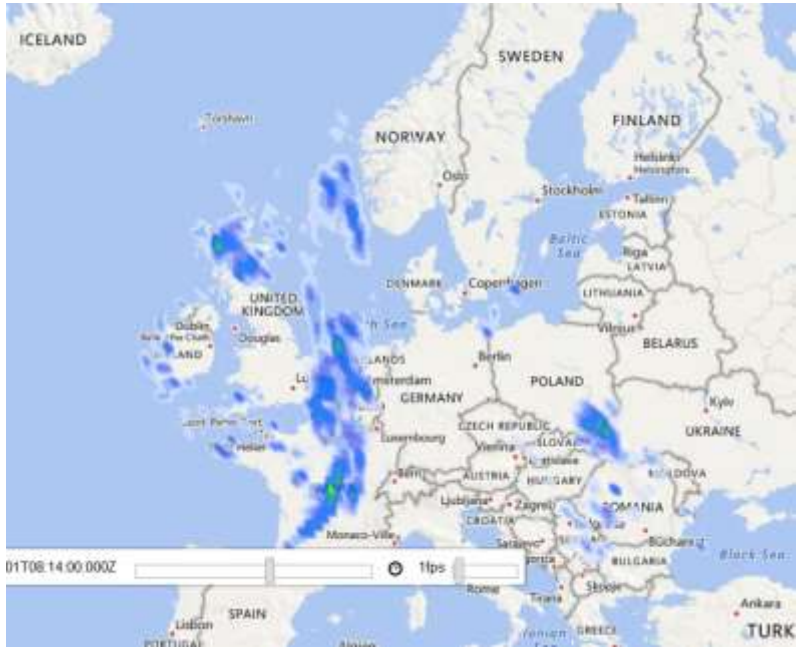
	Product name	Description (established over forecast horizon)	Outputs	Forecast horizon	Forecast Model (# of forecast)	Gaps for urban applications
Long range	ERICHA hourly accumulated precipitation	1-h precipitation accumulation estimated from the European OPERA radar rainfall composites. This product is displayed in a loop with 15-minute time interval. It shows the estimated precipitation for several hours in the past up to current time and nowcasts (when the loop bar turns red) up to 6 hours. Deterministic precipitation nowcasts are generated by Lagrangian extrapolation. Recently, a multiplicative adjustment factor map (retrieved from long-term comparison with	Map Animated maps (15 min only) 	Every 15min up to 6 hours	NOWCAST (1)	Inadequate time span to be used as early warning system

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	Product name	Description (established over forecast horizon)	Outputs	Forecast horizon	Forecast Model (# of forecast)	Gaps for urban applications
		rain gauge observations) is applied to compensate for systematic biases in the original OPERA radar rainfall estimates.				

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7.1.4.2 Enhanced weather forecast system: requirements

Urban floods are one of the most devastating natural hazards due to the economic/human losses that they can cause. Therefore, better and earlier warnings and improved situational awareness are vital. High resolution hydro-meteorological models or radar nowcasting are classical approaches in flash flood warning systems as highlighted in section 1.5 and are the backbone of current operation in EFAS and GLOFAS systems. However, these techniques cannot offer global coverage, and they commonly reduce warning lead times to a few hours.

Global numerical weather prediction models are not used extensively because they tend to underestimate very localized heavy rainfall. To understand the problem we are facing let's consider Figure 92.

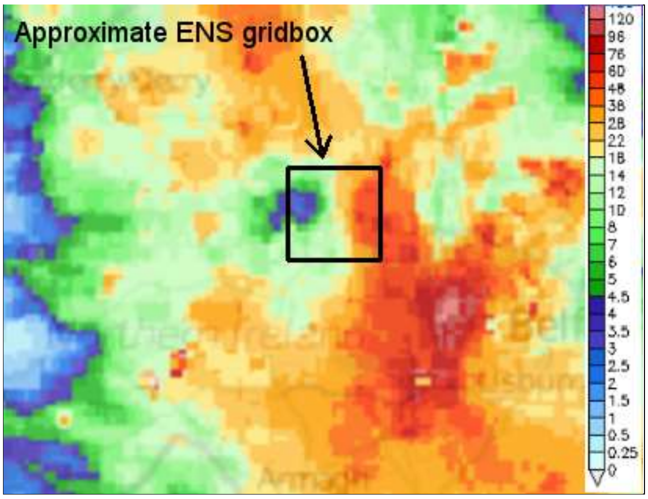

Figure 92: Radar-derived rainfall totals over part of Northern Ireland for the 12h period ending 00UTC 29 July 2018. Scale is in mm. Flash floods occurred in some locations. Figure based on data from netweather.tv

Let us assume here that the radar-derived totals shown are accurate, and also indicate what would have been measured locally by rain gauges. Then we consider the weather forecast ensemble prediction gridbox highlighted. Within this box, whilst the gridbox average rainfall total is about 17mm, the minimum and maximum rainfall amounts are about 2mm and 60mm respectively. This implies a lot of sub-grid variability. A completely accurate ENS member forecast would predict 17mm. But clearly this of itself would give the user no idea that locally there was much more (and indeed much less) than this amount. And to cause flash floods, as were observed, probably a 17mm total, locally, would not have been sufficient.

Successful post calibration techniques must therefore aim to estimate the range of totals likely within the gridbox, and indeed deliver probabilities for different values within that gridbox. This is particularly relevant for convective precipitations that are highly spatially inhomogeneous. In other scenarios (e.g. frontal systems associated with large-scale cyclogenesis) rainfall totals will be much more uniform across grid boxes, but there are also recorded instances of even larger sub-grid variability. An unusual event in southern Spain in 2018 led to a range of 12h rainfall in one ENS gridbox from 0 to ~350mm.

So three key aspects needs to be taken into consideration to deliver a successful pre- warning systems fit-for purpose for urban floods applications:

- The new product must be a post-processed product, based on calibrating ensemble forecasting simulations as they can provide inherent probabilistic information.
- The new product must provide probabilistic forecasts of several rainfall thresholds associated to a grid box (e.g. the probability of having 100 mm precipitation in 6 hours). This in addition to information about the gridbox-average rainfall.

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- The new product should provide an information on the expected impact as for example the probability of exceeding the 20 years return period event

There are several ways to achieve this but given the need to calibrate over a large number of points to ensure scalability of the solution a machine learning approach is probably preferable. The proposed strategy proposed by CENTAUR will be outlined in section 3

7.1.5 Innovative indicators

Due to the multi-disciplinary approach of CENTAUR, numerous definitions of what constitutes an indicator exist. For the purpose of the project and in order to be able to combine indicators of different provenance, a common definition will be adopted.

There are numerous definitions of indicator. Broadly speaking, an indicator can be a sign, symptom, signal, tip, clue, grade, rank, object, organism, or warning of some sort — many things in everyday life[224]. In a more restricted sense, as is often used in the scientific literature, an indicator refers to a variable or an aggregate of multiple related variables whose values can provide information about the conditions or trajectories of a system or phenomenon of interest. In other words, an indicator is simply "an operational representation of an attribute (quality, quantity, characteristic, property) of a system"[225].

An index, instead, is an aggregate of two or more indicators.

Socio-economic indicators as outlined above are expected to be developed with the aim to combine them with other kinds of indicators. In principle, they are expected to be of a quantitative nature, allowing for combination with other kinds of indicators into compound-indicators (or indices). Indicators derived from traditional and social media may serve as proxies, provide first-hand on-the-ground information, complementing and extending more traditional kinds of indicators.

7.1.5.1 Urban flood indicators

With reference to the urban flood context, in CENTAUR project different indicators will be considered:

- UF-ID-1: Historical 6 hourly return period static precipitation maps (pre-event phase);
- UF-ID-2: ML Data Driven Forecast of return period based precipitation events in urban area (early warning-phase);
- UF-ID-3: Urban inundation probability maps and water depth for scenarios defined by return period at a spatial resolution in the order of <10 m;
- UF-ID-4: Inferred INSAR urban flood extent;
- UF-ID-5: Urban flooding map based on geomorphological and InSAR approach for an enhanced damage assessment;
- UF-ID-6: Social/Traditional media indicators for Urban Flooding Maps;
- UF-ID-7: Hazard web sources indicator.

[224] Meadows, Donella H. "Indicators and information systems for sustainable development." (1998).
[225] Gallopin, Gilberto C. "Environmental and sustainability indicators and the concept of situational indicators. A systems approach." Environmental modeling & assessment 1 (1996): 101-117.

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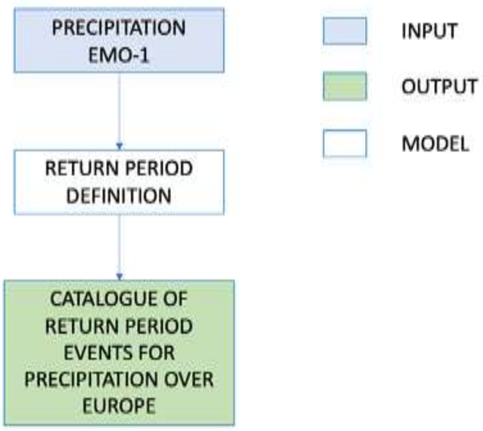
Below the ID-cards related for each indicator reported in the list.

UF-ID-1: Historical 6 hourly return period static precipitation maps (pre-event phase)

Name of Indicator	Historical 6 hourly return period static precipitation maps (pre-event phase)
Brief Description	Static maps of expected precipitation intensity accumulated over 6 hours corresponding to 1-,5-,10-,20- return period events will be calculated. These maps will be used in conjunction with the speed-flood hydraulic model to derive inundation maps connected to return periods which will be employed to allow for a more efficient pre acquisitions tasking workflow.
Gap(s) addressed	Global weather forecast 9 km res. that is unsuited for urban floods early warning detection alternative methods of prediction will be explored. The generated maps will be used as a training dataset to derive ML models to predict return period events.
List of input data required with relative sources (where are available)	EMO-1 dataset (CEMS product available 6-hourly precipitation)
Output indicator type and format	Precipitation map and refined return period (.tif)
Spatial and temporal resolutions obtainable	1.5 km spatial resolutions.
Thematic area covered	Urban Flood
Workflow schema and brief steps description	 Step1 - Acquisition of EMO-1 database historical time series. Step 2 - Classifying the precipitation events in base of their return period. Step3 - Creating the European archive of return period events.

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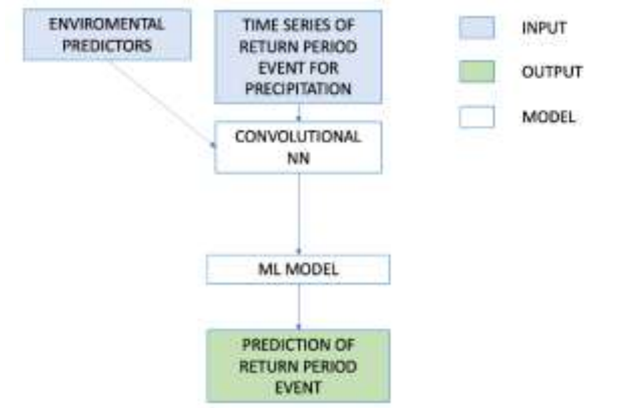
UF-ID-2: ML Data Driven Forecast of return period based precipitation events in urban area (early warning-phase)

Name of Indicator	ML Data Driven Forecast of return period based precipitation events in urban area (early warning-phase)
Brief Description	A novel forecasting system will be implemented based on a convolutional neural network model to predict return period based precipitation event 2 -3 days in advance. The return period forecast will be related to the catalogue of static precipitation and inundation maps
Gap(s) addressed	Improve the prediction of very intense and localised precipitation event
List of input data required with relative sources (where are available)	Environmental predictors related to the thermodynamic status of the atmosphere. Return period static maps of precipitation (training dataset)
Output indicator type and format	Environmental predictors related to the thermodynamic status of the atmosphere.
Spatial and temporal resolutions obtainable	1.5 Km
Thematic area covered	Urban Flood
Workflow schema and brief steps description	 Step1 classify all past events in terms of return period and define a training dataset Step 2 define the environmental predictors in terms of thermodynamically variables Step 3 define a ML based predictive model to predict return period event Step 4 Create the operational infrastructure to run the model in real time

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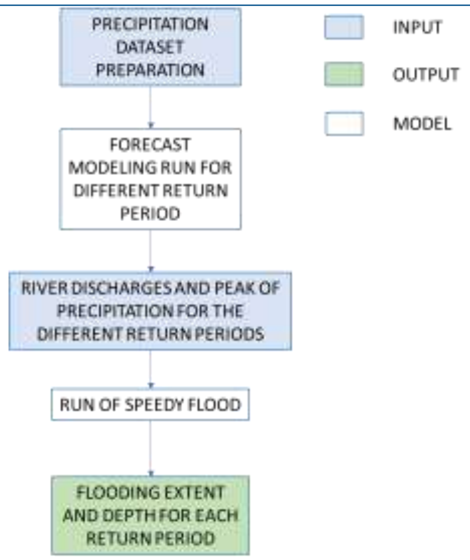
UF-ID-3: Urban inundation probability maps and water depth for scenarios defined by return period at a spatial resolution in the order of <10 m (pre-event phase)

Name of Indicator	Urban inundation probability maps and water depth for scenarios defined by return period at a spatial resolution in the order of <10 m (pre-event phase)
Brief Description	Speedy-flood model with precipitation intensity maps based on return period analysis which allows to reconstruct future floods scenarios.
Gap(s) addressed	Improved spatial resolution(<10m) Scalability Use of DTM High Resolution than ongoing applications
List of input data required with relative sources (where are available)	Precipitation for different return period calculated by ID 2 VHR DTM Flood footprint (from satellite data for past event with the same return period) Land Use Social-media markers Hydrography vector layer
Output indicator type and format	Flooding extent and depth map. Output format will be raster type (.tiff)
Spatial and temporal resolutions obtainable	Spatial resolution strongly dependent on the DTM resolution. Temporal resolution is related to the persistence of the simulated flood (hours, days, week).
Thematic area covered	Urban Flood
Workflow schema and brief steps description	 Step1 – Precipitation dataset preparation In this first phase a preparation and homogenization of rainfall data to be used in the predictive model is required Step2 – Forecast modelling run for different return period Predictive model is run for all predicted return times in order to provide, for each of these, the achievable peak precipitation and flow values in the main rivers. Step3 – River discharges and peak of precipitation for the different return periods

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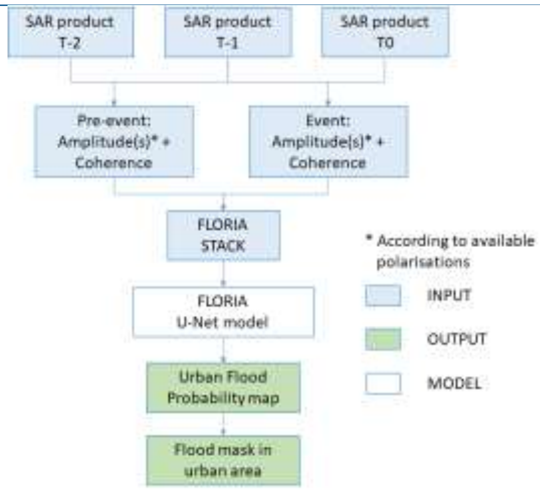
Name of Indicator	Urban inundation probability maps and water depth for scenarios defined by return period at a spatial resolution in the order of <10 m (pre-event phase)
	These are the main outputs from the predictive model run. These layers will serve as inputs to the Speedy Flood model for flood assessment for all return times. **Step4 – Run of Speedy Flood** The Speedy Flood is run for all the return times predicted by the analysis. This geomorphological model uses data derived from EO for calibration and social media for validation. **Step5 – Flooding extent and depth for each return period** Flooding extent and depth are the main outputs of the Speedy Flood. Two indicators are produced, for each required return time. The one inherent in extent is in vector format, while the one inherent in depth in raster type.

UF-ID-4: Inferred InSAR urban flood extent

Name of Indicator	Inferred InSAR urban flood extent
Brief Description	Floodwater detection over urban areas using Radar and artificial intelligence (FLORIA).
Gap(s) addressed	Mapping of urban flooding using SAR satellite images with a water-extraction workflow not yet exploited in the CEMS RM - RRM.
List of input data required with relative sources (where are available)	-PRE and POST event INSAR compatible data; -IA U-Net architecture.
Output indicator type and format	Flooding mask in urban area (vector layer)
Spatial and temporal resolutions obtainable	Events related
Thematic area covered	Urban Flooding
Workflow schema and brief steps description	 **Step1 - Input data** This indicator require 3 SAR products that are interferometrically consistent: two pre-event images and one acquired during the flood. **Step2 - SAR processing**

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Name of Indicator	Inferred InSAR urban flood extent
	Compute coherences and amplitudes derived from inputs and generate the stack to be ingested by the U-Net model. **Step3 - U-Net model** Generate a probability map of flood inundations from the ingested stack. **Step4 - Flood mask** Flood mask as a vector file is generated from an adaptive thresholding.

UF-ID-5: Urban flooding map based on geomorphological and InSAR approach for an enhanced damage assessment

Name of Indicator	Urban flooding map based on geomorphological and InSAR approach for an enhanced damage assessment
Brief Description	Speedy Flood Tool combined with InSAR coherence analysis for floods maps generation.
Gap(s) addressed	Enhance the post-event damage analysis: assess urban areas vulnerability.
List of input data required with relative sources (where are available)	VHR DTM Flood Footprint (EO data) InSAR urban flooding indicator Flood Delineation Polygon Land Use Social/Traditional Media Markers Hydrography Vector Layer Ancillary Data for Flood Hazard
Output indicator type and format	Improved damage assessment based on exposure elements to floods risks. Output format will be a vector layer with flood damage information.
Spatial and temporal resolutions obtainable	Spatial resolution: strongly related to DTM resolution Temporal resolution: event related
Thematic area covered	Urban Flood

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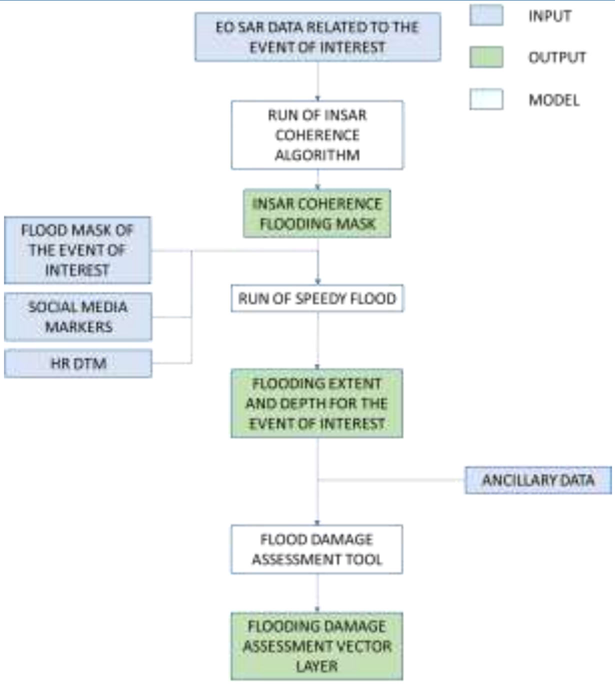
Name of Indicator	Urban flooding map based on geomorphological and InSAR approach for an enhanced damage assessment
Workflow schema and brief steps description	 Step1 – InSAR coherence algorithm run At this stage, the InSAR consistency algorithm is run. Using SAR images, particularly S-1, a water mask in an urban environment will be extracted. Step2 – InSAR coherence flooding mask The water mask in the urban environment obtained through the algorithm based on InSAR techniques, summed with the other inputs needed for Speedy flooding allows to obtain a rather accurate flood map and to overcome the limitations related to satellite sensing. Step3 – Run of Speedy Flood The Speedy Flood, thanks in part to information obtained from InSAR analysis and social media allows for accurate reconstruction of flooding in the urban environment. InSAR is particularly used in the calibration phase of the geomorphological model and social media in the validation phase of the flood depth results. Step4 – Flooding extent and depth used as input of the damage assessment tool Correlating damage classes to depth parameters extracted from the Speedy Flood, the damage assessment tool will allow for a very accurate view of what happened in the city context, providing much more precise information than is done to date. Step5 – Flooding damage assessment layer The damage assessment layer, referring to the different ancillary data used in the analyses, will return a vector layer with the damage classes.

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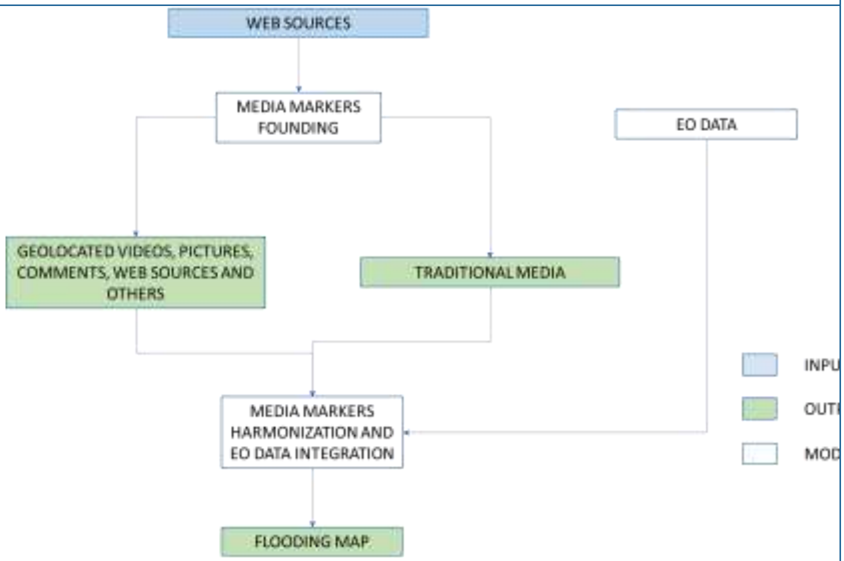
UF-ID-6: Social/Traditional media indicators for Urban Flooding Maps

Name of Indicator	Social/Traditional media indicators for Urban Flooding Maps
Brief Description	Floods maps rebuilt using social/traditional media markers information like videos, pictures, etc
Gap(s) addressed	Floods extraction from urban areas blind to SAR techniques
List of input data required with relative sources (where are available)	Geo-located social/traditional media markers recorded during the events of interest
Output indicator type and format	Points (locations) Classification Media references
Spatial and temporal resolutions obtainable	Events related
Thematic area covered	Urban Flood
Workflow schema and brief steps description	 **Step1 –Media markers algorithm founding** At this stage the algorithm run intervenes, which allows, through keywords, to find all the social and traditional media for the event of interest. **Step 2 – Markers harmonization and mapping** Social data, derived from different sources and of different nature (photos, videos, etc.) in order to be used as an element to be mapped must be properly harmonized. The data should be transformed into point elements (.shp or JSON) and organized in such a way that within it are the references found during the event. **Step3 – Flooding map indicator** The indicator in this case refers to a map in which, in the urban context, the socials collected during the extreme event are reported in point format. In this indicator, the EO component is also considered and, will be represented by the InSAR analysis that allows delineation of flooding in the urban context.

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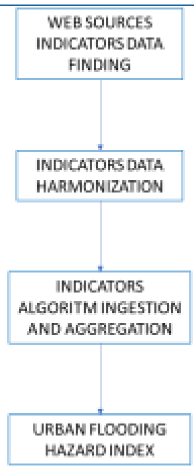
Name of Indicator	Social/Traditional media indicators for Urban Flooding Maps
	This indicator provides a better sense of which areas were most affected by the flood.

UF-ID-7: Hazard web sources indicator

Name of Indicator	Hazard web sources indicator
Brief Description	Index based on several indicators available on the web that allow to characterize an extreme flood event in an area of interest in terms of hazard.
Gap(s) addressed	This index takes into account different indicators dataset, to homogenise them and to give information in terms of hazard related to the affected population.
List of input data required with relative sources (when are available)	Global Precipitation Measurement (GPM) constellation data referred to the period of interest; GDACS hazard indicator; WORLDPOP data; CEMS RM and/or RRM activations info in terms of affected population and size of the flooded area; Web Sources (facilities and industries present in the context of interest, economic damages estimated; poverty distribution, elements of particular interest hit by flood, etc;) (all the input data here must be intended as indicators)
Output indicator type and format	Table of content (.xls)
Spatial and temporal resolutions obtainable	N.A.
Thematic area covered	Urban Flood
Workflow schema and brief steps description	 **Step1 – Web sources indicators data finding** In this first phase, a thorough analysis of available web sources is carried out in terms of indicators that are able to provide very precise indications of:

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Name of Indicator	Hazard web sources indicator
	➢ hazard of the event ➢ damage caused; ➢ particular industries present in the area of interest; ➢ population distribution in the area of interest; ➢ poverty classes. **Step2 – Indicators data harmonization:** The data from the different indicators have different formats. For example, in the case of GDACS, we have tabular information, in the case of the precipitation that occurred which is useful for defining the hazard of the event is a raster, while for population and poverty distribution we have vector layers. These different formats, in order for them to be considered in the algorithm, must be unified. The final format that is given as input to the model, is tabular. **Step3 – Indicators algorithm ingestion and aggregation** The input files properly harmonized, are then aggregated- if there is more than one reporting information on the same issue- so that they are ready for the run of the extreme event hazard assessment model. **Step4 – Urban Flooding hazard index definition** Each indicator considered is represented in the model as a weight (Ix) and intervenes in the following equation useful for defining hydraulic hazard (main output of the model): $FH(I_x) = (I_1) + (I_2) + (I_3) + (I_4)$ In quantitative terms, the sum of the proposed indices will result in 3 possible hazard classes: - Low - Medium - High

FH(Ix)	Hazard class
0-2	LOW
2-4	MEDIUM
4-6	HIGH

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7.1.5.2 Demographic and socio-economic indicators

The following is a collection of ideas for creating novel indicators for socio-economic vulnerability to urban floods along the categories defined in section 7.1.3.1 above. The indicators shall address the gaps previously identified, i.e. limitations in spatial and temporal resolutions, cost and effort involved in acquisition, and applicability in the context of developing countries.

In general, the indicators shall:

- have greater spatial and temporal precision than conventionally used indicators
- have wider coverage (preferably global)
- be suitable for use in developing countries
- be relatively inexpensive to produce
- be valid measurements of socio-economic vulnerability to urban floods

Indicators shall also draw from traditional and social media sources. Based on initial work (as noted in section 7.1.3.3 above), media-based indicators are planned to be derived in a principled manner. This entails a clear and operational definition of indicators in a way which allows further fusion with other kinds of indicators. Based on this definition a set of indicators targeting urban floods (as well as food (in-)security) will be developed. Sources and concepts (within the Media Mining system) will be extended and refined (in terms of both geographic and language coverage).

Indicators derived from media are expected to complement more traditional types of indicators. They may serve as proxies for phenomena discussed by the local population and media, thus extending official statistics or surveys. The goal is to establish a sound definition of what a socio-economic indicator based on media constitutes, to later design and develop such indicators according to this methodology and finally compute the indicators from relevant sources. In principle, indicators are expected to be of a quantitative and robust nature which will allow combining them with other kinds of indicators such as ones produced by climatic or geo-spatial analysis.

The below list presents an initial set of categories for the generation of (socio-economic) indicators (from media).

Flooding:

- Preparedness or vulnerability with regard to flooding events
- Information from and about first responders and (local) government institutions, governance and law-making, planning and construction of infrastructure, information about (large-scale) exercises
- Information about critical infrastructure and its maintenance
- Information about (negligence of) maintenance, congestion of drainage systems, state of sewage, dams, bridges, and reservoirs
- Complaints about violations of regulations or laws

Flooding events:

- Information about heavy rainfall
- Comments about local effects of climate crisis
- Reporting of specific incidents (in particular with images)

The above items only represent an initial set of categories and are expected to be extended and fine-tuned over time as the use-cases develop. For each category, sources will be identified (which can be expected to yield information for the respective category) and a set of concepts (linked via ontologies) will be created. A set of

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(quantitative) indicators based on the sources and concepts will be devised in a principled manner. The methodology will be distilled into a blueprint for further use-cases (such as the food security use-case).

All in all, for the CENTAUR project, the following indicators will be considered with regards to socio-economic vulnerability to urban floods:

- UF-ID-8: Robustness and quality of the built environment
- UF-ID-9: Assets and financial resources
- UF-ID-10: Public services and government support
- UF-ID-11: Social networks and community support
- UF-ID-12: Timely access to information
- UF-ID-13: Ability to flee
- UF-ID-14: Economic impact of floods

Below the ID-cards related for each indicator reported in the list.

UF-ID-8: Robustness and quality of the built environment

Name of Indicator	Robustness and quality of the built environment
Brief Description	This group includes indicators of fragile urban infrastructure (e.g. poor drainage network and pipelines). It also includes indicators of uncontrolled urbanisation and settlement on marginalised land, as well as different indicators of the quality of materials used to build houses (e.g. for roofing). For example, garbage, adobe, clay bricks, and plastic are considered as poor building materials that increase households' vulnerability to floods.
Gap(s) addressed	Generating measures of socio-economic vulnerability to urban floods with broader coverage (including in developing countries) and greater spatial/temporal precision at comparably lower costs (i.e. bypassing tedious and expensive data collection techniques like surveys).
List of input data required with relative sources (when are available)	Building materials ➢ Pleiades or WorldView: VHR multispectral imagery of roofing materials. ➢ AI-based analysis such as Mask R-CNN model to distinguish buildings based on roofing material using panoptic segmentation of satellite imagery. ➢ National reference databases on roofing materials (e.g. BD TOPO distributed by the *Institut National de l'information Géographique et Forestière* of France). ➢ OpenStreetMap: roof material key. ➢ GHS-BUILT-V: construction dates, regulations, and type of materials used. State/deformation of critical flood protection infrastructure: EO data. Traditional and social media: ➢ Mention of issues around maintenance or absence of critical protective infrastructure.

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Name of Indicator	Robustness and quality of the built environment
	➢ Information about (negligence of) maintenance, congestion of drainage systems, state of sewage, dams, bridges, and reservoirs. ➢ Mention of poor quality of building materials, poor maintenance of buildings, lack of (enforcement of) building codes, etc.
Output indicator type and format	To be defined according in relation to the urban flood indicators
Spatial and temporal resolutions obtainable	Pending available data
Thematic area covered	Urban Flood
Workflow schema and brief steps description	**Step 1: assigning geospatial and temporal coordinates to input data, if not already included (e.g. in the case of media data).** **Step 2: join data with table containing units of analysis.** **Step 3: aggregate data by unit of analysis to create indicators** (e.g. average quality score for roofing materials in neighbourhood). **Step 4: create composite indices,** if necessary, by combining different indicators (e.g. average quality of roofs combined with quality of flood protection infrastructure score).

UF-ID-9: Assets and financial resources

Name of Indicator	Assets and financial resources
Brief Description	This group includes indicators of household wealth/poverty (which can be proxied by population density, as well-off neighbourhoods tend to be less dense in terms of population and built structure, although this assumption may not apply in all regions/contexts), house ownership, housing prices, job opportunities/unemployment, and access to insurance, credit, and community safety nets.
Gap(s) addressed	Generating measures of socio-economic vulnerability to urban floods with broader coverage (including in developing countries) and greater spatial/temporal precision at comparably lower costs (i.e. bypassing tedious and expensive data collection techniques like surveys).
List of input data required with relative sources (when are available)	Population distribution: GHSL Base layer: OpenStreetMap and VHR DSM data sources Housing prices: Web scraping of online real estate listings (subject to availability in target country) Traditional and social media • Mention of lack of financial means (or insurance) to cope with/prepare for floods ➢ Mention of poverty, unemployment, etc.

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Name of Indicator	Assets and financial resources
Output indicator type and format	To be defined according in relation to the urban flood indicators
Spatial and temporal resolutions obtainable	Pending available data
Thematic area covered	Urban Flood
Workflow schema and brief steps description	**Step 1: assigning geospatial and temporal coordinates to input data, if not already included (e.g. in the case of media data).** **Step 2: join data with table containing units of analysis.** **Step 3: aggregate data by unit of analysis to create indicators** (e.g. average quality score for roofing materials in neighbourhood). **Step 4: create composite indices,** if necessary, by combining different indicators (e.g. average quality of roofs combined with quality of flood protection infrastructure score).

UF-ID-10: Public services and government support

Name of Indicator	Public services and government support
Brief Description	This group includes indicators of access to basic health and other emergency response services, as well as the general capacity and predisposition of responsible actors to protect people against the detrimental effects of floods. For the latter, housing density per block as well as density of communication networks such as roads and railways could be used as proxies for government efforts in investing in urban planning.
Gap(s) addressed	Generating measures of socio-economic vulnerability to urban floods with broader coverage (including in developing countries) and greater spatial/temporal precision at comparably lower costs (i.e. bypassing tedious and expensive data collection techniques like surveys).
List of input data required with relative sources (when are available)	Population distribution: GHSL Base layer: OpenStreetMap and VHR DSM data sources Density of communication networks: OpenStreetMap and national reference databases Distance to nearest hospital and other relevant services: EO data Quality of roads (e.g. paved vs. sand): EO data. Traditional and social media ➢ Mention of poor or lacking services (e.g. water, sanitation, health, hospital beds, shelters). ➢ Mention of poor, lacking or delayed response by (local) government and first responders. ➢ Complaints about violations of relevant regulations or laws (e.g. on flood protection).

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Name of Indicator	Public services and government support
	➢ Sentiment towards actors responsible for flood preparedness and response of government officials more generally. Mention of corruption, nepotism, or political neglect (e.g. with regards to critical protective infrastructure)
Output indicator type and format	To be defined according in relation to the urban flood indicators
Spatial and temporal resolutions obtainable	Pending available data
Thematic area covered	Urban Flood
Workflow schema and brief steps description	**Step 1: assigning geospatial and temporal coordinates to input data**, if not already included (e.g. in the case of media data). **Step 2: join data with table containing units of analysis.** **Step 3: aggregate data by unit of analysis to create indicators** (e.g. average sentiment towards public officials score in neighbourhood). **Step 4: create composite indices,** if necessary, by combining different indicators (e.g. average sentiment towards officials combined with average corruption perception score and other indicators).

UF-ID-11: Social networks and community support

Name of Indicator	Social networks and community support
Brief Description	This group includes indicators that measure access to social networks and support by fellow community members, which are essential to effectively cope with or prepare for urban flood events.
Gap(s) addressed	Generating measures of socio-economic vulnerability to urban floods with broader coverage (including in developing countries) and greater spatial/temporal precision at comparably lower costs (i.e. bypassing tedious and expensive data collection techniques like surveys).
List of input data required with relative sources (when are available)	Traditional and social media: ➢ Sentiment (trust in) neighbours and members of other social groups (based on religion, ethnicity, race, class, political/ideological affiliation, etc.).
Output indicator type and format	To be defined according in relation to the urban flood indicators
Spatial and temporal resolutions obtainable	Pending available data
Thematic area covered	Urban Flood
Workflow schema and brief steps description	**Step 1: assigning geospatial and temporal coordinates to input data**, if not already included (e.g. in the case of media data). **Step 2: join data with table containing units of analysis.**

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Name of Indicator	Social networks and community support
	Step 3: aggregate data by unit of analysis to create indicators (e.g. average trust in neighbours score in neighbourhood). **Step 4: create composite indices,** if necessary, by combining different indicators (e.g. average trust in neighbours combined with average trust in people of another faith and other indicators).

UF-ID-12: Timely access to information

Name of Indicator	Timely access to information
Brief Description	This group includes indicators that measure the level of access to information that is crucial to quickly react and adequately prepare for urban flood risks.
Gap(s) addressed	Generating measures of socio-economic vulnerability to urban floods with broader coverage (including in developing countries) and greater spatial/temporal precision at comparably lower costs (i.e. bypassing tedious and expensive data collection techniques like surveys).
List of input data required with relative sources (when are available)	Education and skill levels: e.g. from DHS surveys Traditional and social media: ➢ Richness of flood risk prevention information by first responders, NGOs, (local) government, etc. ➢ Access and re-distribution of information provided by official institutions and first-responders.
Output indicator type and format	To be defined according in relation to the urban flood indicators
Spatial and temporal resolutions obtainable	Pending available data
Thematic area covered	Urban Flood
Workflow schema and brief steps description	**Step 1: assigning geospatial and temporal coordinates to input data**, if not already included (e.g. in the case of media data). **Step 2: join data with table containing units of analysis.** **Step 3: aggregate data by unit of analysis to create indicators**. **Step 4: create composite indices,** if necessary, by combining different indicators.

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UF-ID-13: Ability to flee

Name of Indicator	Ability to flee
Brief Description	This group includes indicators that measure people's abilities to move out of harm's way, in terms of available infrastructure, physical conditions, and social context (e.g. presence of vulnerable and dependent groups such as children, elderly, and disabled persons).
Gap(s) addressed	Generating measures of socioeconomic vulnerability to urban floods with broader coverage (including in developing countries) and greater spatial/temporal precision at comparably lower costs (i.e. bypassing tedious and expensive data collection techniques like surveys).
List of input data required with relative sources (when are available)	Transport networks, infrastructure, and evacuation routes: OpenStreetMap and VHR DSM data sources. Traffic information: data on travel speed information per type of road and road density (e.g. Google data), population density, density of built structures, etc. Quality of roads: EO data. Traditional and social media: ➢ Mentions of entrapment and inability to move. ➢ Mentions of difficulties for vulnerable groups to move away (e.g. children, elderly, disabled persons, etc.). ➢ Information about (damage to) infrastructure.
Output indicator type and format	To be defined according in relation to the urban flood indicators
Spatial and temporal resolutions obtainable	Pending available data
Thematic area covered	Urban Flood
Workflow schema and brief steps description	**Step 1: assigning geospatial and temporal coordinates to input data,** if not already included (e.g. in the case of media data). **Step 2: join data with table containing units of analysis.** **Step 3a: aggregate data by unit of analysis to create indicators** (e.g. number of evacuation routes in neighbourhood) **Step 3b: develop model to analyse transport congestion**, using data on traffic speed and building/population density **Step 4: create composite indices,** if necessary, by combining different indicators (e.g. number of evacuation routes combined with frequency of mentions of situations of entrapment in neighbourhood in a day).

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UF-ID-14: Economic impacts of floods

Name of Indicator	Economic impacts of floods
Brief Description	This group includes indicators of estimated economic damage of floods.
Gap(s) addressed	Generating measures of socioeconomic vulnerability to urban floods with broader coverage (including in developing countries) and greater spatial/temporal precision at comparably lower costs (i.e. bypassing tedious and expensive data collection techniques like surveys).
List of input data required with relative sources (when are available)	Economic assessments of flood damages: e.g. EM-DAT Traditional and social media: ➢ Visual evidence of flood damages (e.g. images, videos) to improve or verify damage estimations Transport networks, infrastructure, and evacuation routes: OpenStreetMap and VHR DSM data sources.
Output indicator type and format	To be defined according in relation to the urban flood indicators
Spatial and temporal resolutions obtainable	Pending available data
Thematic area covered	Urban Flood
Workflow schema and brief steps description	**Step 1: assigning geospatial and temporal coordinates to input data,** if not already included (e.g. in the case of media data). **Step 2: join data with table containing units of analysis.** **Step 3: aggregate data by unit of analysis to create indicators** (e.g. average estimated flood damage in neighbourhood in a day).

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7.2 DATASETS AND INDICATORS TO SUPPORT CSS-SEA APPLICATIONS

7.2.1 Biophysical parameters and agriculture monitoring data sources and indicators

Following is a summary of the raw biophysical parameters and agricultural monitoring dataset that will be used to develop the new water and food security indicator as part of the CENTAUR project.

The purpose of the biophysical parameter indicators (Table 7-1) is to evaluate (diagnose) the current crop health status. Actual conditions serve as the basis for synoptic (3 to 6 month) projections of the health condition. Combining the current health conditions with the ECMWF-provided climate projections, projections will be made.

Table 31. This table summarizes the indicators that will be used in order to generate the new indicators in the framework of the CENTAUR project.

Variable	Input data	Web address	Methodology	Spatial Resolution	Temporal Resolution	Format
NDVI	Harmonized NIR and red reflectance bands derived from Proba-V and Sentinel-3 sensors	https://land.copernicus.eu/global/products/ndvi	(NIR - R)/(NIR + R)	330 m	Dekad	GeoTIFF
LAI	Harmonized optical surface reflectance bands from Proba-V and Sentinel-3 sensors	https://land.copernicus.eu/global/products/	Derived from NDVI data using a trained neural network.	330 m	Dekad	GeoTIFF
FAPAR	Harmonized optical surface reflectance bands from Proba-V and Sentinel-3 sensors	https://land.copernicus.eu/global/products/fapar	Derived from NDVI data using a trained neural network.	330 m	Dekad	GeoTIFF
ESI	ESI describes temporal anomalies in evapotranspiration,	https://servirglobal.net/Global/Evaporative-Stress-Index	ET is retrieved via energy balance using	5Km		GeoTIFF

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	highlighting areas with anomalously high or low rates of water use across the land surface The ESI also demonstrates capability for capturing early signals of "flash drought," brought on by extended periods of hot, dry, and windy conditions leading to rapid soil moisture depletion		remotely sensed land-surface temperature (LST) time-change signals. LST is a fast-response variable, providing proxy information regarding rapidly evolving surface soil moisture and crop stress conditions at relatively high spatial resolution			
FCOVER	Harmonized optical surface reflectance bands from Proba-V and Sentinel-3 sensors	https://land.copernicus.eu/global/products/fcover	Derived from NDVI data using a trained neural network.	330 m	Dekad	GeoTIFF
SMA	Is used for determining the start and duration of agricultural drought conditions, which arise when soil moisture	https://edo.jrc.ec.europa.eu/gdo/php/index.php?id=2001	It is computed as a deviation from the climatological reference period, and is	0.1 degree	10 days	GeoTIFF

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	availability to plants drops to such a level that it adversely affects crop yield, and hence, agricultural production		updated 3 times a month (after the 10th, the 20th and the last day of the month			
NDMI	Normalized Difference Moisture Index (NDMI) is used to determine vegetation water content. It is calculated as a ratio between the NIR and SWIR values in traditional fashion .	Sentinel-2 and Landsat 8 satellites	NDWI use the NIR-SWIR combination to detect moisture content in leaves	30-60 m	5-15 days	GeoTIFF
Thermal drought stress indicator	Land surface temperature data derived from AVHRR (NOAA and METOP satellites), MODIS and Sentinel-3, combined with air temperature data from ECMWF's ERA5 and AgERA5 meteorological datasets		Difference between land surface temperature and air temperature as measured at 2 m above the ground.	300 m – 1 km	Daily	GeoTIFF
Drought Intensi	Harmonized NDVI time series based on		The indicator is based on	1 km	Dekadal -	GeoTIFF

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ty (VICI)	SPOT, Proba-V and Sentinel-3 data and land cover information.		deviations in NDVI from the normal baseline situation as expected in the region, the latter being based on statistics derived from 20 years of NDVI data.		Seasonal	

Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) is a well-established method to quantify vegetation greenness and is useful in understanding vegetation density and assessing changes in plant health captured in a satellite image. NDVI is one of the most common remote sensing indices. Its practical applications are incredibly diverse, including quantifying forest supply, serving as a drought indicator, forecasting fire zones and mapping desertification (Kogan, 1996[226]).

Healthy vegetation has a very characteristic spectral reflectance curve which we can benefit from by calculating the difference between two bands – visible red (R) and near-infrared (NIR). NDVI is that difference expressed as a number – ranging from -1 to 1. NDVI defines values from -1.0 to 1.0, where negative values mainly represent clouds, water and snow, and values close to zero primarily depict rocks and bare soil. Very small values (0.1 or less) of the NDVI function correspond to empty areas of rocks, sand or snow. Moderate values (from 0.2 to 0.3) represent shrubs and meadows, while large values (from 0.6 to 0.8) indicate temperate and tropical forests.

[226] Kogan, F.N., 1995: Droughts of the late 1980s in the United States as derived from NOAA polar-orbiting satellite data. Bulletin of the American Meteorology Society, 76(5)

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Figure 93. NDVI images from Sentinel 2 in Zomba, Lake Chilwa in Malawi illustrating the seasonal changes in 2021 (May right after the end of the raining season and August at the end of the dry season).

Leaf Area Index (LAI)

Leaf area index (LAI) quantifies the amount of leaf area in an ecosystem and is a critical variable in processes such as photosynthesis, respiration, and precipitation interception. As a fundamental attribute of global vegetation, LAI has been listed as an essential climate variable by the global climate change research community and is a critical parameter for understanding terrestrial, ecological, hydrological and biogeochemical processes (Willian, 1946[227]). LAI can be estimated from remote sensing data using either statistical or physical methods. The statistical methods use the empirical relationship between the LAI and surface reflectance or vegetation indices. The physical methods determine the LAI based on radiative light transfer processes within the canopy. Various retrieval methods, including neural network methods, genetic algorithms, Bayesian networks, and lookup table methods can be used to retrieve LAI. In addition major global moderate-resolution LAI products, such as Moderate Resolution Imaging Spectroradiometer, GEOV1, GLASS, GLOBMAP, ECOCLIMAP, and CCRS have been developed.

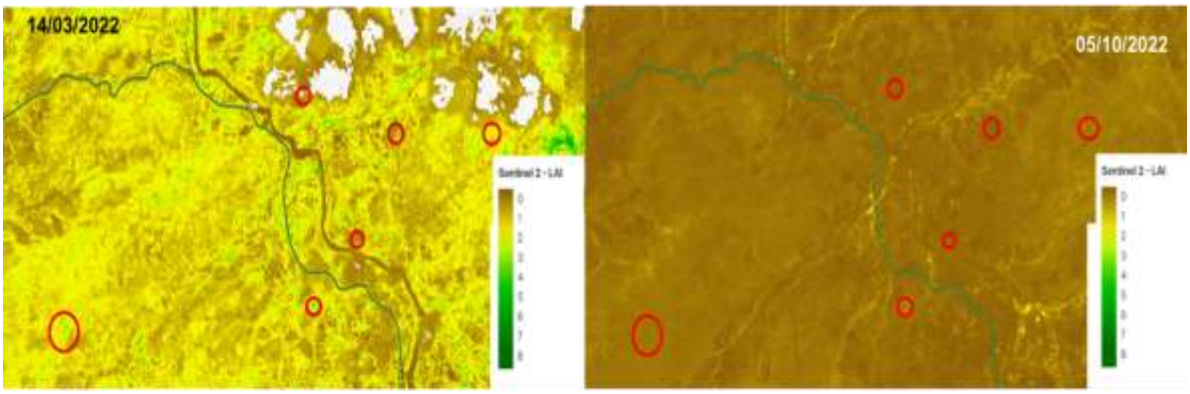

Figure 94. LAI images from Sentinel 2 Birriri, Chimanimani Biosphere Reserve in Zimbqbwe illustrating the seasonal changes in 2022 (March end of the raining season and 0ctober after the end of the dry season).

[227] Williams, R.E. (1946). Ann. Bot., 10: 41-71

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Fraction of Absorbed Photosynthetically Active Radiation (FAPAR)

The fAPAR (fraction of Absorbed Photosynthetically Active Radiation) quantifies the fraction of the solar radiation absorbed by live leaves for the photosynthesis activity (Sellers et al., 1992[228]). Then, it refers only to the green and alive elements of the canopy. The fAPAR depends on the canopy structure, vegetation element optical properties, atmospheric conditions, and angular configuration. fAPAR is recognized as an Essential Climate Variable (ECV) by the Global Climate Observing System (GCOS).

Regarding drought monitoring for agriculture and vegetation growth status, the FAPAR can serve as a proper proxy for greenness and vegetation health. The inter-comparison between fAPAR, SPEI, and soil moisture can to some extent show the ability of FAPAR for drought monitoring, as the fAPAR standardized anomaly generally agrees well with soil moisture standardized anomaly and SPEI. In particular, the high correlation appears in highly vegetated areas, which suggests the ability of fAPAR to be useful for agricultural drought monitoring.

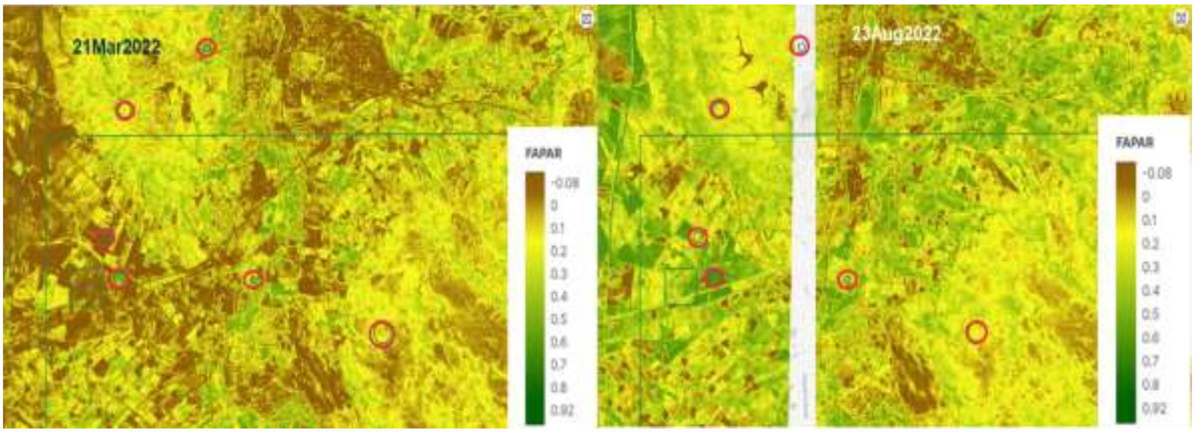

Figure 95. FAPAR images from Sentinel 2 Paarl, Cape Wineland Biosphere Reserve in South Africa illustrating the seasonal changes in 2022 (March end of the raining season and August at the end of the dry season).

Evaporative Stress Index (ESI)

The Evaporative Stress Index (ESI) describes temporal anomalies in evapotranspiration, highlighting areas with anomalously high or low rates of water use across the land surface (Anderson et al., 2011[229]). Here, ET is retrieved via energy balance using remotely sensed land-surface temperature (LST) time-change signals. LST is a fast-response variable, providing proxy information regarding rapidly evolving surface soil moisture and crop stress conditions at relatively high spatial resolution. The ESI also demonstrates capability for capturing early signals of “flash drought," brought on by extended periods of hot, dry, and windy conditions leading to rapid soil moisture depletion.

Fraction of Vegetation Cover (FCOVER)

The Fraction of Vegetation Cover (FCOVER) defines an important structural property of a plant canopy, which corresponds to the complement to unity of the gap fraction at nadir direction, accounting for the amount of vegetation distributed in a horizontal perspective (Roujean et al., 1992230). Because it is independent from the illumination direction and it is sensitive to the vegetation amount. FCOVER is related with the partition between

[228] Sellers, P.J.; Berry, J.A.; Collatz, G.J.; Field, C.B.; Hall, F.G. Canopy reflectance, photosynthesis, and transpiration, III. A reanalysis using improved leaf models and a new canopy integration scheme. Remote Sens. Environ. 1992, 42, 187–216.

[229] Anderson, M.C., C. Hain, B. Wardlow, A. Pimstein, J.R. Mecikalski and W.P. Kustas, 2011: Evaluation of drought indices based on thermal remote sensing of evapotranspiration over the continental United States. Journal of Climate, 24(8): 2025–2044

[230] Roujean, J.L., M. Leroy and P.Y. Dechamps, (1992). A bidirectional reflectance model of the earth's surface for the correction of remote sensing data. Journal of Geophysical Research, 97 (D18), pp. 20455-20468.

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soil and vegetation contribution for emissivity and temperature. This property is necessary for describing land surface processes and surface parameterization schemes used for climate and weather forecasting. Besides, the FCOVER is relevant for a wide range of Land Biosphere Applications such as agriculture and forestry, environmental management and land use, hydrology, natural hazards monitoring and management, vegetation-soil dynamics monitoring, drought conditions and fire scar extent.

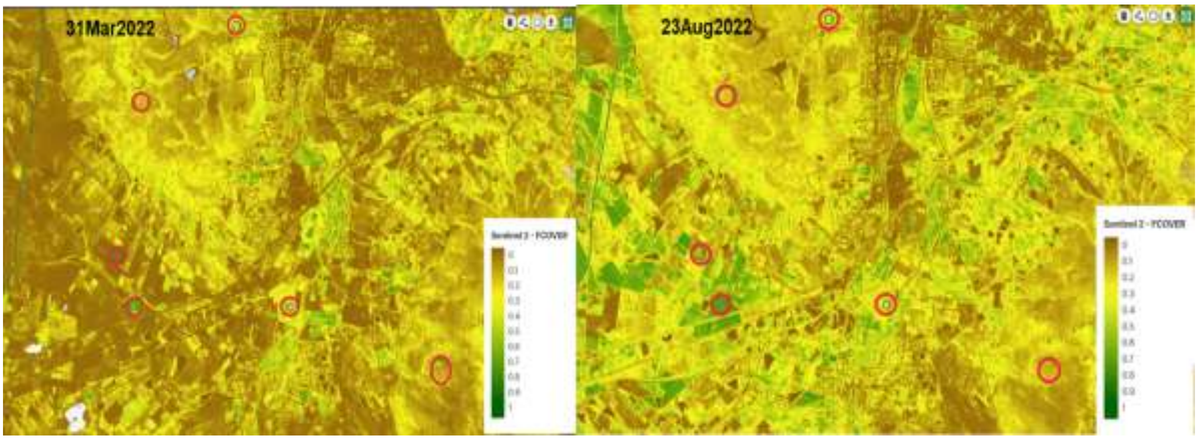

Figure 96. FCOVER images from Sentinel 2 Paarl, Cape Wineland Biosphere Reserve in South Africa illustrating the seasonal changes in 2022 (March end of the raining season and August at the end of the dry season).

Soil moisture anomaly (SMA)

The Soil Moisture Anomaly (SMA) indicator that is implemented in the Copernicus Global Drought Observatory (GDO) is used for determining the start and the duration of agricultural drought conditions, which arise when soil moisture availability to plants drops to such a level that it adversely affects crop yield, and hence, agricultural production (Bergman et al., 1988[231]). The SMA indicator in GDO is derived from anomalies of estimated soil moisture (or soil water) content - which are produced as an ensemble of three datasets: the JRC's in-house LISFLOOD hydrological model, the MODIS-derived land surface temperature and ESA combined active/passive microwave skin soil moisture.

Normalized Difference Moisture Index (NDMI)

Normalized Difference Moisture Index (NDMI) is used to determine vegetation water content. It is calculated as a ratio between the NIR and SWIR values in traditional fashion (McFeeters (1996232). NDMI has the capacity to detect water stress at an early stage. Further, using NDMI to monitor irrigation, especially in areas where crops require more water than nature can supply, helps to significantly improve crop growth. All of this makes NDMI an excellent agricultural tool. Although colloquially NDMI is often compared with the NDWI index, the two should be effectively viewed as different indices. While NDMI and Gao's version of NDWI use the NIR-SWIR combination to detect moisture content in leaves, the McFeeters's NDWI uses the GREEN-NIR combination to highlight water bodies and monitor their turbidity. NDMI is calculated using the near-infrared (NIR) and the short-wave infrared (SWIR) reflectance. The NIR and SWIR bands were selected for the NDMI band equation to mitigate the effects of illumination and atmosphere. The short-wave infrared spectral channel (SWIR) is sensitive to the vegetation water content and the mesophyll structure of leaves. On the other hand, the near-infrared band (NIR) picks up the bright reflectance off the leaf internal structure and leaf dry matter content. When combined, the accuracy of data on

[231] Bergman, K.H., P. Sabol and D. Miskus, 1988: Experimental Indices for Monitoring Global Drought Conditions. Proceedings of 13th Annual Climate Diagnostics Workshop, United States Department of Commerce, Cambridge, MA.

[232] S. K. McFeeters (1996) The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features, International Journal of Remote Sensing, 17:7, 1425-1432

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the vegetation water content becomes much higher. Additionally, NDMI is a better deforestation indicator than NDVI thanks to a less abrupt decrease in values. The NDMI haves values between -1 and 1. Water stress would be signaled by the negative values approaching -1, while the +1 may indicate waterlogging. Therefore every value in between will correspond to a slightly different agronomic situation. Thermal drought stress indicator

To ensure global water and food security, it is of the utmost importance to identify plant water stress or drought. Consequently, knowledge of crop water status across expansive farming areas has the ability to optimize agricultural water use. Water-deficit stress (drought) refers to the physiological reactions of plants generated by a shortage of accessible water caused by either a soil water deficit or a high evaporative demand from the atmosphere. Water stress is one of the most important abiotic stressors that limit plant development, crop yield, and food quality. Before apparent indications of water stress show, plants might be irreparably damaged. Consequently, a pre-symptomatic or pre-visual identification of plant physiological changes might significantly aid in preventing severe crop losses.

Cell turgor and leaf water content are diminished under severe and/or persistent water stress. As a result, stomatal closure reduces the exchange of water vapour between plants and the atmosphere, reducing the evaporative cooling effect and resulting in an increase in plant surface temperature relative to a plant that is not under water stress. Nonetheless, stomata regulate not just plant transpiration but also plant respiration, which prevents CO2 absorption and fixation. Due to stomatal closure, the photosynthetic rate is lowered, resulting in a decrease in yield. While a decrease in CO2 uptake owing to stomatal closure reduces the photosynthetic rate, irradiance and absorbed photosynthetically active radiation (fAPAR) remain unchanged. It is well established, based on the leaf energy balance equation, that leaf temperature fluctuates with (evapo-) transpiration rates of the leaves and is, thus, a function of stomatal conductance. Temperature of the leaf has an inverse relationship with transpiration rate. Typically, the leaf temperature of a fully transpiring plant is between 2 and 5 degrees Celsius below the ambient air temperature. As a result, the difference between land surface temperature and ambient air temperature is a well-established indicator for drought stress occurring in crops.

Thermal infrared (TIR) multi-/hyperspectral method and conventional solar-reflective (visible, near-, and shortwave infrared reflectance (VNIR - SWIR) hyperspectral remote sensing are the most advanced techniques for detecting agricultural water stress. Since the 1970s, TIR remote sensing (8–14 µm) has been recognized as a "possible" method for early detection of plant water stress. TIR remote sensing is currently the main data source for land surface temperature estimations. TIR indices would theoretically offer significant application potential in precision agriculture, particularly in irrigation management, to determine the optimal time, place, and amount of water to apply in order to reduce the amount of water consumed per unit of yield. For highest benefit in agricultural water management applications, frequent thermal imaging (4-day revisit) at sub-field (100 m or less) spatial resolution is necessary. However, current TIR satellite platforms either offer data at low spatial resolution (e.g. MODIS, Sentinel-3) or low temporal frequency (Landsat 8), limiting their relevance for precision agriculture purposes. New high-resolution TIR satellite missions will be launched in the coming 5 years (ESA LSTM mission, NASA SBG mission, Thrishna mission) which will dramatically increase our capability of detecting crop water stress at individual field level. While waiting for these new data sources to become available, multi-sensor scaling, such as pan-sharpening, or more advanced disaggregation techniques are being employed to artificially increase temporal and spatial resolution of available TIR imagery. As an example, in the recent ESA Sen-ET project, a sharpening workflow was established to downscale Sentinel-3 land surface temperature (LST) from 1 km to 20 m using high-resolution optical data from Sentinel-2. An example of a high resolution drought stress indicator (defined by LST – air temperature) is visualized in **Errore. L'origine riferimento non è stata trovata.** LST in this example was based on the combined Sentinel-2 and Sentinel-3 Sen-ET LST product.

As occurrence of agricultural droughts is primarily a regional phenomenon, the thermal indicators to be used in the context of the CENTAUR project will be characterized by low spatial resolution, yet high temporal frequency as offered through the Sentinel-3 mission (two observations per day at 1 km resolution). This is in line with what

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has been implemented in FAO's ASIS system[233], where low resolution thermal data from AVHRR is combined with NDVI into the Vegetation Health Index (VHI), in turn quantifying the impact of drought on vegetation condition.

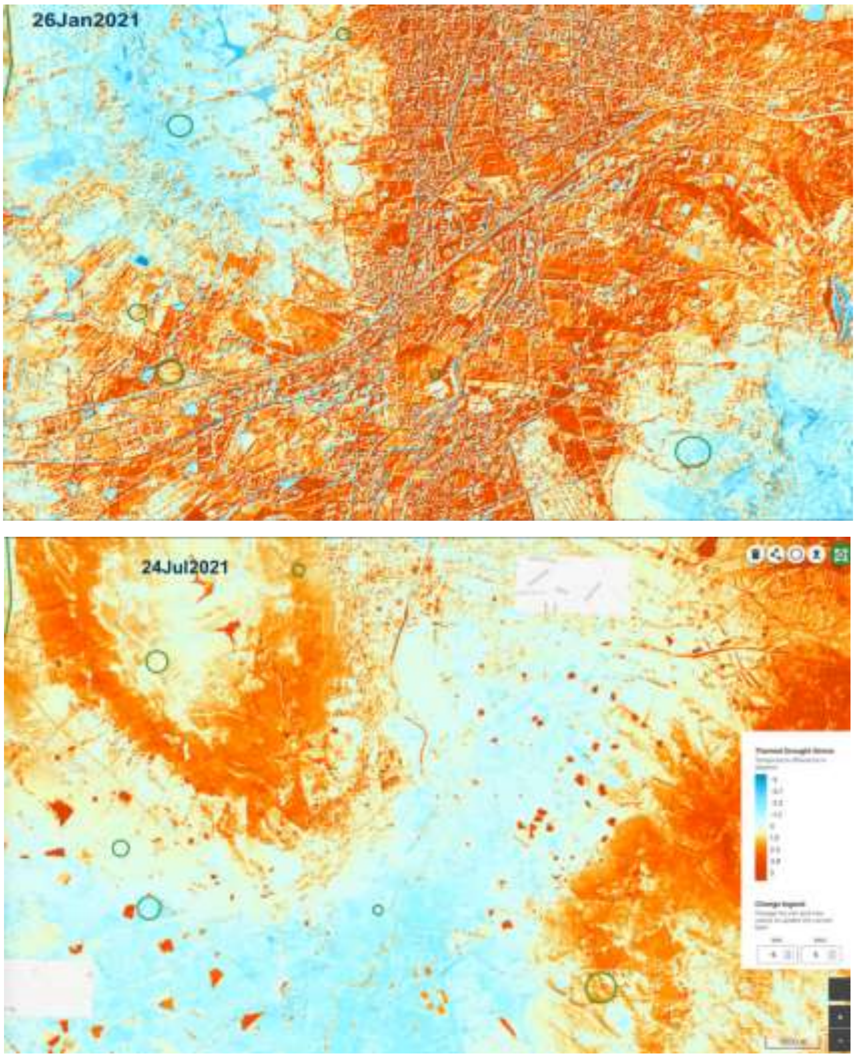

Figure 97. Thermal drought stress indicators for Paarl in Cape Wineland Reserve in South Africa in January and July of 2021. It is easy to notice the difference between both scenarios at different seasonal moments.

Drought Intensity

Traditionally, drought impact assessments make use of the concept of temporal anomaly analysis, i.e. how are current observations on vegetation condition deviating from the "normal" situation. In most drought early warning systems running today (e.g. FAO ASIS233, JRC's ASAP234, East Africa Drought Watch235, European Drought Observatory236), the NDVI is used as the main/only indicator of vegetation health. Typically, these systems operate at a decadal time interval and determine for every 10-day period how the current NDVI deviates from the normal baseline situation, the latter computed as the long-term historical average NDVI for that particular 10-day

[233] https://www.fao.org/giews/earthobservation/index.jsp?lang=en
[234] https://mars.jrc.ec.europa.eu/asap/
[235] https://droughtwatch.icpac.net/mapviewer/
[236] https://edo.jrc.ec.europa.eu/edov2/php/index.php?id=1000

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period. Two main limitations of this approach include that it runs on individual pixel basis (not considering natural variability in the region) and the interpretation of the resulting temporal anomaly does not consider regional meteorological conditions (identified anomalies can be problematic in one region but normal in another). VICI (Vegetation Index for Crop Insurance) is an indicator developed at ITC (UTwente) which aims to tackle both limitations by abandoning the purely pixel-based method of computing temporal anomalies, but instead clusters the landscape into homogeneous regions in terms of long-term NDVI behaviour and considers these regions to determine the normal baseline situation for a particular pixel. The workflow uses 20 years of harmonized NDVI time series based on SPOT, Proba-V and Sentinel-3 data and land cover information as main inputs. Within the CENTAUR project, this indicator will be adopted as one of the indicators for the occurrence of agricultural drought.

7.2.2 Water indicators

In the preceding section, the primary biophysical indicators of vegetation were introduced, explained, and illustrated. However, these indicators are the consequence of a combination of factors. For an accurate estimation of drought severity and effects, it is necessary to include the key water indicators in the analysis. These indicators will be utilized in the development of the new agricultural drought indicator to estimate the effects on crop yields. The main water indicators are shown in Table 7-2.

This section will also include the groundwater indicator as an exception because it does not directly affect vegetation health conditions but provides valuable information for mitigating the impact of drought conditions from a source of water other than surface water. Finally global surface water products are introduced, useful for surface water mapping.

Table 32. Summary of the main water indicators that will be used for the evaluation of drought conditions and severity as well as for projections at synoptic time period.

Variable	Input data	Web address	Methodology	Spatial Resolution	Temporal Resolution	Format
GPM	Global Precipitation Measurement is an international network of satellites that provide next-generation global observations of rain and snow.	Precipitation Data Directory | NASA Global Precipitation Measurement Mission	The GPM Core Observatory carries the first space-borne Ku/Ka-band Dual-frequency Precipitation Radar (DPR) and a multi-channel GPM Microwave Imager (GMI).	10 km	30 min	Several
CRU-TS	CRU TS monthly high-resolution gridded climate dataset	High-resolution gridded datasets (uea.ac.uk)	Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset | Scientific Data (nature.com)	50 km	Monthly	Several
GPCC	The GPCC offers gridded gauge-analysis products	GPCC: Global Precipitation	The GPCP Monthly product provides	2.5 °	Monthly	Several

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	made from station data that has undergone quality control.	[Climatology Centre | Climate Data Guide (ucar.edu)](https://climatedataguide.ucar.edu)	a consistent analysis of global precipitation based on the integration of numerous satellite data sets over land and water and a gauge analysis of land precipitation.			
ERA 5	ERA5 provides hourly estimates of a large number of atmospheric, land and oceanic climate variables.	https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5	ERA5 includes information about uncertainties for all variables at reduced spatial and temporal resolutions. Quality-assured monthly updates of ERA5 (1959 to present) are published within 3 months of real time. Preliminary daily updates of the dataset are available to users within 5 days of real time.	30 km	Monthly	Several
GRACE Ground water & Root Zone Soil Moisture indicator	NASA's Goddard Space Flight Center generates soil moisture drought indicators each week based on the GRACE sensor. Lower values (warm colours) meaning dryer than normal, and higher values (blues) meaning wetter than normal.	https://nasagrace.unl.edu/	NASA's GRACE sensor measures the gravimetric field of the Earth in high detail, allowing to derive a relative measure of root zone soil moisture, along with other components of the water balance.	25 km	Weekly	GeoTIFF
Soil Moisture (SMOS)	The SMOS mission is a direct response to the existing shortage of worldwide measurements	https://www.eoportal.org/satellite-missions/smos		30 – 50 km	3 days	Several

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	of soil moisture, which are essential for advancing our understanding of the water cycle and improving weather, extreme-event, and seasonal-climate forecasts. The estimation of soil moisture at the root zone is crucial for developing short- and medium-term meteorological models, hydrological models, the monitoring of plant growth, and the prediction of disastrous events such as floods.					
Soil Moisture Active Passive SMAP	The Soil Moisture Active Passive (SMAP) project is an orbiting observatory that measures the water content of the Earth's surface soil. The SMAP radiometer has been performing without defect. The three-year prime mission phase of SMAP was concluded in 2018, and the mission is now in its extended operating phase.	SMAP - Soil Moisture Active Passive | NASA https://nsidc.org/data/spl4smlm/versions/7	Such estimates are obtained by merging SMAP observations with estimates from a land surface model in a data assimilation system. The land surface model component of the assimilation system is driven with observations-based meteorological forcing data, including precipitation, which is the most important driver for soil moisture. The model also encapsulates knowledge of key land surface processes, including the vertical transfer of soil moisture between the surface and root zone reservoirs.	9km x 9km	Daily	Several

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			Finally, the model interpolates and extrapolates SMAP observations in time and in space, producing 3-hourly estimates of soil moisture at a 9 km resolution			
JRC Global surface water	The Landsat-based JRC Global surface water product maps the location and extent of surface water at 30 meter resolution over the 1984 – 2021 period. Each pixel is classified into water or non-water. Information is broken down in 3 layers : the number of detections over the observation period, the number of valid observations and the total number of observations during the study period.	https://storage.googleapis.com/global-surface-water/downloads_ancillary/DataUsersGuidev2021.pdf	Water presence / absence is mapped in all available and cloud free Landsat images over the 1984 – 2021 period. Methods are further explained here : https://www.nature.com/articles/nature20584	30 m	once	
GLAD Global Surface Water Dynamics	The GLAD Global Surface Water Dynamics layer highlights changes in surface water extent during the 1999 – 2021 period on top of unbiased estimators of the area of permanent water, seasonal water, water loss, water gain, temporary land, temporary water, and high-frequency change 1999-2018	https://glad.umd.edu/dataset/global-surface-water-dynamics	Water presence is mapped based on Landsat imagery	30m	Monthly	

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7.2.2.1 Precipitation data sources

Global Precipitation Measurement (GPM) – Constant production of measured data every 30 min since June 2000

GPM mission is an international network of satellites that provide next-generation global observations of rain and snow. The GPM concept centers on the deployment of a "Core Observatory" satellite carrying an advanced radar / radiometer system to measure precipitation from space and serve as a reference standard to unify precipitation measurements from a constellation of research and operational satellites.

Through improved measurements of precipitation globally, the GPM mission is helping to advance our understanding of Earth's water and energy cycles, improve forecasting of extreme events that cause natural hazards and disasters, and extend current capabilities in using accurate and timely information of precipitation to directly benefit society. GPM comprises a consortium of international space agencies, including the Centre National d'Études Spatiales (CNES), the Indian Space Research Organization (ISRO), the National Oceanic and Atmospheric Administration (NOAA), the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT), and others.

IMERG Final Run: Research-quality gridded global multi-satellite precipitation estimates with quasi-Lagrangian time interpolation, gauge data, and climatological adjustment. This algorithm is intended to intercalibrate, merge, and interpolate "all" satellite microwave precipitation estimates, together with microwave-calibrated infrared (IR) satellite estimates, precipitation gauge analyses, and potentially other precipitation estimators over the entire globe.

The system is run several times for each observation time, first giving a quick estimate (IMERG Early Run) and successively providing better estimates as more data arrive (IMERG Late Run). The final step uses monthly gauge data to create research-level products (IMERG Final Run).

It is advised to use the Final Run for research unless their application will require the use of Early or Late data due to latency. The precipitation from the GPM is the most advanced direct primary source of precipitation event information around the world. With a temporal resolution of 30 minutes and a spatial resolution of 10 kilometers by 10 kilometers, its contribution to regional evaluation is invaluable. Nevertheless, its estimation accuracy can still be significantly enhanced. Overall, the GPM overstates the precipitation values for events with the lowest intensities. This may pose a significant challenge for assessing actual drought conditions.

CRU TS monthly high-resolution gridded climate dataset (CRU TS) – 1901 - 2018

CRU TS is one of the most widely used observed climate datasets and is produced by the UK's National Centre for Atmospheric Science (NCAS) at the University of East Anglia's Climatic Research Unit (CRU).

CRU TS provides monthly data on a 0.5° x 0.5° grid covering land surfaces (except Antarctica) from 1901 to 2018 (the next release, which is imminent, will extend this to 2019). There are ten variables, all based on near-surface measurements: temperature (mean, minimum, maximum and diurnal range), precipitation (total, also rain day counts), humidity (as vapor pressure), frost day counts, cloud cover, and potential evapotranspiration. CRU TS has been produced and shared openly to facilitate research and analysis in all areas related to climate and climate change since the first version was released in 2000. Version 4 is the first major update since version 3 was published in 2013. Version 4 features an improved interpolation process, which delivers full traceability back to station measurements. The station measurements of temperature and precipitation are provided as well as the gridded dataset and national averages for each country. Cross-validation was performed at a station level, and the results can be examined in the paper as a guide to the accuracy of the interpolation. The overall process is always being refined and improved, an approach made possible by NCAS funding as part of the NCAS Long-Term Global Change theme.

CRU TS is used in many different contexts, from analysis of climate variability/change and evaluation of climate models, through to the many sectors that are impacted by climate such as hydrology, insurance and civil engineering. Although it is not possible to measure the full extent of its use due to inconsistent (and occasionally

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absent) citations, Google Scholar citations of the scientific papers describing the first three versions provide a guide (>2300 for version 1, >4200 for version 2, and >3900 for version 3). This dataset has proven valuable as a long-term precipitation reference; however, its temporal and spatial resolution is insufficient for regional drought evaluation. Rapid onsets of drought (flash drought) can occur within days to one or two weeks. Consequently, CRU-TS cannot be utilized to evaluate these novel types of flash drought events

Global Precipitation Climatology Centre (GPCC) 1901 – 2010

The GPCC offers gridded gauge-analysis products made from station data that has undergone quality control. There are two products for studying climate variability and trends: (a) the VASClimO50-Year Data Set, which is for studies of climate variability and trend, and (b) the Full Data Reanalysis Product (1901–2010), which is advised for studies of global and regional water balances, calibration/validation of remote sensing-based rainfall estimates, and verification of numerical models. A systematic gauge measurement error bias correction is not applied to the products. The number of gauges utilized on the grid and estimates for that mistake are also provided by the GPCC.

- 64,400 or so stations are in use, and the gauge network goes beyond the GHCN
- A significant source of inhomogeneity can be the fluctuating number of stations non each grid throughout time.
- While climate products are not often updated, monitoring items are.

The Global Precipitation Climatology Project (GPCP) Monthly Precipitation Climate Data Record (CDR) – 1979 – present

The GPCP Monthly product provides a consistent analysis of global precipitation based on the integration of numerous satellite data sets over land and water and a gauge analysis of land precipitation. Since 1979, data from rain gauge stations, satellites, and sounding measurements have been used to estimate monthly precipitation on a 2.5-degree worldwide grid. The meticulous combining of satellite-based rainfall estimates gives the most comprehensive analysis of rainfall to date over the world's oceans and adds important spatial depth to analyses of rainfall over land. In addition to the combining of these data sets, the GPCP outputs also provide estimates of the uncertainties in the rainfall analysis. Current version number is 2.3. There may be interim data at the end of the dataset. There is a netcdf attribute that contains the interim data for the first month. Due to its temporal and spatial resolution, this dataset has proven useful as a long-term precipitation reference for subcontinental drought evaluations but not for regional drought evaluations.

ERA5 – 1959 – present

ERA5 provides hourly estimates of a large number of atmospheric, land and oceanic climate variables. The data cover the Earth on a 30km grid and resolve the atmosphere using 137 levels from the surface up to a height of 80km. ERA5 includes information about uncertainties for all variables at reduced spatial and temporal resolutions. Quality-assured monthly updates of ERA5 (1959 to present) are published within 3 months of real time. Preliminary daily updates of the dataset are available to users within 5 days of real time. A preliminary ERA5 dataset from 1950 to 1978 is also available on the Climate data store (CDS) (1959-1978 is superseded by the quality assured dataset). ERA5 combines vast amounts of historical observations into global estimates using advanced modelling and data assimilation systems. ERA5 replaces the ERA-Interim reanalysis which stopped being produced on 31 August 2019. You can read about the key characteristics of ERA5 and important changes relative to ERA-Interim. This dataset has proven valuable as a long-term precipitation reference; however, its temporal resolution is insufficient for regional drought evaluation. Rapid onsets of drought (flash drought) can occur within days to one or two weeks. Consequently, CRU-TS cannot be utilized to evaluate these novel types of flash drought event.

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7.2.2.2 Soil Moisture data sources

GRACE-groundwater & based root zone soil moisture and surface soil moisture

Scientists at NASA's Goddard Space Flight Center generate groundwater and soil moisture drought indicators each week. They are based on terrestrial water storage observations derived from GRACE-FO satellite data and integrated with other observations, using a sophisticated numerical model of land surface water and energy processes. The drought indicators describe current wet or dry conditions, expressed as a percentile showing the probability of occurrence for that particular location and time of year, with lower values (warm colors) meaning dryer than normal, and higher values (blues) meaning wetter than normal. These are provided as both images and binary data files.

The Contiguous U.S. (CONUS) indicators are generated at 0.125 degree, while the Global Land indicators are at 0.25 degree resolution. NASA's Gravity Recovery and Climate Experiment satellites, which were launched in 2002, were the only ones capable of measuring fluctuations in water stored at all levels above and within the ground surface (terrestrial water storage). The GRACE mission concluded in 2017, however the GRACE-FO mission, which started on May 22, 2018, is already extending the data record. The spatial (>150,000 km2) and temporal (monthly with a substantial time lag) resolutions of the GRACE and GRACE-FO fields restrict their direct use for drought assessment. NASA/GSFC scientists integrate GRACE and GRACE-FO data with other ground- and space-based meteorological observations (precipitation, solar radiation, etc.) within the Catchment Land Surface Model, employing Ensemble Kalman smoother type data assimilation, in order to increase the resolution, eliminate the time lag, and isolate groundwater and other components from total terrestrial water storage. The generated fields of soil moisture and groundwater storage fluctuations are then utilized to construct drought indicators based on the Catchment model's simulation of the cumulative distribution function of wetness conditions from 1948 to 2014. Houborg et al. (2012) provide comprehensive information on the creation of U.S. GRACE-based drought indicator products. Li et al. (2019) present information on the assimilation of global GRACE and GRACE-FO data and the production of drought indicator products. Getirana et al. (2020) provide information on the creation of drought/wetness forecast products for the CONUS. Based on the measurement of the Earth's gravimetric field with a temporal resolution of days, these indicators are the most advanced in comparison to other satellites or sensors with the same purpose of measuring root zone soil moisture. Unfortunately, it has a very low spatial resolution. Sharpening technologies enable global estimates with a spatial resolution of 25 km. This fact precludes the use of accurate root zone soil moisture and groundwater evaluations for practical purposes.

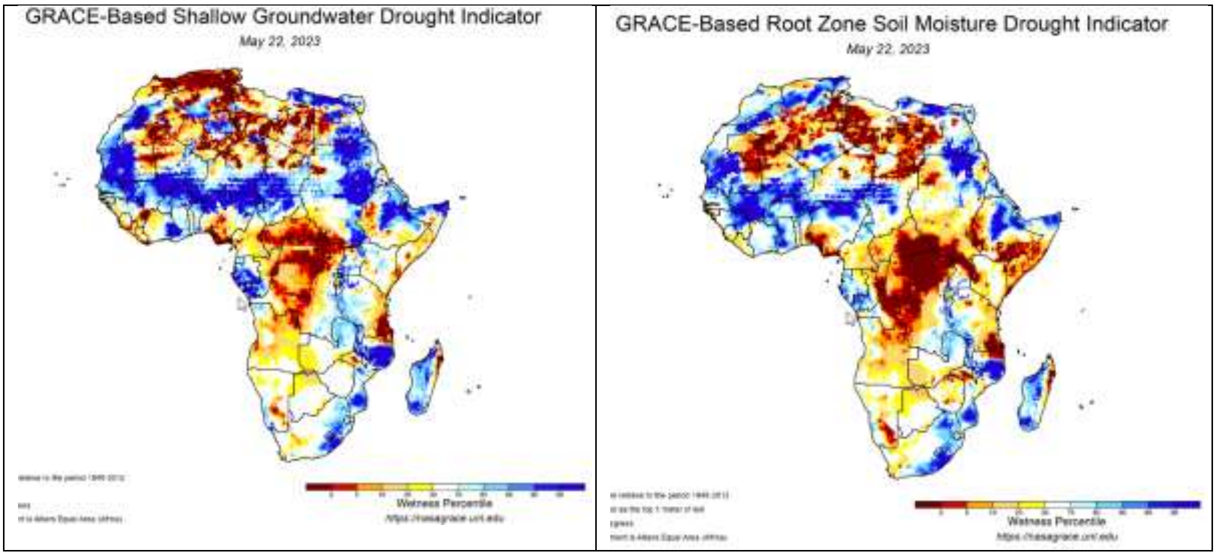

Figure 98. Last images from GRACE showing Shallow ground water and soil root zone moisture drought indicators.

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Soil Moisture and Ocean Salinity (SMOS)

The SMOS mission is a direct response to the existing shortage of worldwide measurements of soil moisture and ocean salinity, which are essential for advancing our understanding of the water cycle and improving weather, extreme-event, and seasonal-climate forecasts. Variation in soil moisture and ocean salinity is a result of the constant exchange of water between the oceans, atmosphere, and land - the water cycle of the Earth. Variability in soil moisture is mostly determined by varying evaporation and precipitation rates. The estimation of soil moisture at the root zone is crucial for developing short- and medium-term meteorological models, hydrological models, the monitoring of plant growth, and the prediction of disastrous events such as floods.

Obviously, soil moisture is essential for primary production, but it is also inextricably tied to our weather and climate. This is due to the fact that soil moisture is a crucial factor in regulating the exchange of water and heat energy between the ground and the atmosphere. The terrestrial portion of the water cycle is comprised of precipitation, soil moisture, percolation, runoff, soil evaporation, and plant transpiration. Therefore, there is a direct relationship between soil moisture and atmospheric humidity, as dry soil contributes little or no moisture to the atmosphere, whereas moist soil contributes a great deal. Moreover, because soil moisture is linked to evaporation, it is also significant in regulating the distribution of heat flux from the land to the sky, such that regions with high soil moisture not only increase local atmospheric humidity but also decrease local temperatures. Accuracy of 4% volumetric soil moisture; Spatial resolution 35-50 km; Revisit time 1-3 days.

Soil Moisture Active Passive (SMAP)

The Soil Moisture Active Passive (SMAP) project is an orbiting observatory that measures the water content of the Earth's surface soil. The SMAP radiometer has been performing without defect. Due to the loss of the radar's power source, the radar instrument ceased operation in early 2015, after collecting close to three months' worth of scientific data. The three-year prime mission phase of SMAP was concluded in 2018, and the mission is now in its extended operating phase. The topsoil is the layer in which our food and other vegetation grow and thrive. Indirectly, soil moisture influences us in a variety of ways. During its observations, SMAP will also identify whether the ground in colder regions of the globe is frozen or thawed. Every two to three days, SMAP is meant to measure soil moisture. This enables the observation of global changes on time-scales ranging from extreme weather events to recurrent seasonal surveys.

SMAP estimates the amount of water in the top layer of soil everywhere on Earth not covered by water or frozen. It also distinguishes between frozen and thawed ground. It quantifies the quantity of water found between the minerals, rocky material, and organic particles found in soil everywhere in the world when the earth is not frozen (SMAP measures liquid water in the top layer of ground but is not able to measure the ice.). SMAP will generate global soil moisture maps. These will be utilized by scientists to enhance our comprehension of how water, energy, and carbon fluxes (in their various forms) manage our climate and environment. The water cycle encompasses more than the obvious processes of evaporation from the oceans and land, condensation generating clouds that eventually drop rain or snow (precipitation), and water travelling through the land before returning to the sea. For instance, plants absorb water from the soil in order to develop, but they also "transpire" a portion of it directly into the air.

Water cycle has fewer branches than carbon cycle. It refers to the transport of carbon between and among the atmosphere (air), pedosphere (soil), lithosphere (rock), hydrosphere (surface water: ocean, lakes, and rivers), and cryosphere (frozen regions) of the Earth (all forms and places where ice is found on Earth including sea ice, snow, glaciers, and permafrost). Carbon (in the form of carbon dioxide) is present in the air, dissolved in water, emitted from subsurface sources, and exhaled by all living organisms. There are carbonate minerals on the ocean floor, in mountains, and in the famed White Cliffs of Dover. Carbon is contained underground in petroleum and coal until it is pumped or mined. All of these kinds of carbon can cycle through the spheres in diverse ways.

Weather and climate studies will also utilize SMAP data. The soil moisture determines the amount of water that evaporates from the land surface into the atmosphere. Information on soil moisture is essential for comprehending the water and heat energy exchanges between the surface and atmosphere that influence

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weather and climate. Since April 2015, SMAP data have offered an abundance of information regarding regional and global soil moisture variability. SMAP's frequent and accurate monitoring of soil moisture will enhance the forecasting abilities of weather and climate models.

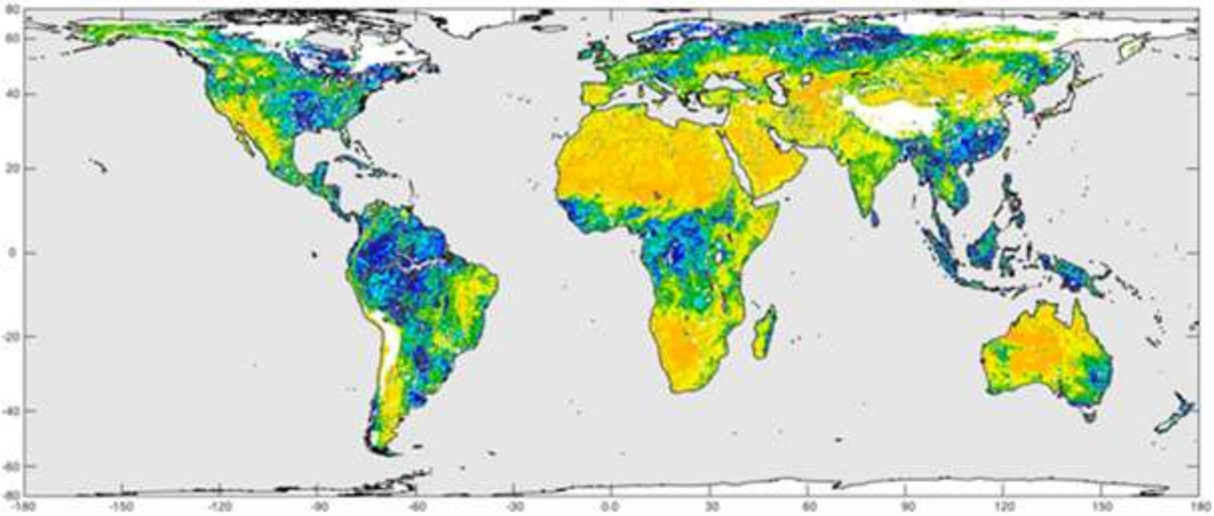

Figure 99. Retrieved soil moisture based on the SMAP “active” and “passive” radiometer data. SMAP Active-Passive Soil Moisture Product (9 km). Three Days Composite May 21st to May 23rd, 2015.

7.2.3 Meteorological variables and forecasts

7.2.3.1 Present meteorological variables and forecasts available

This section reviews operational meteorological drought monitoring and forecasting systems that are presently available, and briefly introduces common meteorological drought indicators that are often used for these purposes.

- Drought indicators

The most prominently used drought indicator is the standardised precipitation index (SPI), which quantifies the severity of a drought event with respect to a long-term mean. The SPI is usually calculated for a specific time scale k, which is typically set to 1, 3, 6, 9, 12 or 24 months. Through the standardisation, the SPI returns a single numeric value that is comparable across different climates and that quantifies the rarity of an event.

Another prominent drought indicator is the standardised precipitation evapotranspiration index (SPEI), which is calculated analogously to the SPI but accounts for potential evapotranspiration from the land surface. Through the incorporation of potential evapotranspiration, the SPEI captures the impact of temperature on water demand. Similarly, the Palmer drought severity index (PDSI) estimates dryness using precipitation and temperature data and a simplified water balance model, and thus also captures the basic feedbacks of global warming on drought.

The impact of meteorological drought on agriculture is often assessed using the soil moisture index (SMI) or soil moisture anomaly (SMA). The combined drought indicator (CDI) also focuses on agricultural drought, i.e., regions that may suffer reduced crop production due to lower-than-usual soil moisture. The CDI is based on the SPI, the soil moisture anomaly and an anomaly related to the vegetation stress (fraction of absorbed photosynthetically active radiation, FAPAR). This index distinguishes between five drought impact levels, i.e. **watch** (a relevant precipitation deficit is observed), **warning** (the precipitation deficit is accompanied by a soil moisture anomaly), **alert** (precipitation deficit and soil moisture anomaly is accompanied by a negative anomaly of vegetation growth), **partial recovery** (after a drought episode, meteorological conditions have returned to normal but not the vegetation growth), **full recovery** (meteorological conditions and vegetation growth have returned to normal).

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Current drought monitoring systems

To date, there exist only a few operational drought monitoring systems, i.e., systems that estimate the current state of drought — an overview of these systems and their coverage is provided in Table 1 and briefly described here. The European Drought Observatory (EDO) and the Global Drought Observatory (GDO) provide several indicators and overview products which describe the current drought situation in Europe and over the globe, respectively. These products are based on observations of precipitation, temperature, soil moisture from either in-situ observations or derived from satellites, and sometimes ingested in models to monitor the current drought situation. The Spanish National Research Council (CSIC) provides monthly updates of the global SPEI using observed precipitation and modelled potential evapotranspiration. The National Oceanic and Atmospheric Administration monitors the drought condition over the continental United States using the PDSI. Data from EDO and GDO provided through Copernicus is further downscaled by other operational drought monitoring systems, such as the Intergovernmental Authority on Development (IGAD) Climate Prediction & Applications Centre (ICPAC) for the Horn of Africa, and the Northern Australia Climate Prediction Centre (NACP) for Australia. The New Zealand National Institute of Water and Atmospheric Research (NIWA) monitors the local drought conditions using the SPI and a drought indicator specifically developed for the region. Most continental and global monitoring systems are updated weekly or monthly and run at rather coarse resolutions, from 1° to 0.25°.

Current drought forecasting systems

Even fewer operational drought forecasting systems exist. EDO and GDO provide a basic forecast up to 6 months ahead, which indicates unusually dry or wet conditions, as estimated with the SPI and through the calculation of extreme return periods. NOAA estimates a drought tendency based on the simulated soil moisture anomalies for the coming three months. Both services provide only monthly updates and are restricted to Europe and the United States, respectively. Only New Zealand provides weekly updates of their drought forecast with a lead time of 35 days and with a resolution of 5 km — but this service remains restricted to New Zealand.

7.2.3.2 Enhanced meteorological variables and forecasts: requirements

To enhance the current drought monitoring and forecasting systems, we aim to provide near real-time monitoring of drought, and a novel, seamless and high-resolution prediction of drought for the coming 6 months, and drought warning levels, which evaluate the drought forecast in relation to the current monitoring status. Further, we briefly elaborate on some of the required code developments to produce such products.

Near real-time drought monitoring

The challenges of assessing the current drought situation is the lack of reliable observations of, e.g., precipitation and temperature, on a global scale and near real-time. Further, monitoring systems require a long record of past observations to provide mean climatological conditions and evaluate the severity of an event. Due to the lack of such observations in time and space, especially in regions with sparse observational networks such as Africa, localized events are often overlooked. To address these gaps, we aim to develop a novel drought monitoring product that employs the long-term climatology of precipitation from observational data sets, such as the Global Precipitation Climatology Centre (GPCC), and a high-resolution reanalysis (ECMWF's ERA5) that is the best modelled estimate of the current state as constrained by observations. Using these products, we can calculate drought indicators, such as the SPI and the SPEI (Section 1.1), near real-time at a resolution of 0.25°.

Seamless drought predictions and warning levels

Droughts need to be forecasted in advance to leave enough time for mitigating actions. Especially "flash droughts" — droughts that develop rapidly within weeks due to changes in precipitation, temperature, wind, and radiation — pose a challenge for present day mitigation strategies. Current drought forecasting systems mostly rely on seasonal forecasts and provide updates of the drought forecast every month (EDO / GDO, NOAA) or week (NIWA).

To provide timely information of slow- and fast evolving droughts that is actionable, we aim to provide a seamless forecast of droughts. This forecast employs a combination of ECMWF forecasts covering a lead time from day 1

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up to 6 months. For the first 15 days, we will use the high-resolution ensemble forecast (ENS), supplemented with the extended-range ensemble forecast up to 46 days (ENS–ER). This time range is short enough so that the atmosphere retains some memory of its initial state, and long enough so that the ocean variability has an impact on the atmospheric circulation. This forecast comprises an ensemble of 101 members that is provided daily. Both forecasts come with a reforecast of 20 years that facilitate the calculation of drought indices on a sub-monthly scale (e.g., 10-day or weekly anomalies) using a homogenous and coherent long-term data set. This forecast will be extended up to 6 months using the seasonal forecasts (SEA). The seasonal forecast comes with a reforecast of more than 30 years, thus enabling a correction of bias and variance errors. A schematic with the seamless drought prediction product, delivering 6 months forecasts at spatial resolutions of up to 9 km as planned within CENTAUR is shown in Figure 1.

Finally, the seamless drought forecast will be evaluated with respect to the current drought status and translated into easy-to-understand warning levels that are actionable. The development of such warning levels may be carried out using machine-learning.

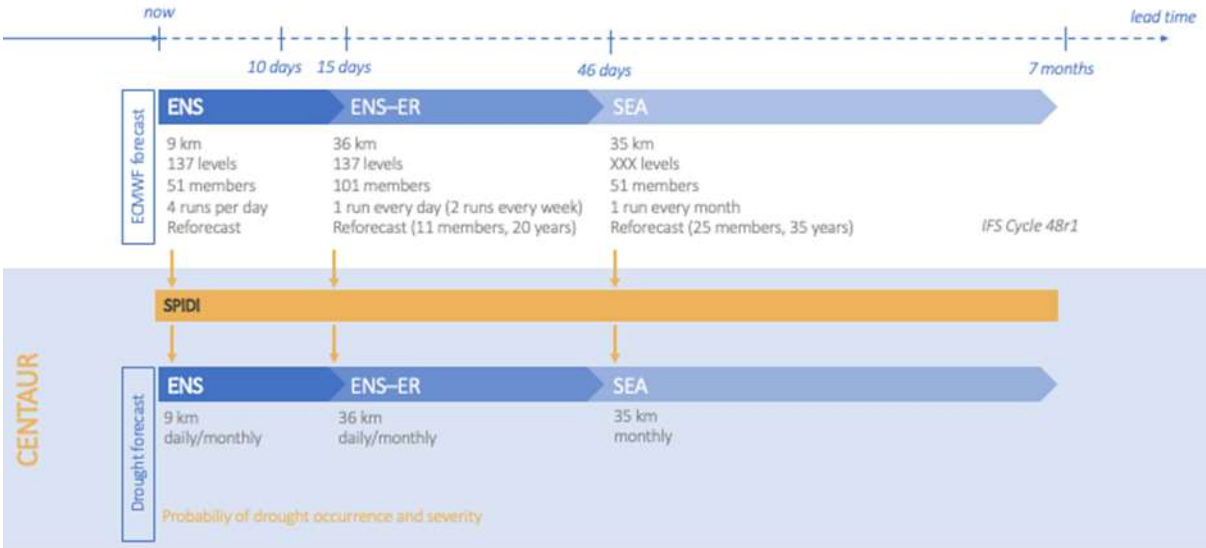

Figure 100: Overview of the seamless drought forecast planned within CENTAUR.

- ➢ Code development

To develop the above products, we will build upon an existing open-source software library that calculates standardized precipitation index and other drought indices (SPIDI, https://github.com/corentincarton/spidi) and further develop it for production purposes and to entail additional drought indices.

The quality of forecasts will be monitored in real-time using tools available at ECMWF, and additional tools will be developed that target the verification of droughts specifically. An operational verification suite will be setup and allows operators to immediately identify issues with forecasts and act on it. Independent observations, as well as ECMWFs own analysis and reanalysis products, such as ERA5, will be used to evaluate the skill of the forecast for various locations around the globe and various lead times and will emphasize the usefulness of the product.

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Table 33 List of current operational large-scale drought monitoring systems that provide meteorological drought indicators.

Service	Region	Drought indicator(s)	Spatial resolution	Update frequency	References
EDO / GDO	Europe / Global	SPI-1, SPI-3, CDI, SMA	SPI at 0.25° (SYNOP) and 1.0° (GPCC), CDI and SMA at 5km	SPI daily (SYNOP) and monthly (GPCC), CDI and SMA every 10 days	https://edo.jrc.ec.europa.eu/edov2/php/index.php?id=1000 https://edo.jrc.ec.europa.eu/gdo/php/index.php?id=2001
CSIC	Global	SPEI	1°	Monthly	https://spei.csic.es
NOAA	US	PDSI, PDSI_Percentiles, SPI → objective drought indicator blend		Weekly	https://www.drought.gov/
ICPAC [using EDO data]	Horn of Africa	SPI-1, SPI-3, SPI-6, SPI-9, SPI-12, SPI-24, SPI-36, CDI	5 km (SPI and CDI), 10 km (CDI)	Every 10 days (CDI at 10 km, SMA) or every month (CDI at 5 km, SPI)	https://droughtwatch.icpac.net/
NACP [using EDO data]	Australia	CDI	-	-	https://www.nacp.org.au/drought_monitor
NIWA	New Zealand	New Zealand drought indicator (NZDI), SPI	5 km	Weekly	https://shiny.niwa.co.nz/drought-forecast/

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Table 34 List of current operational large-scale drought forecasting systems that provide meteorological drought indicators.

Service	Region	Drought indicator(s)	Spatial resolution	Update frequency	Lead time	References
EDO / GDO	Europe / Global	Indicator for forecasting unusually wet or dry conditions (SPI-1, SPI-3, SPI-6; intensity based on extreme forecast index EFI and return period)	1°	Monthly	6 months	https://edo.jrc.ec.europa.eu/edov2/php/index.php?id=1000
NOAA	US	SMA, drought tendency	-	Monthly	3 months	https://droughtmonitor.unl.edu/ConditionsOutlooks/Outlooks.aspx
NIWA	New Zealand	NZDI	5 km	Weekly	35 days	https://shiny.niwa.co.nz/drought-forecast/

Accurate and reliable estimates and projections on the current and future size of the human population and its spatial distribution are critical for the studies of climate change. Within the context of the CENTAUR project, access to this information is a requirement to produce indicators of exposure to security risks and resources shortage (e.g. water and food).

7.2.4 Fine-scale population distribution and exposure to security risks and resources shortage

Accurate and reliable estimates and projections on the current and future size of the human population and its spatial distribution are critical for the studies of climate change. Within the context of the CENTAUR project, access to this information is a requirement to produce indicators of exposure to security risks and resources shortage (e.g. water and food).

Herein, to comply with the objectives of WP1-Task 1.2, the following sections present a complete state-of-art review on fine-scale population distribution datasets that could potentially be used as long-term open data sources to derive indicators of exposure for the Copernicus SEA and EMS service models. Here, we specifically focus on globally available products, providing a detailed description on their spatial and temporal resolution, coverage, quality, suitability and accessibility, as well as their advantages and limitations.

First, section 7.2.4.1 presents a state-of-the art on fine-scale population distribution dataset, diving the information into 1) large-scale top-down gridded population datasets which describe “historical and/or current situations” of the global human population distribution; and 2) large-scale projected gridded population datasets which simulate population distribution until the end of the century. Second, section 7.2.4.2, presents a review on indicators of exposure to security risks and resource shortage which have employed existing fine-scale population distribution datasets and discusses the limitations of commonly used data sources. Finally, section 7.2.4.3 provides a list of exposure indicators that will be consider in the CENTAUR project.

7.2.4.1 State-of-the-art: Fine-scale population distribution datasets

Large-scale top-down gridded population datasets

Top-down gridded population datasets are geospatial datasets that provide estimates of population counts for individual grid cells or pixels covering the entire surface of the Earth. These datasets are typically produced using a top-down modelling approach, which involves combining satellite imagery and other remote sensing data to distribute population counts from administrative units (e.g. collected from census data) to grid cells of a given

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spatial [237,238] .There are presently several large-scale gridded population data sets with various spatial resolutions and timespans (see Table). These datasets focus on providing “historical and/or current situations” on the size and the spatial distribution of the human population, are commonly used in academic research, and have been produced to support governments, organisations and institutions around the world. The main technical characteristics of these datasets are briefly described as follows[239]:

GPW4.11

The Gridded Population of the World, version 4 (GPWv4.11) produced by CIESIN, Columbia University [240] are the only population grids produced using an area-weighting technique, relying simply on a water mask to ensure that population counts are only assigned to land pixels. The final datasets represent the residential population (e.g. people counted at their place of living) either as population counts (people per pixel) or population density (people per km^2) for the years 2000,2005,2010,2015 and 2020, respectively. The datasets are available at a global scale and are produced at a spatial resolution of 30 arc-seconds, which corresponds to ~1km at the Equator. The datasets are published and made openly available in WGS1984 geographic coordinate system in ASCII, GeoTiff and NetCDF formats.

GRUMP

The Global Rural-Urban Mapping Project (GRUPM) datasets produced by CIESIN[241] are based on population data collected from the GPW, version 3. They are model based on a binary dasymetric technique to allocate population according to rural or urban gradients derived, —in part—, from night-light imagery. The final datasets represent the residential population either as population counts or population densities for the years 1990, 1995 and 2000, respectively. The datasets are available at a global scale and are produced at a spatial resolution of 30 arc-seconds, which corresponds to ~1km at the Equator. The datasets are published and made available in WGS1984 geographic coordinate system in ASCII, BIL and GRID formats.

GHS-POP R2023A

The Global Human Settlement Population layer (GHS-POP_GLOBE_R2023A) produced by the European Commission Joint Research Centre (EC-JRC) in collaboration with CIESIN[242] , is modelled using a weighted dasymetric technique that relies on the distribution of population counts from administrative units into settlement pixels describing the residential built-up density. The main input datasets include the GHS- BUILT-S_GLOBE_R2023A, the non-residential built-up surface (GHS_BUILT-S_NRES_GLOBE_R2023A), the built-up volume (GHS-BUILT-V GLOBAL_R2023A, and raw global census data harmonized by CIESIN for the GPW, version 4.11. The final datasets represent the residential population as the number of people per cell for every 5 years interval between 1975 and 2030. The datasets are available at a global scale and are produced at a spatial resolution of 100m and 1km at the Equator. The datasets are published and made available in a World Mollweide projection in GeoTiff format.

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[237] Allen, C., et al. (2021). A review of scientific advancements in datasets derived from big data for monitoring the Sustainable Development Goals. *Sustainability Science*, *16*(5), 1701-1716.
[238] Freire, S., et al. (2020). Enhanced data and methods for improving open and free global population grids: putting ‘leaving no one behind’ into practice. *International Journal of Digital Earth*, *13*(1), 61-77.
[239] Unless specified otherwise, the descriptions presented here correspond to the latest versions of each product.
[240] Doxsey-Whitfield, E., et al. (2015). Taking advantage of the improved availability of census data: a first look at the gridded population of the world, version 4. *Papers in Applied Geography*, *1*(3), 226-234.
[241] CIESIN. (2011). *Global Rural-Urban Mapping Project, Version 1 (GRUMPv1): Population Density Grid* NASA Socioeconomic Data and Applications Center (SEDAC).
[242] Freire, S., et al. (2016, 14-17 June). *Development of new open and free multi-temporal global population grids at 250 m resolution*. AGILE, Helsinki, Finland.

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HRSL

The High-Resolution Settlement Layer (HRSL) produced by Facebook Connectivity Lab in collaboration with CIESIN[243], is a dataset produced using a binary dasymetric technique that redistributes population from administrative units to built-up areas as defined by proprietary settlement layer produced using high resolution (0.5m at the Equator) satellite imagery from Digital Globe. The final datasets represent the residential population as people per pixel for the year 2015 and 2018. The datasets are currently available for 140 countries and are produced at a spatial resolution of 1 arc-second, which corresponds to ~30m at the Equator. The datasets are published and made available in WGS1984 geographic coordinate system in GeoTiff format.

LandScan

The LandScan datasets produced by the Oak Ridge National Laboratory (ORNL)[244,245] are produced using a weighted intelligent dasymetric technique that consists of dynamically adaptable algorithms used to generate a weighting layer based on statistically-derived relationships among multiple proxy layers. So far, the methods employed to produce the LandScan datasets are not publicly available, however, the population grids are openly available with no restrictions. The final datasets represent the ambient population (e.g. population at the place of work) as population people per pixel, for the years 2000-2021. The datasets are available at a global scale and are produced at a spatial resolution of 30 arc-seconds, which corresponds to ~1km at the Equator. The datasets are made available in WGS1984 geographic coordinate system, in GRID and binary raster formats.

WorldPop

The WorldPop datasets produced by the WorldPop project in the University of Southampton[246] are modelled using a weighted intelligent dasymetric technique that consists of locally modelled Random Forest algorithms used to generate a weighting layer based on the relationships between population densities and multiple proxy layers (e.g. built-area extents, land-cover, density of roads, topography). Here, redistributions are done in two ways, first where population counts are redistributed to all grid cells or pixels (unconstrained), and second, where population counts are redistributed only within areas identified as settlements (constrained). In the case of the latter, different built-area layers are employed depending on the location. For Africa, for example, satellite-derived building footprint data from Maxar/Ecopia[247] are used, whereas for the rest of the countries a novel built settlement growth model is employed [248,249] derived from other built-area layers such as the GUF[250,251], the GHSL and the European Space Agency (ESA) CCI land cover 300m[252]. The final datasets represent the residential population as people per pixel, for the years 2000-2020. The datasets are available at a global scale and are

[243] Tiecke, T. G., et al. (2017). Mapping the world population one building at a time. *arXiv*, arXiv:1712.05839.
[244] Bhaduri, B., et al. (2007). LandScan USA: a high-resolution geospatial and temporal modeling approach for population distribution and dynamics. *GeoJournal*, *69*(1-2), 103-117
[245] Dobson, J. E., et al. (2000). LandScan: a global population database for estimating populations at risk. *Photogrammetric Engineering and Remote Sensing*, *66*(7), 849-857.
[246] Stevens, F. R., et al. (2015). Disaggregating census data for population mapping using random forests with remotely-sensed and ancillary data. *PLoS One*, *10*(2), e0107042.
[247] Maxar Technologies. (2020). *Building Footprints*. Retrieved 08 August from https://www.maxar.com/products/building-footprints
[248] Nieves, J. J., et al. (2020a). Predicting Near-Future Built-Settlement Expansion Using Relative Changes in Small Area Populations. *Remote Sensing*, *12*(10), 1545.
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[250] Esch, T., et al. (2017). Breaking new ground in mapping human settlements from space–The Global Urban Footprint. *ISPRS Journal of Photogrammetry*, *134*, 30-42.
[251] Esch, T., et al. (2018). Where we live—A summary of the achievements and planned evolution of the global urban footprint.
[252] ESA. (2015). *Climate Change Initiative*. https://www.esa-landcover-cci.org/?q=node/164

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produced at a spatial resolution of 3 arc-seconds, which corresponds to ~100m at the Equator. The datasets are made available in WGS1984 geographic coordinate system in GeoTiff format.

World Settlement Footprint Population (WSF-Population)

The World Settlement Footprint – Population datasets produced by the German Aerospace Center are modelled using a dasymetric modelling approach that relies on information extracted from WSF3D (e.g. building height, area, fraction and volume) , the WSF-Imperviousness and OSM data (e.g. residential vs non-residential)[253,254,255] .First, settlements identified as non-residential in the OSM data are masked-out from the WSF-Imp and the WSF3D datasets. Then, a dasymetric weighted approach in the applied using a framework that relies on the percent of impervious values, the area, fraction and volume of built-up settlements values to distribute population on the remaining residential pixels. The final datasets are still under development and will represent the residential population as people per pixel for the year 2019. The datasets will be available at a global scale, with a spatial resolution of ~10m at the Equator. The datasets will be made available in WGS1984 geographic coordinate system in GeoTiff format.

For a visual comparison, Figure 101 illustrates some of these datasets for the area of Cape Town, South Africa. The datasets are displayed using the same symbology and preserving their native spatial resolution. As observed, there are clear differences in the spatial distribution of the human population produced by each dataset. These differences are highly related to the techniques and input data used for modelling.

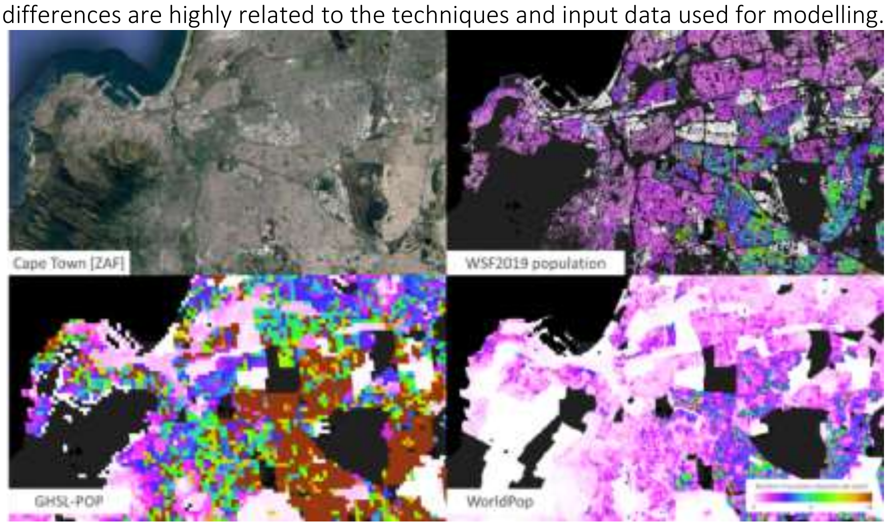

Figure 101: Visual comparison of gridded population distribution maps for Cape Town, South Africa. WSF2019-Population (10m), WorldPop-unconstrained (100m) and GHS-Pop (100m).

[253] Palacios-Lopez, D., et al. (2019). New Perspectives for Mapping Global Population Distribution Using World Settlement Footprint Products. *Sustainability*, *11*(21).

[254] Palacios-Lopez, D., et al. (2021). High-Resolution Gridded Population Datasets: Exploring the Capabilities of the World Settlement Footprint 2019 Imperviousness Layer for the African Continent. *Remote Sensing*, *13*(6).

[255] Palacios-Lopez, D., et al. (2022). Towards an Improved Large-Scale Gridded Population Dataset: A Pan-European Study on the Integration of 3D Settlement Data into Population Modelling. *Remote Sensing*, *14*(2).

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Table 35: Technical summary of state-of-the-art top-down large-scale gridded population dataset

Dataset	Producer	Spatial Resolution	Temporal Resolution	Coverage	Population Concept	Open and Free
GPWv4.11	CIESIN	1 km	2000;2005;2010; 2015;2020	Global	Residential	Yes
GRUMP	CIESIN	1 km	1990;1995;2000	Global	Residential	Yes
GHS-POP	JRC; CIESIN	100m, 1km 3-30 arcsec	1975-2030 5-year interval	Global	Residential	Yes
HRSL	Facebook Connectivity Lab; CIESIN	30m	2015;2018	140 countries	Residential	Yes
LandScan	ORNL	1 km	annual releases 2000-2021	Global	Ambient	Yes
WorldPop (constrained & unconstrained)	WorldPop; University of Southampton	100 m	2000-2020	Global	Residential	Yes
WSF-Population	DLR	10m	2019	Global	Residential	Local[256]

Future population projections in gridded format

Most of the large-scale gridded population datasets mentioned above focus on providing population estimations for historical and current situations. However, to understand the future changes in exposure and vulnerability of humans to the impacts induced by climate change, knowledge on the future size and spatial distribution of the human population is essential.

In this context, today there are a number of fine-scale gridded population datasets that provide future population projections at global to near-global scales (see Table). In their majority, these datasets are developed in a consistent and harmonized manner across the shared socioeconomic pathways (SSPs)[257], which represent five alternative future scenarios of socioeconomic development and greenhouse gas emissions (see Figure 102).

Methodologically speaking, population projections which are calculated at the region or country level for each one of the SSPs[258] scenarios are redistributed/ into grid cells of a given spatial resolution using different techniques. For each dataset a brief description is provided as follows:

[256] Can be provided for the hot-cold use cases

[257] Riahi, K., et al. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, *42*, 153-168.

[258] The population projections within the SSPs are based on a range of data sources, including demographic models and historical trends in fertility, mortality, and migration. These data sources are used to estimate future population size and structure for each country or region in the world, as well as patterns of urbanization and migration between regions.

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NCAR dataset

Jones and O'Neill at the National Center for Atmospheric Research (NCAR) developed a method to produce gridded population projections for each SSPs scenario[259]. Their methodology builds upon previous approaches of population modeling, but also incorporates new features such as accounting for spatially varying urbanization rates and dynamic migration patterns. The final datasets reflect the qualitative narratives about spatial development patterns under the different SSPs.

Concisely, the process involves (i) calibrating the model to historic data to estimate urban and rural parameters indicative of certain patterns of spatial change (based on the 2000-GPW), (ii) selecting regionally representative parameters for each SSPs, and (iii) applying a parametrized gravity-based downscaling procedure on a country-by-country basis for each 1-5 SSPs scenario.

For each of the SSP-scenario the final datasets were produced for 232 countries for the years 2000-2100 (at decadal intervals), and are available at a spatial resolution of 7.5 arcminutes (~13 km at the Equator). The data are available as global grids in ASCII, GeoTIFF, Esri Grid and netCDF-4 formats for urban, rural, and total population.

NCAR Improved dataset

Gao et al (2020),[260] downscaled the NCAR dataset from 7.5 arcminutes to 30 arcsec (1km at the Equator) using the methodology presented in Gao et al (2017) [261] . Concisely, the 1 km 2000-GRUMP population grids were aggregated to the 7.5 arcmin spatial resolution of the NCAR population grids for each SSPs scenario. Then, the 7.5 arcmin GRUMP population grids were divided by the 1 km GRUMP population grids, resulting in a weight map showing how each 7.5 arcmin grid's population is distributed in fractions between the overlapping 1 km grids.

The datasets have global coverage and is available for the years 2000, 2010-2100 (at decadal intervals), and are available at a spatial resolution of 1 km at the Equator. The data are available as global grids in GeoTIFF and netCDF-4 formats for urban, rural, and total population.

MY19

Murakami and Yamagata[262] developed a method which is based on a downscaling approach that considers interactions among cities and an ensemble learning method to address the complex relationships between a number of covariates and population distribution (e.g. road density, distance to airports, distance to oceans, etc.). They do so, by fitting a city growth model trained by analyzing city population change between 1995 and 2000 (source: GRUMP Settlement Point dataset version 1). For the downscaling of urban and non-urban population, the authors use the following assumptions: (a) city population changes over time; (b) urban area expands or shrinks according to the city population change; and (c) city population, urban expansion/shrinkage, and other auxiliary variables determine gridded populations and gross productivities.

The datasets have global coverage and is available for the years 2000, 2010-2100 (at decadal intervals), and are available at a spatial resolution of 0.5 degrees at the Equator. The data are available as global grids in GeoTIFF and netCDF-4 formats for urban, rural, and total population.

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[259] Jones, B., & O'Neill, B. C. (2016). Spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways. *Environmental Research Letters*, *11*(8), 084003.
[260] Gao, J. (2020). Global 1-km Downscaled Population Base Year and Projection Grids Based on the Shared Socioeconomic Pathways, Revision 01. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC).
[261] Gao, J. (2017). Downscaling global spatial population projections from 1/8-degree to 1-km grid cells. *National Center for Atmospheric Research, Boulder, CO, USA*, *1105*.
[262] Murakami, D., & Yamagata, Y. (2019). Estimation of Gridded Population and GDP Scenarios with Spatially Explicit Statistical Downscaling. *Sustainability*, *11*(7).

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FPOP

Li et al. (2022)[263] from the East China Normal University developed one of the newest global population projections under the SSPs scenarios, known as the Future population projection dataset (FPOP). For their methodology, the authors incorporated a newly available future built-up and land dataset[264] and other predictive variables to train a random forest (RF) algorithm. Concisely, the core methodology is based in recursive projections to extend gridded projection at an earlier time T_i onto the next time point T_{i+10}.

The datasets have a global coverage and is available for the years 2020-2100 (at decadal intervals), and are available at a spatial resolution of 1 km at the Equator. The data are available as global grids in GeoTIFF format.

OL22

Olén and Lehsten [265]researchers form the Centre for Environmental and Climate Research in Sweden and the Swiss Federal Institute for Forest, Snow and Landscape developed a methodology to produce global gridded population projections which are consistent not only with the country level population projections of the SSPs (comparable to the aforementioned dataset), but that are also consistent with the land cover projections of the Representative Concentration Pathways (RCPs).

Concisely, the datasets can be generated using 6 combination of SSPs and RCPs (SP1-RCP2.6, SSP2-RCP3.4, SSP3-RCP7.0, SSP4-RCP3.4, SSP4-RCP6.0, SSP5-RCP8.5). First, global population data from the WorldPop Project for year 2010 is used as a starting point for the population projections. The starting dataset was combined with population centre of gravity, distance to road, and distance to urban areas to allow each pixel to be ranked uniquely into urban or non-urban. With this ranking the first 2010 population dataset is created, and this newly created dataset is used as input for the next year, thus creating a loop.

The datasets have a global coverage and is available in yearly bases from 2010 to 2100, and are available at a spatial resolution of 1 km at the Equator. The data are available in GeoTIFF format for each scenario combination and year.

Table 36: Technical summary of state-of-the-art projected population grids.

Dataset	Producer	Spatial Resolution	Temporal Resolution	Coverage	Population Concept	Open and Free
NCAR-dataset	National Center for Atmospheric Research	7.5 arcmin	2000),2010-2100 (10y-interval)	Global	Residential	Yes
Improved-NCAR	National Center for Atmospheric Research	1 km	(2000), 2010-2100 (10y-interval)	Global	Residential	Yes
MY19	Center for Global Environmental Research, Japan	0.5 degrees	(2000), 2010-2100 (10y-interval)	Global	Residential	Yes

[263] Li, M., et al. (2022). Spatiotemporal dynamics of global population and heat exposure (2020–2100): based on improved SSP-consistent population projections. *Environmental Research Letters*, *17*(9), 094007.

[264] Chen, Y., et al. (2020). High-Resolution Gridded Population Projections for China Under the Shared Socioeconomic Pathways. *Earth's Future*, *8*(6), e2020EF001491

[265] Olén, N. B., & Lehsten, V. (2022). High-resolution global population projections dataset developed with CMIP6 RCP and SSP scenarios for year 2010–2100. *Data in Brief*, *40*, 107804.

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Dataset	Producer	Spatial Resolution	Temporal Resolution	Coverage	Population Concept	Open and Free
FPOP	East China Normal University	1 km	2020-2100 (10y-interval)	Global	Residential	Yes
OL22	Centre for Environmental and Climate Research in Sweden	1 km	2010-2100 (yearly)	Global	Residential	Yes

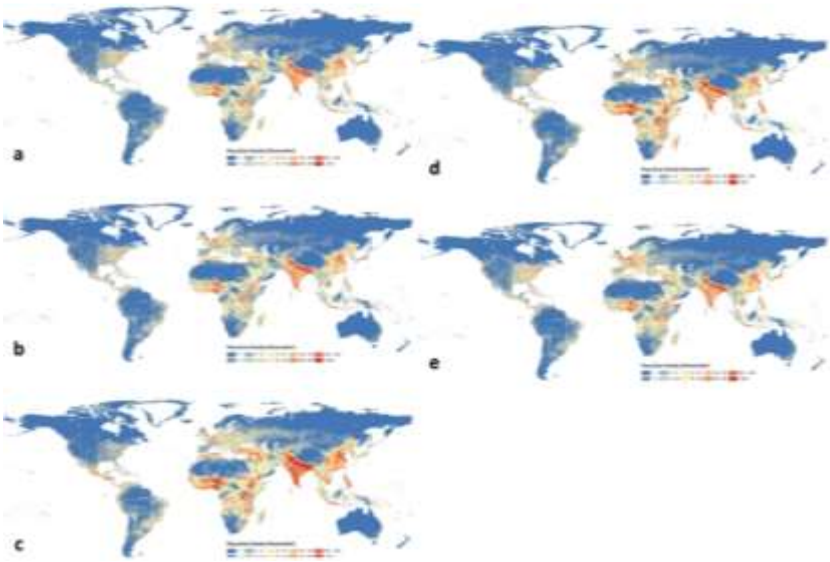

Figure 102: Projected population density for the five SSP-scenarios (2100). Maps represent the distribution maps generated by Jones and O'Neill (2016).

7.2.4.2 State-of-the-art: Indicators of exposure to security risks and resources shortage

The aforementioned gridded population datasets have been used as indicators of population counts/population totals in a large number of applications to quantify the number of people "at risk of", "in the proximity of" or "affected by" different social, political or environmental events. Due to their spatial resolution and gridded format, these datasets allow researchers and policymakers to analyze population patterns and trends at a fine scale, and to identify areas of high population exposure to different climatic events.

To comply with the objectives of the CENTAUR project, in this section we provide a list of **compound-indicators or indices** that have been used for assessing the exposure of the human population to resource shortage and security risks. A literature review was conducted build upon the premise that conflicts (e.g. crime, resource competition and radicalisation) are interconnected to resource shortages such as large-scale acute food and water insecurity, which at the same time are sparked by climatic events such as flooding or drought (see Section 7.2.6.2). With that being said, we decided to limit the collection of indicators to those that have been derived using fine-scale gridded population datasets, and to those that are present in the majority of the reviewed studies.

Indicators of exposure to resource shortage

- Populations at risk of hunger: This indicator is normally used to estimate the proportion of the population in different levels of food insecurity. Some of the most employed datasets to derive this indicator include the FEWS NET Integrated Food Security Phase Classification (IPC) and the WFP Hunger Maps, which are

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tools for classifying and analyzing the severity and magnitude of food insecurity in a given area. These datasets are preferred among other well-known products (e.g. the Global Human Index, FEEDME) due to their higher spatial resolution which allow conducting analysis at administrative district level versus country level. Concisely, using the livelihood zones from the FEWS NET, for example, population statistics are extracted, and the proportion of the population living in crisis, emergency and famine are calculated. While somehow simplistic, this indicator can also be combined with drought, floods and conflict-event data to estimate the amount of population who have their food security status impacted either in-real-time or in projected scenarios. Contemporary studies that have calculated this indicator under different scenarios include Anderson et al. (2021)[266] and Reed et al. (2022)[267] who relied in gridded population datasets such as WorldPop, LandScan and the GHS-Pop.; and Hasegawa et al., 2015-2018[268,269], who relied on gridded population projections (e.g. NCAR dataset) to estimate populations at risk of hunger at the national scale.

- Populations at risk of water scarcity: One of the most employed methods to calculate water scarcity, is founded on Falkenmark's approach, who classified values ranging from "no stress" (>17,000 m^3/person/year) to "absolute scarcity" (< 500 m^3/person/year) based on water availability indicators. These thresholds are still commonly used and have been widely adopted given their ease of computation and interpretation[270].In general, the explicit assessment of net water availability relies on complex use and hydrological models that integrate the impact of demographic, socioeconomic and technological change on water use, as well as the impact of climate change and seasonal variability when possible. Examples of such models include the WaterGAP Global Hydrological Model (WGHM) which provide measures at the grid level, with a 0.5° spatial resolution. Concisely, water availability per capita is computed by dividing water availability at the pixel level (m^3) by the no. of people at the pixel level. These estimates can be then aggregated at the basin level , which are then classified using Falkenmark's thresholds to derive water scarcity maps.

Indicators of exposure to security risk

- Number of people living in proximity to violent conflict: Competitions over scarce resources caused by climate change can lead to substantial conflicts and crises affecting the safety of the population[271]. Currently, there are different sources that provide data on conflict events, which combined with population data are used in the development of climate-conflict risk indices, to ensure all those affected get the help they need. For example, in Corral et al. (2020)[272] the authors use georeferenced conflict event data from the Uppsala Conflict Data Program together with the LandScan dataset to calculate the number of people living in close proximity of conflict. Concisely, estimates of affected populations are derived from zonal statistical analyses using pre-defined buffers around each of the events.

Limitations on commonly employed fine-scale population distribution datasets

While different research has integrated fine-scale population distribution datasets to analyse exposure to resource shortages and security risks, little discussion exists on the how the quality and accuracy of the input population

[266] Anderson, W., et al. (2021). Violent conflict exacerbated drought-related food insecurity between 2009 and 2019 in sub-Saharan Africa. *Nature Food*, *2*(8), 603-615.
[267] Reed, C., et al. (2022). The impact of flooding on food security across Africa. *Proceedings of the National Academy of Sciences*, *119*(43), e2119399119.
[268] Hasegawa, T., et al. (2015). Scenarios for the risk of hunger in the twenty-first century using Shared Socioeconomic Pathways. *Environmental Research Letters*, *10*(1), 014010.
[269] Hasegawa, T., et al. (2018). Risk of increased food insecurity under stringent global climate change mitigation policy. *Nature Climate Change*, *8*(8), 699-703.
[270] McNally, A., et al. (2019). Acute water-scarcity monitoring for Africa. *Water*, *11*(10), 1968.
[271] Unfried, K., et al. (2022). Water scarcity and social conflict. *Journal of Environmental Economics and Management*, *113*, 102633.
[272] Corral, P., et al. (2020). *Fragility and conflict: On the front lines of the fight against poverty*. World Bank Publications.

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data affects or biases the analyses. This limitation is mainly rooted in the lack of independent ground truth data needed to validate the estimates of exposure outputted by the analyses.

Therein, to select the most appropriate dataset for a given application, users need to consider that each dataset has its own limitations derived from 1) the inaccuracies of the underlying census and survey data used to produce them, and 2) the uncertainties derived from the auxiliary data and modelling methods. Table briefly summarises the strengths and limitations of each dataset as presented in different reviews[273].

Table 37: Strengths and weaknesses of state-of-the-art large-scale top-down gridded population datasets.

Dataset	Population Data	Strengths	Weaknesses
GPWv4.11	Census between 2005 and 2014	- Light modelled and not affected by covariates - Suitable for independent measure of population studies	- Population is evenly distributed, so there is a loss of spatial detail. - Overestimation of population counts are expected in rural areas and underestimations urban areas. - Does not differentiate residential from other land uses - Poor spatial resolution
GRUMP	GPWv3	- First global dataset to estimate population for rural and urban areas separately	- The coarse resolution of the night-time data used for modelling, leads to overestimation in some urban areas - It underperforms in estimation the spatial dynamics of the population in complex urban settings. - Does not differentiate residential from other land uses - Poor spatial resolution
GHS-POP	GPW4.11	- The method is easily reproducible - Global consistency - First global dataset to differentiate residential from other land uses	- Uses the GHSL as built-up area layer, which is known to have large over- and underestimation of settlements. - Poor spatial resolution
HRSL	GPW4.11	- More detailed urban and rural population estimates than GRUMP	- Relies only on 2D built-area layers - Does not differentiate residential from other land uses

[273] Kuffer, M., et al. (2022). The Missing Millions in Maps: Exploring Causes of Uncertainties in Global Gridded Population Datasets. *ISPRS International Journal of Geo-Information*, *11*(7).

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Dataset	Population Data	Strengths	Weaknesses
		- High-spatial resolutions that allows better integration with other geospatial datasets	- Is not yet complete for the entire world
LandScan	Subnational census and administrative data	- Uses a complex model that captures the spatial variability of the population in urban areas	- Relies on a complex modelling approach that is not openly documented. - Model varies across country, introducing bias in cross-comparative analyses - Does not integrate 3D information globally
WorldPop	GPW4.11	- Uses machine learning to identify significant covariates for disaggregation - Captures the spatial variability of the population	- Does not integrate 3D information globally - Does not differentiate residential from other land uses - Poor spatial resolution
WSF-Population	GPW4.11	- High-spatial resolution that allows better integration with other geospatial datasets - Concurrently exploits information on building location (WSF settlement extent) density (WSF imperviousness) and height (WSF 3D) - Excludes a priori from the redistribution all areas not suitable to host resident population based on OpenStreetMap information (e.g., commercial, industrial, retail, religious, educational, etc.)	- Non-residential areas are not comprehensively outlined in OpenStreetMap -

Comparably, it is worth noticing, that while important progress has been made in producing globally SSP-consistent gridded population projections, a series of limitations have been identified in the literature. According to Li et al. (2022) all datasets suffer from low spatial resolution and poor accuracy in certain areas which generate bias in the analysis of climate change impacts. For example, Chen et al. (2020) found that for the particular case of China, approximately 30-43% of the estimated population produced by the NCAR dataset is located in uninhabited areas with cropland, forest or pasture covertures in 2050. Comparably, according to Gao (2020), the NCAR-improved dataset suffers from spatial artifacts that propagate from 13km to 1km layers. While these

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artifacts can be subtle for regional or national-scale analyses, they can be detrimental for local-scale applications. Finally, the MY19 are produced considering only partial SSPs, meaning they are not available for all scenarios.

In conclusion, although complex spatial population models may address the limitations of the products presented here, their development can be time-consuming. For regional projections, datasets that benefit from the availability of additional predictive data and complex models, include high-resolution gridded population datasets that have been developed for Africa (1 km), global coastal areas (1 km)[274] and the Mediterranean coastal zone (1 km)[275]. However, due to their different input data and methods, combining these regional population datasets for global applications would induce unknown uncertainties.

7.2.4.3 Proposal to fill-in gaps within fine-scale population distribution

As specified in the previous sections, reliable indicators on population counts or population totals are essential for the construction of indices for exposure to resource shortage and security risk. In recent years, with the improved availability of satellite imagery and the advancement of machine learning technologies, large-scale gridded population datasets are being produced not only with higher spatial resolution, but also with improved quantitative and qualitative accuracy.

Concisely, different studies have shown that novel gridded population datasets that employ proxies such as built-area layers (e.g. GHS-BUILT, WSF, GUF) and proxies that provide information on the height, volume and functional use of the built-up environment (e.g. residential vs residential), provide population estimations and spatial distributions that are more accurate compared with products that exclude this information. Exemplary products, include for example, the recently released GHS-POP R2023A dataset, and the gridded population layers produced at the Pan-European scale using the WSF-Suite layers[276]

With that being said, while both of these two datasets present revolutionary advantages, for the purposes of the CENTAUR project their temporal resolution (e.g. single year, or 5-years interval) limit their usability and applicability, especially for tasks of continuous monitoring. Therein, to overcome this limitation we propose a strategy that exploits the synergy of both products as follows:

1 First, for tasks of **continuous monitoring**, gridded population datasets covering the cold and warm AOIs will be produced on the basis of the WSF-Suite layers by the German Aerospace Center (DLR). These datasets, will integrate volume and functional use information collected from the WSF3D and OSM datasets. Specifically, population counts and projections for each country will be acquired for the years 2016-to-present from governmental institutions (e.g. census dataset) or other open sources (e.g. UN projections, Worldpop). Then, relying on a dasymetric modelling approach, population counts available at the administrative unit level will be redistributed into grid cells of 10m spatial resolution delivering disaggregated estimates on a yearly basis.

2 Second, **for forecasting or predictive tasks**, our initial proposal is to rely on the GHS-POP datasets which currently is the only datasets that offers population estimations for the year 2025 and 2030. The selection on this dataset, is based on the premise that both, this and the datasets produced by DLR in step will integrate similar sources information, allowing to generate results that are more consistent and comparable over space and time.

[274] Merkens, J.-L., et al. (2016). Gridded population projections for the coastal zone under the Shared Socioeconomic Pathways. *Global and Planetary Change*, *145*, 57-66.
[275] Reimann, L., et al. (2018). Regionalized Shared Socioeconomic Pathways: narratives and spatial population projections for the Mediterranean coastal zone. *Regional Environmental Change*, *18*(1), 235-245.
[276] Palacios-Lopez, D., et al. (2022). Towards an Improved Large-Scale Gridded Population Dataset: A Pan-European Study on the Integration of 3D Settlement Data into Population Modelling. *Remote Sensing*, *14*(2).

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7.2.5 Demographic and socio-economic stress, vulnerability

7.2.5.1 State of the art: indicators

This section presents key socio-economic and political variables of the water-food-security-displacement nexus. It builds on the idea that climatic stressors have effects on the availability of natural resources that are essential for food production and for sustaining rural livelihoods. Variations in the availability of those resources, in many cases, are likely to have knock-on effects of human well-being, which, under certain conditions, might lead to maladaptive responses with the potential to affect the security situation in a given area (see Figure 103).

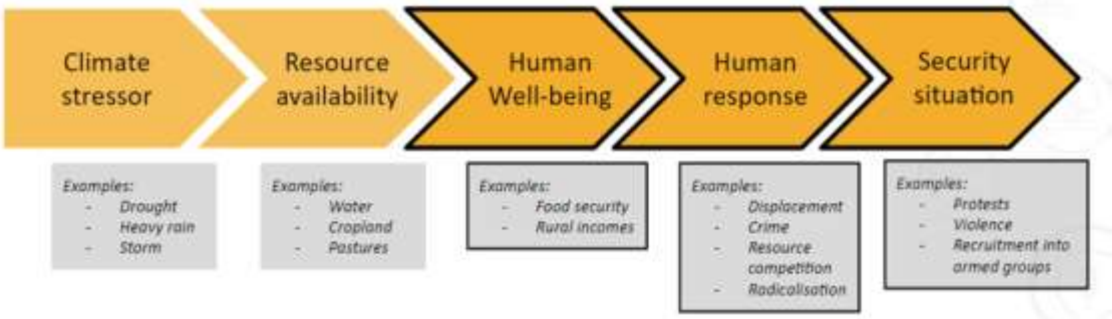

Figure 103: Relevant socio-economic variables for the climate-food/water security nexus: drivers and outcomes.

For example, under particularly unfavourable conditions, severe drought can deplete pastures, leading to falling incomes for pastoralists and inciting criminal behaviour (e.g. cattle theft) with the potential to ignite violent conflicts between pastoralist communities. Within such a risk “cascade”,[277] socio-economic and political indicators play an important part mainly at the stages affecting human well-being, human responses, and security more broadly (highlighted arrows in Figure 103). Relevant indicators here include, for example, indicators of food and livelihood (or economic) security, of resource competition, and of manifest physical violence (see grey boxes in Figure 103) that are routinely mentioned in the climate-security literature.[278]

Further relevant socio-economic indicators intervene along the risk cascade, as each step is not only affected by the preceding step(s) but potentially also by additional factors; some of which are socio-economic (or political) in nature (see green boxes in Figure 104). For example, resource availability is not only affected by climatic conditions, but often also by pollution and anthropogenic degradation, resource consumption habits, and other factors. Likewise, the well-being (e.g. food security) of people is not only affected by available resources (e.g. cropland) but potentially also by changes in food prices and disruptions in food supply chains.

[277] See: Carter et al. (2021). A conceptual framework for cross-border impacts of climate change. Global Environmental Change, 69, 1-14. https://www.cascades.eu/publication/a-conceptual-framework-for-cross-border-impactsof-climate-change/.

[278] von Uexkull and Buhaug (2021). Security implications of climate change: A decade of scientific progress. Journal of Peace Research, 58(1), 3–17.

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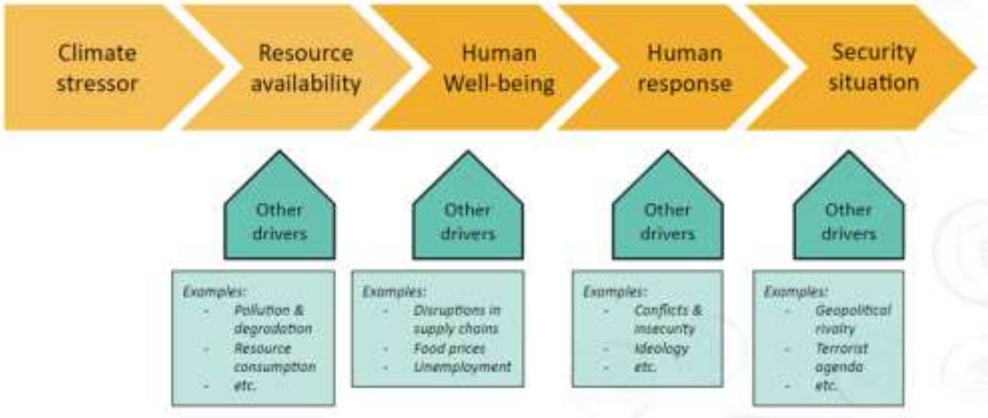

Figure 104: Relevant socio-economic variables for the climate-food/water security nexus: control variables.

Lastly, as alluded to at the start of this section, context and local circumstances matter. Climatic stress will have a different effect on resource availability depending, for example, on local irrigation capacities. And depleted resources affect people differently, depending on whether they have reserves, insurances, etc. (see blue boxes in Figure 105). These are examples of further socio-economic factors that ***moderate*** the relationship between key variables of the climate-security nexus and determine the likelihood of risk propagation along the risk cascade. The latter are particularly relevant for the development of "what if" scenarios: for example, it is fairly obvious to assume that rainfall shortages will have different repercussions in situations with or without irrigation potential, crop insurance, job opportunities outside of agriculture, legal mechanisms for addressing land disputes, etc.

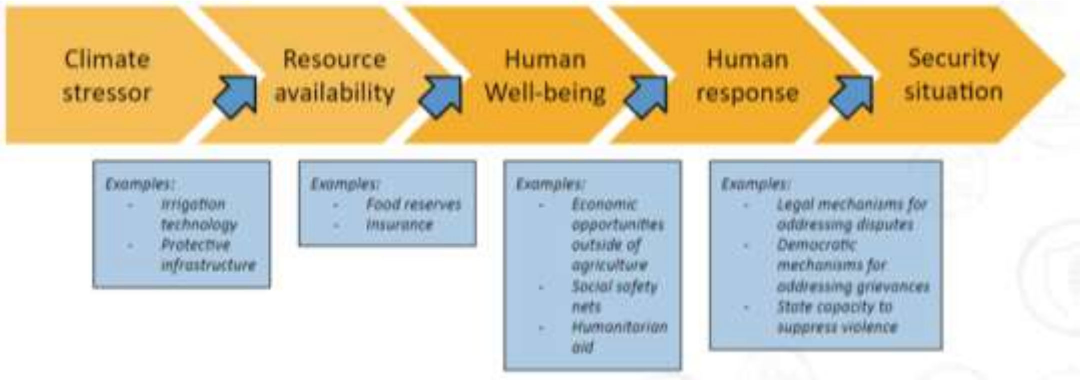

Figure 105: Relevant socio-economic variables for the climate-food/water security nexus: moderating variables.

Considering the above, there is potentially a plethora of socio-economic factors that play a part in connecting climate and security issues and that can, at least in theory, be captured by different indicators. Which indicators are most relevant to consider will depend on the application. For example, a model for predicting forced displacement in the wake of climatic stress might require a slightly different selection of indicators than a model for predicting violent conflicts or food insecurity. Likewise, a model for predicting communal clashes, to some extent, might require different indicators than a model for predicting civil conflict or urban riots.

In theory, there is an infinity of possibilities to combine different socio-economic indicators for different applications. However, in practice, the possibilities of modellers are limited by available data. This likewise concerns the realm of media-derived indicators, where the availability of data depends on a multitude of factors, among them the actual use of media (platforms) in different regions, the kinds of contents exchanged, languages used, the terms-of-use or the technical and legal accessibility of data for particular platforms. Furthermore, (traditional) media may be concerned by freedom of speech, state-control, and censure in certain regions.

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Whereas general schemes for media-derived indicators can be envisioned following the above-mentioned cascades of factors, the actual derivable indicators and their underlying sources strongly depend on the individual use-cases and will need to be considered for each specific case separately.

7.2.5.2 State of the art: data

Different components of the water-food-security-displacement nexus have been modelled in the past using different data. This section provides an overview of some of the most important and widely used data sources.

Food and water security

Notable examples of models and applications in the realm of food and water insecurity include the following:

- The **Famine Early Warning Systems Network (FEWS NET)** assesses and provides early warnings of food insecurity along the Integrated Food Security Phase Classification (IPC) scale.[279] Its analyses are based on household survey data on food consumption and household coping strategies, as well as a scenario development process, which involves assessing the current food security situation, developing key assumptions, analysing expected impacts on food and income sources, and identifying the likely responses of various actors.[280] Updates are provided on a monthly basis, and include projections up to four months. Data is available as polygon shapefiles that often encompass several administrative units and/or parts of administrative units.
- The WFP's **Hunger Map** assesses food security based on the Food Consumption Score (FCS) indicator, with input data from mobile Vulnerability Analysis and Mapping (mVAM) surveys (daily or monthly) and face-to-face surveys (biannually, annually, or when available, depending on the country in focus). Data is available at the admin1 level.[281]
- The **Global Food Security Index (GFSI)**, developed by Economist Impact, is an aggregation of normalised food security-related indicators that can be categorised into four components: (1) affordability (including food prices, poverty rates, income, trade, and food safety net programmes), (2) availability (including access to agricultural inputs, producer prices, extension services, infrastructure, food supply adequacy, conflict risks, and food security policy commitments), (3) quality and safety (including dietary diversity, nutritional standards, nutrient availability, and food safety (which entails access to drinking water)), and (4) sustainability and adaptation (including climate hazard exposure, water availability, land and soil degradation, aquatic biodiversity/eutrophication, political commitment to adaptation, and disaster risk management). While the index is conceptually rich as it considers various aspects of food security, its spatial and temporal resolutions are limited at the country-year level.[282]

The temporal and spatial precision of these food security applications vary: some use data that are updated on a monthly basis and are available at the subnational level, while others rely on yearly and country-level observations. It should also be noted that some use objective measures (i.e. based on dietary, nutritional, and monetary indicators), while others rely on more subjective perceptions of food insecurity (i.e. as reported in survey data).[283] Importantly, there seems to be a trade-off in existing applications between using conceptually more dense models (in the sense that more facets and potential drivers of food insecurity are considered) and models with higher

[279] FEWS NET (n.d.) Food Security Data. https://fews.net/sites/default/files/2023-03/White%20Paper%20-%20FSD_0.pdf.

[280] (1) FEWS NET (2018). Scenario development for food security early warning. Guidance document number 1. https://fews.net/sites/default/files/documents/reports/Guidance_Document_Scenario_Development_2018.pdf. (2) FEWS NET (2021). Matrix analysis. Integrated analysis of survey-based indicators for classification of acute food insecurity. Washington, DC: FEWS NET. https://fews.net/sites/default/files/documents/reports/fews-net-matrix-guidance-document.pdf.

[281] See: https://hungermap.wfp.org/.

[282] See: https://impact.economist.com/sustainability/project/food-security-index/.

[283] Desiere et al. (2015). Assessing the cross-sectional and inter-temporal validity of the Household Food Insecurity Access Scale (HFIAS) in Burundi. Public Health Nutrition, 18, 2775-2785.

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spatial and temporal resolution, owing to limitations in the availability of fine-grained data for many relevant indicators.

Additional data on food security can be found in a number of **household surveys**, like for instance the Afrobarometer, which records respondents' experiences and perceptions of food insecurity and government efforts to address it. IOM's Displacement Tracking Matrix (DTM) focuses on IDP and refugee populations and, for certain countries such as Mozambique, keeps record of food-related indicators (e.g. number of displaced households receiving food distribution, access to local markets). Yet, survey data are often patchy: Afrobarometer usually collects data only every three years and data might not be collected for conflict-affected areas, where information on food security would be particularly relevant to have. In contrast, DTM data often target specific areas of relevance during an ongoing humanitarian emergency. As such, DTM puts the emphasis on some of the most vulnerable people at times when they need the strongest support, but it also means that data collection is rather reactive than proactive, which might limit its usefulness for foresight and early warning applications.

In many cases, **food prices** can be considered a reliable proxy measure for food (in)security.[284] Data on local prices for different food items (including different crops and livestock products) with high spatial and temporal precision are readily available for a number of developing countries. A notable source is the WFP Vulnerability Analysis and Mapping (VAM) platform, which provides food product-specific prices at the 'market' level (equivalent to admin1 or 2 depending on country) on a monthly basis. The temporal resolution and level of detail of these data can often be considered superior to those of the above-mentioned more 'direct' measures of food (in)security.

Notable models and data in the **water security** domain include WRI's Aqueduct data or the USGS-NASA's Global Food Security-Support Analysis Data (GFSAD). They capture water resource availability, use, and depletion, generally over short measurement intervals (e.g. monthly) and at a comparably high spatial resolution (e.g. 10x10km or even 30x30m).

<u>Livelihoods and economic security</u>

Changes in the economic value of climate-sensitive livelihood activities, particularly agricultural and livestock production, are commonly used to proxy changes in the livelihood and economic security of agriculturally dependent populations.[285] This can be estimated via **changes in agricultural income, producer prices, and yields**, and such data are readily available at high spatial and temporal resolutions. The FAO Data in Emergencies Monitoring (DIEM) provides such data every three months at the admin1 level, disaggregated according to crop and livestock type.

Changes in the **share and economic value of climate-sensitive livelihood activities**, particularly crop and to some extent livestock production, are also available at high spatial and temporal resolutions. GFSAD and CGIAR's Spatial Production Allocation Model (MapSPAM) provide a more granular coverage of physical and harvested areas of agricultural production at the grid cell level (up to 30x30m and 10x10km respectively), although on a less frequent (>1 year) basis.

[284] Jones et al. (2017). Food scarcity and state vulnerability: Unpacking the link between climate variability and violent unrest. Journal of Peace Research, 54(3), 335-350.

[285] See for e.g.: Wischnath and Buhaug (2014). Rice or riots: On food production and conflict severity across India. Political Geography, 43, 6-15.

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Conflict and fragility

Data on conflict events are readily available at a high level of resolution and detail from a number of sources. Such data sources have widely been used in the climate-conflict literature,[286] as well as in the development of several risk indices such as Strata[287] and INFORM.[288]

The Armed Conflict Location and Event Data (ACLED) project and Uppsala Conflict Data Program Georeferenced Event Dataset (UCDP GED) provide specific geographic coordinates and dates of **conflict events**, and disaggregates events to conflict type (e.g. state vs. non-state violent events, demonstrations, and non-violent actions), enabling flexibility in terms of aggregating and analysing conflict events at the desired spatial and temporal resolution. The Conflict and Humanitarian Data Centre (CHDC) of the International NGO Safety Organisation (INSO) provides monthly updates on recorded security incidents directed at NGOs, although access to this dataset is restricted.

In addition to location-specific events, conflict and fragility indices that take into account a **state's governance and political structure** as well as the **structure and influence of criminal actors** are widely available, although largely at the country level and at limited temporal frequency. For example, the Rules, Elections, and Irregular Governance (REIGN) dataset, provided by One Earth Future, offers a monthly overview of a country's political conditions which include, among other things, the tenure and personal characteristics of world leaders, the types of political institutions and political regimes in effect, election outcomes, and irregular events such as coups and coup attempts. The Global Organized Crime Index, developed by the Global Initiative Against Transnational Organized Crime, has compiled a criminality score and resilience score based on the structure, control, an influence of criminal groups and criminal markets (e.g. drug trade and arms trafficking), as well as the capacity of countries to take action against organised crime for the year 2021.

Displacement

Data on displacement patterns and refugee statistics are largely provided by the IOM and UNHCR. While the geographic and temporal coverages are large (for e.g. the UNHCR Refugee data goes back to the year 1951), the availability, resolution, and level of detail for certain contexts are limited, and can at best only provide a snapshot in time of displacement status. Depending on the data source, one can also collect information about reasons for displacement and priority needs of displacement, some of which are related to food security concerns, although again such information is only available for certain contexts.

The IOM's DTM provides displacement statistics with a spatial resolution down to admin3, though with limited temporal frequency. Among the three case studies that will be used in the CENTAUR project, the DTM provides in-depth questions on food security needs of displaced persons for Mozambique, but the same level of detail is not available for Mali and Somalia. For Somalia specifically, UNHCR Protection and Return Monitoring Network (PRMN) provides displacement statistics along with information on reasons for displacement (e.g. drought, conflict, flood), and priority needs (e.g. food, livelihood support, water, shelter).

Demographics

Section 7.2.4 provides a detailed overview of datasets on historical, current, and projected population size and distribution. Several of these, such as the GPW dataset produced by CIESIN Columbia University, is used to calibrate various predictive models on food security.[289]

[286] See for e.g.: (1) Eberle et al. (2020). Heat and Hate: Climate Security and Farmer-Herder Conflicts in Africa. CEPR Discussion Papers 15542; (2) Ide et al. (2021). First comes the river, then comes the conflict? A qualitative comparative analysis of flood-related political unrest. Journal of Peace Research, 58(1), 83-97; (3) Vesco et al. (2021). Climate variability, crop and conflict: Exploring the impacts of spatial concentration in agricultural production. Journal of Peace Research, 58(1), 98-113.

[287] See: https://unepstrata.org/.

[288] See: https://drmkc.jrc.ec.europa.eu/inform-index/INFORM-Risk.

[289] See for e.g.: (1) Martini et al. (2022). Machine learning can guide food security efforts when primary data are not available. Nature Food, 3, 716-728; (2) Westerveld et al. (2021). Forecasting transitions in the state of food security with machine learning using transferable features. Science of The Total Environment, 786, 147366.

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In addition to population size and distribution, several sources provide other types of demographic information (e.g. age, gender), although at less precise spatial and temporal resolutions. For example, the World Bank compiles country-level data on population figures and their breakdown according to age and gender. ILOSTAT, provided by the International Labour Organization (ILO), gives a breakdown of employment numbers and labour force by gender.

Wealth and (economic) development

Common measures of economic development, such as GDP, are largely provided at the national level, but are increasingly available at subnational levels. Surveys are also a widely used source to estimate the level of **household asset ownership and income** (e.g. DHS).[290] Census or administrative area-level estimates of aggregated poverty levels are also available (see section 7.1.3.1).

Some models, however, are able to utilise GDP data and projections at the subnational level to model **economic distribution at a finer spatial resolution**, and such data are open and freely accessible. For example, Kummu et al. (2018) produced annual gridded datasets for GDP per capita (PPP), total GDP (PPP) and Human Development Index (HDI) for the whole world at 5 arc-min resolution for the period of 1990-2015.[291] Wang and Sun (2022) produced global gridded GDP projections with fine spatial resolutions of 30 arc-seconds and 0.25 arc-degrees for the historical period of 2005 and from 2030-2100 at ten-year intervals under the five SSPs.[292] Similarly, Murakami et al. (2021) downscaled historical GDP data for 1850-2010 and SSP future scenario data for 2010-2100 to produce gridded GDP datasets in a 1/12-degree grid scale.[293]

Dependence on climate-sensitive activities

A population's degree of flexibility to find economic opportunities outside of climate-sensitive activities in times of environmental hardships can be proxied by the level of dependence on agriculture and livestock production. In turn, agricultural dependence can be proxied by the **share of a certain area that is covered by (rainfed) agricultural land**.[294] Satellite imagery provides an important source for such data, although temporal coverage varies. GFSAD provides yearly coverage of agricultural cropland area, productivity, and irrigation area at a resolution of 30x30m. Meanwhile, CGIAR's MapSPAM provides information on physical agricultural production area, harvested area, yield, and production value at a resolution of 10x10km, but is only available for a limited time period (2000-2017) at an approximately five-year basis.

For livestock production, the FAO's Gridded Livestock of the World (GLW) dataset provides high resolution data on livestock density for specific livestock types (i.e. buffaloes, cattle, chickens, ducks, horses, goats, pigs, and sheep) at the grid cell level of up to 10x10km – however, temporal coverage is poor (i.e. available only for the years 2010 and 2015).

Aids, services, and infrastructure

Surveys such as Afrobarometer and DHS provide important insights into households' experiences and perceptions on **access to and availability of essential services** such as improved water sources. For the three case study

[290] See also data used in: de Juan and Hänze (2021). Climate and cohesion: The effects of droughts on intra-ethnic and inter-ethnic trust. Journal of Peace Research, 58(1), 151-167.

[291] Kummu et al. (2018). Gridded global datasets for Gross Domestic Product and Human Development Index over 1990–2015. Scientific Data, 5, 180004.

[292] Wang and Sun (2022). Global gridded GDP data set consistent with the shared socioeconomic pathways. Scientific Data, 9, 221.

[293] Murakami et al. (2021). Gridded GDP Projections Compatible With the Five SSPs (Shared Socioeconomic Pathways). Frontiers in Built Environment, 138.

[294] See for e.g.: (1) Almer et al. (2017). Water scarcity and rioting: Disaggregated evidence from Sub-Saharan Africa. Journal of Environmental Economics and Management, 86, 193-209; (2) Uexkull (2014). Sustained drought, vulnerability and civil conflict in Sub-Saharan Africa. Political Geography, 43, 16-26.

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countries, the DIEM queries respondents on their assistance needs. However, such survey data are often constrained in terms of their temporal coverage and frequency.

Data on **infrastructure** such as roads and electricity lines are more readily accessible at the desired spatial and temporal resolutions. A key source in this regard that is free and openly accessible is OpenStreetMap, used by a number of recent studies to predictively and spatially map global infrastructure distribution. Using OpenStreetMap data, Nirandjan et al. (2022) developed a global dataset of critical infrastructure pertaining to transportation, energy, water, waste, telecommunication, education, and health.[295] More specifically on power grids, Arderne et al. (2020) performed a predictive mapping of global access to low-, medium-, and high-voltage power transmission lines.[296]

Information on **access to aid**, be it for humanitarian or development purposes, are relatively limited in terms of spatial and temporal resolution. UNOCHA's Financial Tracking Service (FTS) provides detailed information on global humanitarian funding flows by source and destination as well as by sector (e.g. agriculture, food security, nutrition, and water). Similarly, the World Bank's World Development Indicators offer datasets on access to services and social safety nets. Both datasets are however only available at the country-year level.

Other existing datasets on access to aid and social safety nets are limited to specific internationally or nationally funded and implemented projects and programmes. Such datasets are thus limited in terms of temporal and geographic coverage, but may provide more granular temporal and spatial resolution.[297] Examples include UNOCHA's Cash Based Programming in Somalia project, which provides monthly data on access to aid at the admin2 level, and USAID's Finance for Food Security and Women Entrepreneurs (FFSWE) project, which provides admin1 level information on agricultural loans provided under the framework of the project in Mali.

Politics, institutional mechanisms, and social relations

Data on public perception on governance structures, institutional mechanisms, and social relations are for the most part available from surveys. For example, the Afrobarometer has been used by Detges (2017) and Petrova (2022) to assess **level of political marginalisation and trust in governments, courts, and law enforcement bodies**, as well as by De Juan and Hänze (2021) to explore **intra- and inter-ethnic attitudes**.[298] Based on data collected from surveys, the Social Cohesion and Reconciliation (SCORE) index provides scores for **intercommunity relations and support for violence** for the year 2021 at the admin2 level. However, the SCORE index is only limited to a number of countries, including Mali, and like most other survey-based data sources, are limited in terms of temporal frequency and coverage.

Data on **democracy, political stability, and government performance** are largely restricted to the country-year level, though widely used in several climate-conflict studies,[299] and for the most part are free and publicly available. Examples include the Database of Political Institutions (DPI) provided by the Inter-American Development Bank, polity scores provided by Center for Systemic Peace, and the Freedom House's data on democratic status, with scores on media freedom, civil liberties, and corruption.

Similarly, the Geo-referencing Ethnic Power Relations (GeoEPR) dataset, provided by ETH Zürich, identifies all **politically relevant ethnic groups**, assesses their **access to political power**, and where relevant, provides location-

[295] Nirandjan et al. (2022). A spatially-explicit harmonized global dataset of critical infrastructure. Scientific Data, 9, 150.

[296] Arderne et al. (2020). Predictive mapping of the global power system using open data. Scientific Data, 7, 19.

[297] See for e.g.: Fetzer (2020). Can Workfare Programs Moderate Conflict? Evidence from India. Journal of the European Economic Association, 18(6), 3337-3375.

[298] (1) Detges (2017). Droughts, state-citizen relations and support for political violence in Sub-Saharan Africa: A micro-level analysis. Political Geography, 61, 88-98; (2) Petrova (2022). Floods, communal conflict and the role of local state institutions in Sub-Saharan Africa. Political Geography, 92, 102511; (3) de Juan and Hänze (2021). Climate and cohesion: The effects of droughts on intra-ethnic and inter-ethnic trust. Journal of Peace Research, 58(1), 151-167.

[299] See for e.g.: Eberle et al. (2020). Heat and Hate: Climate Security and Farmer-Herder Conflicts in Africa. CEPR Discussion Papers 15542.

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specific information of their settlement patterns in the form of polygons, but only on an annual basis. Nonetheless, it is a key data source used by a number of climate-conflict studies investigating the moderating role of ethnically based political marginalisation.[300]

In terms of media coverage and media-driven narratives, the **dependency of outlets on governments** may play an important role. Sources such as Reporters Without Borders or the World Press Freedom Index may provide insights and foundations in attributing importance to media-derived indicators.

7.2.5.3 Limitations in commonly used data sources and indicators

There is a high degree of divergence in the granularity of data and indicators used to measure the various socio-economic and political variables of food and water security. While information derived from surveys provide important insights on several key aspects of food and water (in)security (e.g. perceptions of food and water security, access to services, social relations, and trust in authorities), surveys are often time-consuming and costly to conduct and thus suffer from limited spatial and temporal coverage and frequency, particularly in developing and fragile contexts (see also section 7.1.3.2). Meanwhile, data on political stability and institutional structures are often limited to the country-year level. Thus, they may not sufficiently reflect smaller-scale and shorter-term impacts of socio-political changes and meet the desired spatial and temporal resolutions as required in the scope of the CENTAUR project. The differences in spatial and temporal resolutions of the potential data sources could therefore pose challenges in generating predictions of food insecurity on a regular short-term basis.[301]

Issues of spatial and temporal resolutions can be (partially) addressed by using data derived from satellite imagery, such as night-time light emissions as a proxy for level of wealth and development. However, such data alone may suffer from validity and interpretability issues (see section 7.1.3.2). Furthermore, the performance of models to predict food insecurity hinge upon the size and availability of historical sample data of the country of interest, which may not be the case for a number of countries.[302]

In addition, data collection on food security indicators of some of the most vulnerable population groups (e.g. displaced people) are often only conducted during times of emergencies and are thus reactive in their approach. This limits the applicability of such data for more proactive approaches that aim to anticipate food security crises and formulate effective early warning responses.

Traditional and social media could provide an important data source to complement and validate observations derived from non-media sources. On the one hand, they offer an immediacy in temporal and geographic terms which may surpass that of other sensors. On the other, media coverage depends on region, platform terms-of-use and public accessibility, control of platforms and outlets by individual, groups or governments and should only be regarded as a proxy for different types of phenomena.

7.2.6 Innovative Water and Food Security Indicators

Due to the multi-disciplinary approach of CENTAUR, numerous definitions of what constitutes an indicator exist. For the purpose of the project and in order to be able to combine indicators of different provenance, a common definition will be adopted.

There are numerous definitions of indicator. Broadly speaking, an indicator can be a sign, symptom, signal, tip, clue, grade, rank, object, organism, or warning of some sort — many things in everyday life (Meadows, 1998). In a more restricted sense, as is often used in the scientific literature, an indicator refers to a variable or an aggregate of multiple related variables whose values can provide information about the conditions or trajectories of a system

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[300] See for e.g.: (1) Buhaug et al. (2015). Climate variability, food production shocks, and violent conflict in Sub-Saharan Africa. Environmental Research Letters 10(12), 125015; (2) de Juan and Hänze (2021). Climate and cohesion: The effects of droughts on intra-ethnic and inter-ethnic trust. Journal of Peace Research, 58(1), 151-167; (3) Uexkull et al. (2016). Civil conflict sensitivity to growing-season drought. Proceedings of the National Academy of Sciences of the United States of America 113(44), 12391-12396.

[301] Martini et al. (2022). Machine learning can guide food security efforts when primary data are not available. Nature Food, 3, 716-728.

[302] Martini et al. (2022). Machine learning can guide food security efforts when primary data are not available. Nature Food, 3, 716-728.

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or phenomenon of interest. In other words, an indicator is simply "an operational representation of an attribute (quality, quantity, characteristic, property) of a system" (Gallopin, 1997).

An index, instead, is an aggregate of two or more indicators.

Socio-economic indicators as outlined above are expected to be developed with the aim to combine them with other kinds of indicators. In principle, they are expected to be of a quantitative nature, allowing for combination with other kinds of indicators into compound-indicators (or indices). Indicators derived from traditional and social media may serve as proxies, provide first-hand on-the-ground information, complementing and extending more traditional kinds of indicators.

With reference to the water and food security context, in CENTAUR project different indicators will be considered:

Biophysical parameters and agriculture, water and meteorological variables

- WFS-ID-1: Meteorological drought indicator (Monitoring)
- WFS-ID-2: Meteorological drought indicator (Forecast)
- WFS-ID-3: Meteorological drought indicator (calibrated in danger levels)
- WFS-ID-4: Agricultural drought monitoring (near real-time)
- WFS-ID-5: Agricultural drought forecast
- WFS-ID-6: Risk zone map

Fine-scale population distribution and exposure to security risks and resources shortage

- WFS-ID-7: People movement indicator
- WFS-ID-8: Indicators of exposure to resource shortages: food (in)security
- WFS-ID-9: Indicators of exposure to resource shortages: water (in)security
- WFS-ID-10: Number of people living in conflict-affected areas

Demographic and socio-economic stress, vulnerability

- WFS-ID-11: Food security
- WFS-ID-12: Economic security
- WFS-ID-13: Displaced persons
- WFS-ID-14: Crime and illicit activities
- WFS-ID-15: Radicalisation and polarisation
- WFS-ID-16: Disruptions in food supply chains
- WFS-ID-17: Humanitarian aid
- WFS-ID-18: Resource capture
- WFS-ID-19: Climate sensitivity of agri-food systems
- WFS-ID-20: Obstacles to mobility
- WFS-ID-21: Public services and infrastructures
- WFS-ID-22: Strength of armed groups
- WFS-ID-23: State-citizen relations
- WFS-ID-24: Dispute resolution mechanisms

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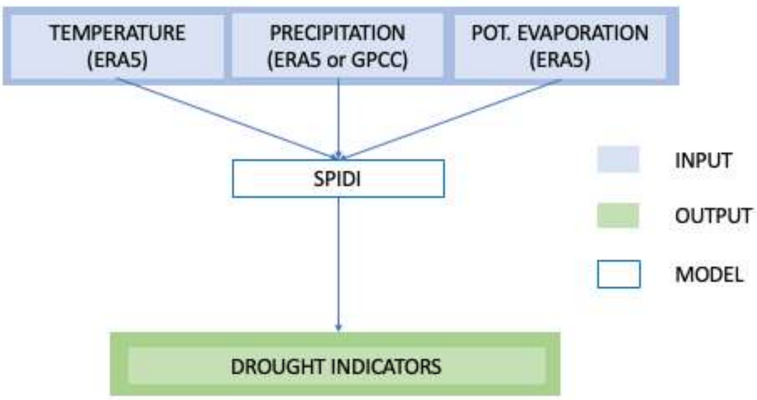
- WFS-ID-25: Social cohesion and trust

7.2.6.1 Biophysical parameters and agriculture, water and meteorological variables.

WFS-ID-1: Meteorological drought indicator (Monitoring)

Name of Indicator	Meteorological drought indicator (Monitoring)
Brief Description	Indicators to monitor current drought conditions expressed in terms of precipitation deficit
Gap(s) addressed	Novel, high-resolution (0.25°) near real-time monitoring product using state-of-the-art reanalyses and observation products. Current monitoring products run at coarser resolutions (0.5° or 1°) and are updated only weekly or monthly.
List of input data required with relative sources (where available)	Precipitation from reanalyses (ERA5 from ECMWF) or from SYNOP stations as a gridded product (GPCC), Temperature from reanalyses (ERA5 from ECMWF), potential evaporation from reanalyses (ERA5 from ECMWF)
Output indicator type and format	List of potential indicators: - Standardized precipitation index (SPI) over various time periods (1,3,6,12 months) - Standardized precipitation evapotranspiration index (SPEI) over various time periods (1,3,6,12 months) - Soil moisture index (SMI) Format: netCDF/grib
Spatial and temporal resolutions obtainable	Spatial resolution: 0.25° (ERA5) or 1° (GPCC) Temporal resolution: monthly (daily)
Thematic area covered	Water and Food Insecurity, Meteorological drought
Workflow schema and brief steps description	 Steps: 1. Acquisition of ERA5 and GPCC time series 2. Identification of drought events using the SPIDI library 3. Generation of an observation-based drought archive near real-time

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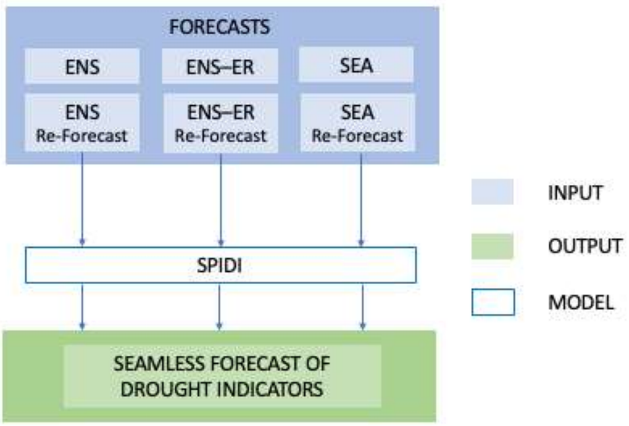
WFS-ID-2: Meteorological drought indicator (Forecasting)

Name of Indicator	Meteorological drought indicator (Forecasting)
Brief Description	Indicators to forecast drought conditions expressed in terms of precipitation deficit at different lead times
Gap(s) addressed	Novel operational drought forecast employing various numerical weather prediction forecasts to enable a seamless prediction from day 1 to 6 months ahead.
List of input data required with relative sources (where available)	Precipitation and temperature from (i) ECMWFs ensemble forecast (ENS) up to 15 days ahead, (ii) ECMWFs extended-range ensemble forecast (ENS-ER) up to 46 days ahead, and (iii) ECMWFs seasonal forecast up to 6 months ahead (SEA)
Output indicator type and format	List of potential indicators: - Standardized precipitation index (SPI) over various time periods (1,3,6,12 months) - Standardized precipitation evapotranspiration index (SPEI) over various time periods (1,3,6,12 months) - Soil moisture index (SMI) Format: netCDF/grib
Spatial and temporal resolutions obtainable	Spatial resolution: variable (9 km (ENS), 36 km (ENS–ER), 35 km (SEA)); maybe interpolated to communal resolution. Temporal resolution: monthly (daily up to 15/46 days)
Thematic area covered	Water and Food Insecurity, Meteorological drought
Workflow schema and brief steps description	 Steps: 1. Acquisition of latest forecasts and reforecasts from ENS, ENS–ER, SEA 2. Identification of drought events using the SPIDI library 3. Generation of a seamless drought forecast

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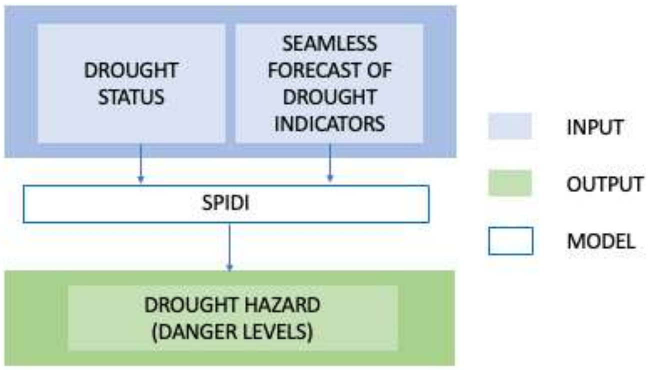
WFS-ID-3: Meteorological drought indicator (calibrated in danger levels)

Name of Indicator	Meteorological drought indicator (calibrated in danger levels)
Brief Description	Evaluation of seamless drought forecast in relation to monitoring status to derive simplified warning/actable levels. Identification of tendency towards intensification of events.
Gap(s) addressed	Easy-to-understand indicators that are not site-specific; (probability of) intensification or alleviation of drought
List of input data required with relative sources (where available)	Drought status + seamless drought forecast
Output indicator type and format	à Probability of drought occurrence and severity ? Probability of drought intensification or alleviation
Spatial and temporal resolutions obtainable	Spatial resolution: variable; maybe interpolated to communal resolution. Temporal resolution: monthly
Thematic area covered	Water and Food Insecurity, Meteorological drought
Workflow schema and brief steps description	 Steps: 1. Acquisition of the latest drought status and drought forecast 2. Evaluation of the drought forecast in relation to the monitoring status using the SPIDI library 3. Generation of a danger levels

WFS-ID-4: Agricultural drought monitoring (near real-time)

Name of Indicator	Agricultural drought monitor
Brief Description	Indicator that expresses the relative impact of drought events on the current vegetation condition and productivity. It integrates current and historical information on plant condition (NDVI), thermal drought stress and environmental conditions (precipitation, temperature and soil moisture).
Gap(s) addressed	Current drought early warning systems are mostly based on pixel-by-pixel temporal anomaly analysis of (primarily) NDVI data. However, an important lag time exists between the onset of impact of droughts on crop production and a visible drop in indicators such as NDVI. By combining NDVI with thermal

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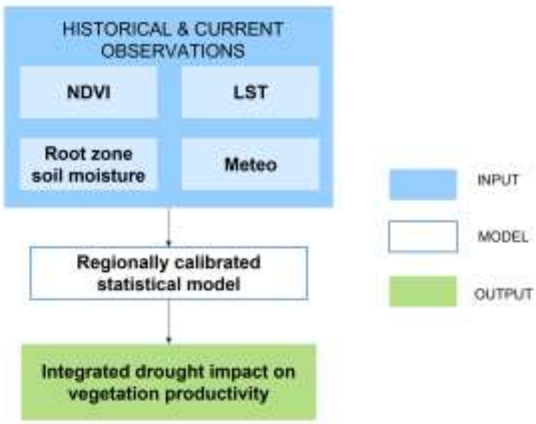
Name of Indicator	Agricultural drought monitor
	drought stress and soil moisture indicators, we will provide more timely estimates of drought impacts on vegetation productivity. In addition, our indicator will be calibrated at regional level, as such taking into account important variations in spatial context, in turn mainly driven by climate, land cover/use and elevation.
List of input data required with relative sources (where are available)	➢ Root Zone Soil moisture from the GRACE and GRACE FO satellites at 25 km spatial resolution and 7 days temporal resolution (Home | NASA Grace (unl.edu)). ➢ Dekadal NDVI time series at 1 km resolution over the last 20 years; derived from the Copernicus Global Land harmonized NDVI dataset (https://land.copernicus.eu/global/products/ndvi). ➢ Land surface temperature data at 1 km resolution derived from Sentinel-3. ➢ Air temperature (2m above ground), relative humidity, precipitation, solar radiation and wind speed, derived from the ERA5-Land dataset (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land?tab=overview).
Output indicator type and format	All following intermediate indicators will be delivered as raster products (GeoTiff format): ➢ Thermal drought stress indicator (difference between land surface temperature and air temperature) ➢ Visible drought severity indicator (based on NDVI data) ➢ Evaporative Stress Index (ESI) Based on the previous intermediate data products, we will provide an integrated indicator on the relative impact of drought on vegetation productivity, also taking into account the timing with regard to the growing season.
Spatial and temporal resolutions obtainable	Spatial resolution: 1 km Temporal resolution: daily - dekadal
Thematic area covered	Water and Food Insecurity; agricultural droughts
Workflow schema and brief steps description	

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Name of Indicator	Agricultural drought monitor
	Step1 - Acquisition of NDVI, LST, root zone soil moisture and meteorological time series Step 2 – Creating of homogeneous zones with regard to typical NDVI behaviour and environmental conditions Step 3 – Determine the timing of the growing season for each zone Step 4 – Computing intermediate indicators such as evaporative stress index and drought severity index Step 5 – Build and apply a local statistical models and/or decision support system that allows to combine the different individual indicators to an integrated indicator which quantifies the impact of drought on vegetation productivity in near real-time

WFS-ID-5: Agricultural drought forecast

Name of Indicator	Agricultural drought forecast
Brief Description	Indicator that expresses the relative impact of future drought conditions on the vegetation condition and productivity. It combines knowledge on the current drought conditions (cf. Agricultural drought monitor product) with meteorological forecasts to predict the likelihood of adverse impacts on vegetation productivity potentially occurring in the future, up to several months in advance.
Gap(s) addressed	Most existing agricultural drought early-warning systems only focus on monitoring the impact of the droughts in near real-time, but do not look into the future (i.e. several months ahead).
List of input data required with relative sources (where are available)	➢ Precipitation and temperature from (i) ECMWFs ensemble forecast (ENS) up to 15 days ahead, (ii) ECMWFs extended-range ensemble forecast (ENS-ER) up to 46 days ahead, and (iii) ECMWFs seasonal forecast up to 6 months ahead (SEA) ➢ Forecasts on Soil moisture anomalies from ECMWF Indicators involved in assessment of current drought conditions (cf. ID-4) ➢ NDVI, Land surface temperature, meteorological data, root zone soil moisture.
Output indicator type and format	Relative impact of drought on vegetation productivity and associated likelihoods of occurrence for different time periods into the future. All products will be delivered in GeoTiff format.
Spatial and temporal resolutions obtainable	Spatial resolution: 1 km Temporal resolution: dekadal for first month, then (bi-)monthly up to six months into the future
Thematic area covered	Water and Food Insecurity; agricultural drought

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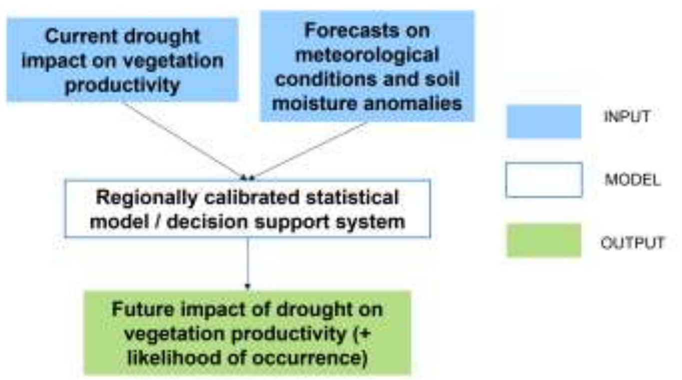
Name of Indicator	Agricultural drought forecast
Workflow schema and brief steps description	 Step1 – Get estimate on current impacts of drought on vegetation productivity (cf. Agricultural drought monitor product) Step 2 – Get meteorological forecasts (temperature, precipitation and soil moisture anomalies) Step3 – Combine both products to generate likelihood of occurrence of adverse drought impact on vegetation productivity and quantify this impact in a relative sense.

WFS-ID-6: Risk zone map

Name of Indicator	Risk Zone map
Brief Description	Risk of occurrence of adverse drought impact on agricultural production, expressed at a categorical scale and at different monthly lead times.
Gap(s) addressed	It addresses the needs for an easily interpretable product capable of displaying visually and efficiently the risk of agricultural droughts at regional, national, and subnational scales, several months ahead in time. It is anticipated that the product will provide critical information in a manner that is immediately intelligible to the end user, who is likely unfamiliar with the underlying science and technology.
List of input data required with relative sources (where are available)	This product is based on the Agricultural drought monitor and Agricultural drought forecast products and their associated input data.
Output indicator type and format	Categorical agricultural drought risk map delivered in ESRI Shapefile or GeoPackage format.
Spatial and temporal resolutions obtainable	Dekadal, monthly and bi-monthly depending on the lead time.
Thematic area covered	Water and Food Insecurity; agricultural drought

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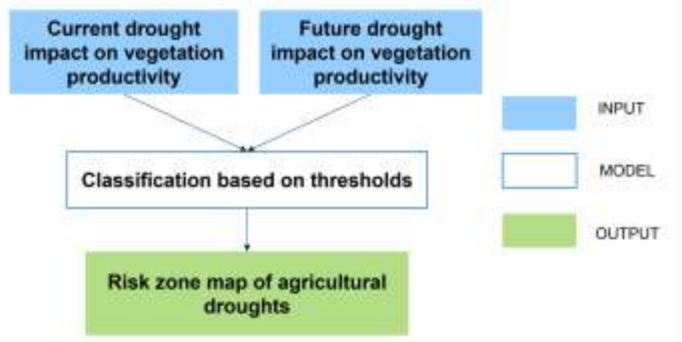
Name of Indicator	Risk Zone map
Workflow schema and brief steps description	 Step1 – Acquisition of current and future drought impacts on vegetation productivity (cf. previous products) Step 2 – Combining both products into a zonal risk map using a regionally specific threshold system

7.2.6.2 Fine-scale population distribution and exposure to security risks and resources shortage

Food security, water availability and crime and illicit activities indicators are expected to be developed with the aim to combine them with fine-scale population datasets to produce compound-indicators of exposure. Hence, in the CENTAUR project the following indicators will be considered:

WFS-ID-7: Camps and border checkpoints status indicator

Name of Indicator	Camps and border checkpoints status indicator
Brief Description	The analysis of the development of camps and checkpoints can provide information about the people movements related to food insecurity events, conflicts or political disorders.
Gap(s) addressed	Integration with different sources of data to detect people movements
List of input data required with relative sources (where are available)	Sentinel -1 SAR data VHR Contributing Mission
Output indicator type and format	Raster Vector (shapefile)
Spatial and temporal resolutions obtainable	~1-3 m and weekly revisit time in regular conditions
Thematic area covered	People movements in SEA applications

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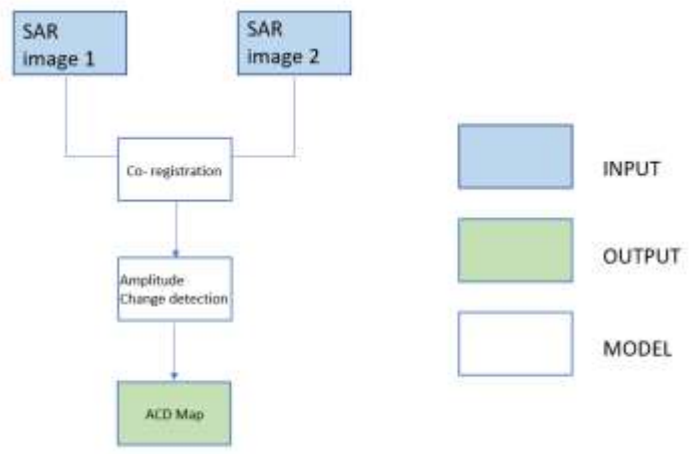
Name of Indicator	Camps and border checkpoints status indicator
Workflow schema and brief steps description	 **Step1 –SAR images collection** Satellite images of the area of interest collection **Step 2 – Data Processing** In the first stage a co-registration operation is needed in order to perfectly match the two data acquired (pre and post event of interest). Then is applied the algorithm to detect the changes occurred between pre and post event collections according to the colour space of the RGB false colour composite stacked image generated. **Step3 – Change detection map generation** The change detection map is generated highlighting the points where changes, e.g. different features, in the second image are present with respect to the first reference image.

WFS-ID-8: Indicators of exposure to resource shortages: food (in)security

Name of Indicator	Populations at risk of hunger (present and future)
Brief Description	Static maps or tabular data describing the number of people at risk of hunger derived from the scale of food security level in a given area.
Gap(s) addressed	With the integration of volume and use information into the modelling of fine-scale gridded population estimates, higher spatial resolution and accuracy will allow to improve the prediction of populations at risk of hunger in relation to food security analyses compared to existing approaches.
List of input data required with relative sources (where are available)	Data from CENTAUR partners: ➢ Food security scale levels and projections in the form of shapefiles holding a security index ➢ WSF-Population (2016-present, 10m) Available data for forecast tasks: ➢ GHS-POP (2025;2030; 100m)

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Name of Indicator	Populations at risk of hunger (present and future)
Output indicator type and format	Tabular of shapefile dataset (.csv or ESRI-Shapefile)
Spatial and temporal resolutions obtainable	Temporal Resolution: Monthly or quarterly observations Spatial resolution: Aggregated estimate at admin 1 or admin 2 level
Thematic area covered	Water and food security
Workflow schema and brief steps description	**Step 1:** Reprojection of food security shapefiles to the corresponding GCS of the population grid employed (if needed) **Step 2:** Derive zonal statistics of population for those spatial units with low ranks of food security. This could include the total, or mean for more conservative estimations. **Step 3:** Aggregate totals to administrative units

WFS-ID-9: Indicators of exposure to resource shortages: water (in)security

Name of indicator	Number of people at risk of water scarcity (present and future)
Brief Description	Static maps or tabular data depicting hot-spots of water scarcity as well as number of people at risk of water scarcity.
Gap(s) addressed	With the integration of volume and use information into the modelling of fine-scale gridded population estimates, higher spatial resolution and accuracy will allow improving the identification of emerging acute water scarcity situations with higher frequency updates.
List of input data required with relative sources (where are available)	Data from CENTAUR partners: ➢ Water availability ➢ Basin or catchment shapefile datasets ➢ WSF-Population (2016-present, 10m) Available data for forecast tasks: ➢ GHS-POP (2025;2030; 100m)
Output indicator type and format	Water scarcity maps. Output format will be raster type (.tif), tabular of shapefile dataset (.csv or ESRI-Shapefile)
Spatial and temporal resolutions obtainable	Temporal resolution: Monthly and quarterly observations. Spatial resolution: Pending
Thematic area covered	Water and food security
Workflow schema and brief steps description	**Step 1:** Harmonising water availability and fine-scale population grids through automated resampling processes **Step 2a:** Use of automated overlay analyses to calculate the water availability per capita m^3/person/year at the grid level

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Name of indicator	Number of people at risk of water scarcity (present and future)
	Step 3: Reclassification will be performed at the grid level to assign a scarcity level to each pixel. Classification thresholds will be based on the Falkenmark's approach **Step 4:** If requested, steps 2-3 can be calculated at the basin/catchment or other AOI of interest. Input data in the form of shapefiles would be necessary for the performance of analyses.

WFS-ID-10: Number of people living in conflict-affected areas

Name of Indicator	Number of people living in conflict-affected areas
Brief Description	Static maps, shapefiles or tabular data describing the no. of people living in conflict-affected areas. This is an important indicator because people living in conflict zones often lack access to water and food and are more exposed to violence.
Gap(s) addressed	With the integration of volume and use information into the modelling of fine-scale gridded population estimates, higher spatial resolution and accuracy will allow estimating the number of people living in the proximity of conflicted-affected areas. Our proposed analyses can be conducted either at different radius from a localized event or at the level of administrative boundaries.
List of input data required with relative sources (where are available)	Data from CENTAUR partners: ➢ Crime and illicit activities ➢ Strength of group arms ➢ WSF-Population (2016-present, 10m) Available data for forecast tasks: ➢ GHS-POP (2025;2030; 100m)
Output indicator type and format	Tabular or shapefile data.
Spatial and temporal resolutions obtainable	Temporal resolution: Monthly and quarterly observations. Spatial resolution: Aggregated estimate at admin1 or admin2 level
Thematic area covered	Water & food security

7.2.6.3 Demographic and socio-economic stress, vulnerability

WFS-ID-11: Food security

Name of Indicator	Food security
Brief Description	Scale for level of food security of the population in a given area. Can contain several components (e.g. available/produced food, food prices, ease of access, etc.). Disaggregating by groups (e.g. IDPs, vulnerable groups) would be useful.
Gap(s) addressed	Indicators for different dimensions of food security and/or drivers of food insecurity exist at different scales and with varying temporal and spatial coverage. Modelling in CENTAUR requires combining them at the required

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Name of Indicator	Food security
	scale and with an explicit integration into climate-security and climate-displacement models in mind.
List of input data required with relative sources (where are available)	Data from CENTAUR partners: ➢ Media data, including mentions of hunger; acute food insecurity; difficulties in accessing/buying food; food price inflation; delays/disruption in food aid, supply chains, storage, and transportation; strikes; boycotts; embargos; information about suppliers (e.g. bankruptcies); etc. ➢ EO data: agricultural productivity; livestock productivity, fishery productivity Available data potentially useful for validating and calibrating the above: ➢ Afrobarometer ➢ DHS (USAID) ➢ DIEM (FAO) ➢ DTM (IOM) ➢ Enquête Agricole de Conjoncture Intégrée aux Conditions de Vie des Ménages (Mali) ➢ Enquête Harmonisée sur le Conditions de Vie des Ménages (Mali) ➢ FEWS NET ➢ FSNAU (FAO) ➢ GIEWS (FAO) ➢ Hunger Map (WFP) ➢ Livelihoods Programme Monitoring Beneficiary Survey (UNHCR) ➢ MICS (UNICEF) ➢ VAM (WFP)
Output indicator type and format	Dataset, with possibility to export as csv and shapefile
Spatial and temporal resolutions obtainable	Spatial resolution: Aggregated estimate at admin1 or admin2 level Temporal resolution: Monthly or quarterly observations
Thematic area covered	Water and food security

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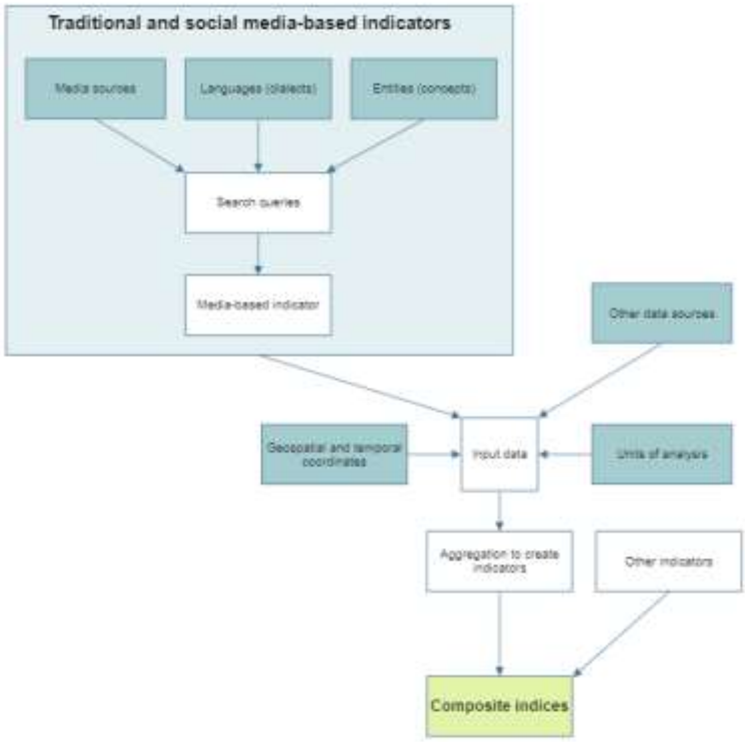
Name of Indicator	Food security
Workflow schema and brief steps description	 Step 1: assigning geospatial and temporal coordinates to input data, if not already included (e.g. in the case of media data) Step 2: join data with table containing relevant units of analysis (e.g. admin1 by month) Step 3: aggregate data by unit of analysis to create indicators (e.g. average agricultural productivity score in admin1-month) Step 4: create composite indices, if necessary, by combining different indicators (e.g. average agricultural productivity score combined with average perceived food insecurity and other indicators) For media-based indicators:[303] Step 1: assigning relevant sources, media-outlets, influencers, etc. Step 2: determine relevant languages (dialects) Step 3: determine relevant entities (concepts) Step 4: set up search queries to feed indicator generation Step 5: output in standard form (e.g. csv)

[303] This is the prototypical workflow to be applied for all media-based indicators.

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WFS-ID-12: Economic security

Name of Indicator	Economic security
Brief Description	Scale for level of economic and livelihood security of the population in a given area. Can contain several components (e.g. job and other economic opportunities, incomes).
Gap(s) addressed	Models connecting climatic shocks to conflict and displacement very often assume an indirect link via livelihoods and income. Yet, they rarely include direct measures of the latter due to data gaps. The suggested indicator (or index) fills this gap, providing information on an essential intermediary variable of the climate-security nexus. Moreover, available estimates of wealth and economic opportunities are often not available with the required temporal granularity to capture reciprocal effects and feedback loops between poverty and insecurity.
List of input data required with relative sources (where are available)	Data from CENTAUR partners: ➢ Media data, including mentions of lost incomes and livelihoods; unemployment; inflation; economic difficulties more generally (e.g. lack of money, difficulties to provide for one's family and oneself); sentiment towards general economic performance and one's own economic prospects; information about strikes, embargos, shortages, riots, finance, banking, and politics ➢ EO data: agricultural productivity; livestock productivity; fishery productivity; drought intensity Available data potentially useful for validating and calibrating the above: ➢ Afrobarometer ➢ DIEM (FAO) ➢ Enquête Agricole de Conjoncture Intégrée aux Conditions de Vie des Ménages (Mali) ➢ International Livestock Research Institute (ILRI) ➢ Kummu et al. (2020): Gridded global datasets for Gross Domestic Product and Human Development Index over 1990-2015. Dryad, Dataset. ➢ Livelihoods Programme Monitoring Beneficiary Survey (UNHCR) ➢ Murakami et al. (2021): Gridded GDP projections compatible with the five SSPs. Frontiers in Built Environment, 7, 760306. ➢ Wang and Sun (2022). Gross domestic product (GDP) downscaling: a global gridded dataset consistent with the Shared Socioeconomic Pathways. Scientific Data, 9, 221.
Output indicator type and format	Dataset, with possibility to export as csv and shapefile
Spatial and temporal resolutions obtainable	Spatial resolution: Aggregated estimate at admin1 or admin2 level Temporal resolution: Monthly or quarterly observations
Thematic area covered	Water and food security
Workflow schema and brief steps description	Step 1: assigning geospatial and temporal coordinates to input data, if not already included (e.g. in the case of media data) Step 2: join data with table containing relevant units of analysis (e.g. admin1 by month) Step 3: aggregate data by unit of analysis to create indicators (e.g. average perceived economic opportunities score in admin1-month)

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Name of Indicator	Economic security
	Step 4: create composite indices, if necessary, by combining different indicators (e.g. average agricultural productivity score combined with average perceived economic opportunities and other indicators) For the general workflow schema and prototypical workflow for media-based indicators, see ID-11.

WFS-ID-13: Displaced persons

Name of Indicator	Displaced persons
Brief Description	Estimate of the number of persons displaced, including IDP and refugees in neighbouring countries. Disaggregation by mobility type would be useful.
Gap(s) addressed	Capacities of humanitarian organisations to record the number of displaced persons on the ground are limited, leading to incomplete records. Often data collection starts only once a crisis is ongoing. The aim here is to produce more complete data and more precise estimates that are collected and calculated ahead of potential crises.
List of input data required with relative sources (where are available)	Data from CENTAUR partners: ➢ EO data: queues at border crossings and on major migration routes; people movement and accumulation points; growth of refugee and IDP camps; rapid growth of secondary towns, peri-urban areas, and urban slums ➢ Media data, including mentions of displacement; violence; smuggling; trafficking activities; refugees; refugee camps; and border incidents Available data potentially useful for validating and calibrating the above: ➢ DTM (IOM) ➢ GHLS ➢ Google imagery ➢ HRSL ➢ Humanitarian Data Exchange (HDX) ➢ OpenStreetMap ➢ PRMN (UNHCR) ➢ World Settlement Footprint: evolution; high frequency layers
Output indicator type and format	Dataset, with possibility to export as csv and shapefile
Spatial and temporal resolutions obtainable	Spatial resolution: Aggregated estimate at admin1 or admin2 level Temporal resolution: Monthly or quarterly observations
Thematic area covered	Water and food security
Workflow schema and brief steps description	Step 1: assigning geospatial and temporal coordinates to input data, if not already included (e.g. in the case of media data) Step 2: join data with table containing relevant units of analysis (e.g. admin1 by month) Step 3: aggregate data by unit of analysis to create indicators (e.g. average size of queues at border crossings in admin1 in a month) Step 4: create composite indices, if necessary, by combining different indicators (e.g. average size of queues at border crossings combined with average growth of refugee camps and other indicators)

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Name of Indicator	Displaced persons
	For the general workflow schema and prototypical workflow for media-based indicators, see ID-11.

WFS-ID-14: Crime and illicit activities

Name of Indicator	Crime and illicit activities
Brief Description	Number/frequency of crimes and other illicit activities that are indicative of maladaptive practices and susceptible to conflict escalation (e.g. cattle theft leading to communal clashes) or to provide financial opportunities to armed groups (e.g. drug trade, human trafficking).
Gap(s) addressed	Conflict prediction models tend to rely on data on manifest violent events and are hence not able to capture earlier stages of conflict escalation like smaller violent (or non-violent) incidents involving a few people but with the potential to fuel wider social tensions and even collective violence. However, from an early warning and conflict prevention perspective, this would make sense.
List of input data required with relative sources (where are available)	Data from CENTAUR partners: ➢ Media data, including mentions of crime (e.g. cattle theft); changes in other illicit activities (e.g. drugs, human trafficking); police and law enforcement (counter-)activities and legislation ➢ EO data: illegal logging; illegal fishing; anomalous ship movements (Somalia) Available data potentially useful for validating and calibrating the above: ➢ Afrobarometer ➢ Global Organized Crime Index
Output indicator type and format	Dataset, with possibility to export as csv and shapefile
Spatial and temporal resolutions obtainable	Spatial resolution: Aggregated estimate at admin1 or admin2 level Temporal resolution: Monthly or quarterly observations
Thematic area covered	Water and food security
Workflow schema and brief steps description	Step 1: assigning geospatial and temporal coordinates to input data, if not already included (e.g. in the case of media data) Step 2: join data with table containing relevant units of analysis (e.g. admin1 by month) Step 3: aggregate data by unit of analysis to create indicators (e.g. average area of illegal logging in admin1 in a month) Step 4: create composite indices, if necessary, by combining different indicators (e.g. average area of illegal logging combined with frequency of reported crimes and other indicators) For the general workflow schema and prototypical workflow for media-based indicators, see ID-11.

WFS-ID-15: Radicalisation and polarisation

Name of Indicator	Radicalisation and polarisation
Brief Description	Scale for level of radicalisation, polarisation, and animosity in the population that is conducive to periodic outbursts of violence (e.g. riots, clashes) and/or recruitment into armed groups. If necessary, possibility to distinguish sub-

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Name of Indicator	Radicalisation and polarisation
	classes for this indicator, e.g. anti-government sentiment, ethnic/communal tensions, ideological/religious radicalisation, etc.
Gap(s) addressed	Conflict prediction models usually rely on data on manifest violent events and are hence not able to capture earlier stages of conflict escalation like growing grievances and increasingly radical attitudes that generally precede and/or enable manifest violent behaviour. However, from an early warning and conflict prevention perspective, this would make sense. Survey data on radical attitudes exist but are incomplete and collected in wide time intervals (e.g. every three years), which makes monitoring difficult.
List of input data required with relative sources (where are available)	Data from CENTAUR partners: ➢ Media data: sentiment towards the government and other public figures; sentiment towards other social groups (ethnicity, religion, party affiliation, etc.); hate and dangerous/inflammatory speech by influential persons; support/sympathy for radical organisations ➢ Fine-scale gridded population Available data potentially useful for validating and calibrating the above: ➢ ACLED ➢ Afrobarometer
Output indicator type and format	Dataset, with possibility to export as csv and shapefile
Spatial and temporal resolutions obtainable	Spatial resolution: Aggregated estimate at admin1 or admin2 level Temporal resolution: Monthly or quarterly observations
Thematic area covered	Water and food security
Workflow schema and brief steps description	Step 1: assigning geospatial and temporal coordinates to input data, if not already included (e.g. in the case of media data) Step 2: join data with table containing relevant units of analysis (e.g. admin1 by month) Step 3: aggregate data by unit of analysis to create indicators (e.g. average sentiment towards the government in admin1 in a month) Step 4: create composite indices, if necessary, by combining different indicators (e.g. average sentiment towards the government combined with average sentiment towards members of other ethnic groups and other indicators) For the general workflow schema and prototypical workflow for media-based indicators, see ID-11.

WFS-ID-16: Disruptions in food supply chains

Name of Indicator	Disruptions in food supply chains
Brief Description	Disruptions in food supply occasioned by non-climatic/non-environmental factors, such as fuel price hikes and embargos. Relevant for modelling food security and economic security in rural and urban areas.
Gap(s) addressed	Complements more conventional indicators of food supply disruptions based on climatic/environmental factors (e.g. rainfall, temperature, drought intensity).

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Name of Indicator	Disruptions in food supply chains
List of input data required with relative sources (where are available)	Data from CENTAUR partners: ➢ Media data, including mentions of price hikes/difficult access to fuel, fertilisers, and other production inputs; restrictions on the mobility of seasonal workers; disruptions to logistic centres (e.g. harbours, airports, terminals); damages or malfunctioning of transportation infrastructure (e.g. roads, railways, bridges, waterways) and storage systems (e.g. silos, victualling warehouses); strikes; embargos; boycotts; etc.
Output indicator type and format	Dataset, with possibility to export as csv and shapefile
Spatial and temporal resolutions obtainable	Spatial resolution: Aggregated estimate at admin1 or admin2 level Temporal resolution: Monthly or quarterly observations
Thematic area covered	Water and food security
Workflow schema and brief steps description	Step 1: assigning geospatial and temporal coordinates to input data, if not already included (e.g. in the case of media data) Step 2: join data with table containing relevant units of analysis (e.g. admin1 by month) Step 3: aggregate data by unit of analysis to create indicators (e.g. frequency of reported supply chain disruptions in admin1 in a month) Step 4: create composite indices, if necessary, by combining different indicators (e.g. frequency of reported supply chain disruptions combined with frequency of reported price hikes and other indicators) For the general workflow schema and prototypical workflow for media-based indicators, see ID-11.

WFS-ID-17: Humanitarian aid

Name of Indicator	Humanitarian aid
Brief Description	Aid provided by national and international actors (e.g. government, international organisations, NGOs) to cushion the effect of extreme climatic conditions. Relevant for modelling food and economic security.
Gap(s) addressed	Enriching food and economic security models with data on aid.
List of input data required with relative sources (where are available)	Data from CENTAUR partners: ➢ EO & other data: tracking humanitarian aid (e.g. vehicles); humanitarian facilities in refugee camps ➢ Media data, including mentions of relief aid or absence thereof; ease of access and fair distribution of aid; sentiment towards performance of main aid organisations in the case study context Available data potentially useful for validating and calibrating the above: ➢ Cash Based Programming in Somalia (UNOCHA) ➢ DIEM - Monitoring (Data in Emergencies Monitoring) (FAO)
Output indicator type and format	Dataset, with possibility to export as csv and shapefile
Spatial and temporal resolutions obtainable	Spatial resolution: Aggregated estimate at admin1 or admin2 level Temporal resolution: Monthly or quarterly observations

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Name of Indicator	Humanitarian aid
Thematic area covered	Water and food security
Workflow schema and brief steps description	Step 1: assigning geospatial and temporal coordinates to input data, if not already included (e.g. in the case of media data) Step 2: join data with table containing relevant units of analysis (e.g. admin1 by month) Step 3: aggregate data by unit of analysis to create indicators (e.g. average number of humanitarian facilities in IDP camps in admin1 in a month) Step 4: create composite indices, if necessary, by combining different indicators (e.g. average number of humanitarian facilities in IDP camps combined with average perceived aid effectiveness and other indicators) For media-based indicators, see prototypical workflow in ID-1.

WFS-ID-18: Resource capture

Name of Indicator	Resource capture
Brief Description	Appropriation of natural resources essential for food production and/or sustaining agricultural and pastoralist livelihoods by powerful actors (e.g. land grabbing by large companies) or specific groups (e.g. communal groups).
Gap(s) addressed	Resource capture reduces access to essential resources for less powerful actors and groups and can aggravate competition over scarce resources. Yet, indicators for the distribution of resources or unequal access to resources are usually not available for quantitative analysis.
List of input data required with relative sources (where are available)	Data from CENTAUR partners: ➢ Media data, including mentions of "land grabbing" and the like; encroachment of fields onto pastoralist transhumance routes; unequal distribution of land; restricted access to wells and water points for pastoralists; etc.
Output indicator type and format	Dataset, with possibility to export as csv and shapefile
Spatial and temporal resolutions obtainable	Spatial resolution: Aggregated estimate at admin1 or admin2 level Temporal resolution: Monthly or quarterly observations
Thematic area covered	Water and food security
Workflow schema and brief steps description	Step 1: assigning geospatial and temporal coordinates to input data, if not already included (e.g. in the case of media data) Step 2: join data with table containing relevant units of analysis (e.g. admin1 by month) Step 3: aggregate data by unit of analysis to create indicators (e.g. number of mentions of "land grabbing" in admin1 in a month) Step 4: create composite indices, if necessary, by combining different indicators (e.g. number of mentions of "land grabbing" combined with average perceived inequality of land distribution score) For the general workflow schema and prototypical workflow for media-based indicators, see ID-11.

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WFS-ID-19: Climate sensitivity of agri-food systems

Name of Indicator	Climate sensitivity of agri-food systems
Brief Description	Degree to which rural livelihoods and food production are sensitive to erratic climatic conditions.
Gap(s) addressed	While not necessarily an 'innovative' indicator, this is nonetheless an important indicator to include in the required analysis as it is a key element of climate-conflict models.[304]
List of input data required with relative sources (where are available)	Data from CENTAUR partners: ➢ EO data: irrigation infrastructure; irrigated agriculture ➢ Media data, including mentions of dysfunctional boreholes; dry wells; lack of irrigation; diseases; pests; etc. Available data potentially useful for validating and calibrating the above: ➢ Crop productivity and evapotranspiration indicators (CCCS) from 2000 ➢ Global Food Security-Support Analysis Data (GFSAD) on irrigation (USGS) ➢ MODIS Global Evapotranspiration Project (MOD16) ➢ Soil water index/surface soil moisture (CGLS)
Output indicator type and format	Dataset, with possibility to export as csv and shapefile
Spatial and temporal resolutions obtainable	Spatial resolution: Aggregated estimate at admin1 or admin2 level Temporal resolution: Monthly or quarterly observations
Thematic area covered	Water and food security
Workflow schema and brief steps description	Step 1: assigning geospatial and temporal coordinates to input data, if not already included (e.g. in the case of media data) Step 2: join data with table containing relevant units of analysis (e.g. admin1 by month) Step 3: aggregate data by unit of analysis to create indicators (e.g. density of irrigation infrastructure (e.g. canals) in admin1) Step 4: create composite indices, if necessary, by combining different indicators (e.g. density of irrigation infrastructure combined with number of mentions of dysfunctional boreholes and other indicators) For the general workflow schema and prototypical workflow for media-based indicators, see ID-11.

WFS-ID-20: Obstacles to mobility

Name of Indicator	Obstacles to mobility
Brief Description	Obstacles to people's ability to move (both voluntarily and involuntarily).
Gap(s) addressed	Improving displacement models by including additional factors that affect mobility opportunities and hence observed displacement dynamics. Possibility to distinguish between obstacles for IDPs and refugees.

[304] See for e.g.: (1) Almer et al. (2017). Water scarcity and rioting: Disaggregated evidence from Sub-Saharan Africa. Journal of Environmental Economics and Management, 86, 193-209; (2) Uexkull (2014). Sustained drought, vulnerability and civil conflict in Sub-Saharan Africa. Political Geography, 43, 16-26.

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Name of Indicator	Obstacles to mobility
List of input data required with relative sources (where are available)	Data from CENTAUR partners: ➢ Media data, including mentions of border closures; tougher restrictions on mobility between and within states (e.g. military blocking access to certain areas); road and transport conditions; information about (state of) infrastructure; etc.
Output indicator type and format	Dataset, with possibility to export as csv and shapefile
Spatial and temporal resolutions obtainable	Spatial resolution: Aggregated estimate at admin1 or admin2 level Temporal resolution: Monthly or quarterly observations
Thematic area covered	Water and food security
Workflow schema and brief steps description	Step 1: assigning geospatial and temporal coordinates to input data, if not already included (e.g. in the case of media data) Step 2: join data with table containing relevant units of analysis (e.g. admin1 by month) Step 3: aggregate data by unit of analysis to create indicators (e.g. number of days border is closed in admin1 in a month) Step 4: create composite indices, if necessary, by combining different indicators For the general workflow schema and prototypical workflow for media-based indicators, see ID-11.

WFS-ID-21: Public services and infrastructure

Name of Indicator	Public services and infrastructure
Brief Description	Degree to which the government effectively and inclusively delivers services that are essential for withstanding extreme climatic conditions
Gap(s) addressed	Indicator commonly mentioned in the qualitative climate-conflict literature but rarely (if at all) included in predictive models with subnational precision.
List of input data required with relative sources (where are available)	Data from CENTAUR partners: ➢ EO data: location/density of public services, road infrastructure, etc. ➢ Media data, including mentions of poor services (e.g. health, infrastructure maintenance); difficulties in accessing essential services; corruption related to service provision; sentiment towards public authorities responsible for service provision Available data potentially useful for validating and calibrating the above: ➢ Humanitarian OpenStreetMap (HOT) (UNOCHA) ➢ OpenStreetMap ➢ Rural Livelihoods Information System (RuLIS) (FAO)
Output indicator type and format	Dataset, with possibility to export as csv and shapefile
Spatial and temporal resolutions obtainable	Spatial resolution: Aggregated estimate at admin1 or admin2 level Temporal resolution: Monthly or quarterly observations
Thematic area covered	Water and food security
Workflow schema and brief steps description	Step 1: assigning geospatial and temporal coordinates to input data, if not already included (e.g. in the case of media data)

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Name of Indicator	Public services and infrastructure
	Step 2: join data with table containing relevant units of analysis (e.g. admin1 by month) Step 3: aggregate data by unit of analysis to create indicators (e.g. number of hospitals/health service providers in admin1) Step 4: create composite indices, if necessary, by combining different indicators (e.g. number of hospitals/health service providers combined with perceived quality of public services score and other indicators) For the general workflow schema and prototypical workflow for media-based indicators, see ID-11.

WFS-ID-22: Strength of armed groups

Name of Indicator	Strength of armed groups
Brief Description	Degree to which armed groups are present and potentially aggressive in an area.
Gap(s) addressed	Essential condition for violent conflict, yet not considered in climate-conflict models with subnational precision.
List of input data required with relative sources (where are available)	Data from CENTAUR partners: ➢ EO data: number of camps, vehicles, troops, etc. in the area ➢ Media data, including mentions of presence of armed groups (camps, recruitment activity); looting/taxation of local population; proliferation of weapons; arms trafficking; absence/weakness of police/security forces (e.g. inadequate equipment, poorly paid); etc.
Output indicator type and format	Dataset, with possibility to export as csv and shapefile
Spatial and temporal resolutions obtainable	Spatial resolution: Aggregated estimate at admin1 or admin2 level Temporal resolution: Monthly or quarterly observations
Thematic area covered	Water and food security
Workflow schema and brief steps description	Step 1: assigning geospatial and temporal coordinates to input data, if not already included (e.g. in the case of media data) Step 2: join data with table containing relevant units of analysis (e.g. admin1 by month) Step 3: aggregate data by unit of analysis to create indicators (e.g. number of training camps in admin1 in a month) Step 4: create composite indices, if necessary, by combining different indicators (e.g. number of training camps combined with perceived weakness of security forces score and other indicators) For the general workflow schema and prototypical workflow for media-based indicators, see ID-11.

WFS-ID-23: State-citizen relations

Name of Indicator	State-citizen relations
Brief Description	Degree to which citizens trust public officials and feel included in political decision making. High levels of trust and inclusion are expected to motivate people to seek non-violent means of addressing concerns and grievances.

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Name of Indicator	State-citizen relations
Gap(s) addressed	Frequently mentioned in qualitative climate-security literature but rarely included in predictive models, with some exceptions.[305]
List of input data required with relative sources (where are available)	Data from CENTAUR partners: ➢ Media data, including mentions of distrust of government officials; incompetence; corruption; lack of concern for citizens; election-rigging; sentiment towards government officials Available data potentially useful for validating and calibrating the above: ➢ Afrobarometer ➢ Ethnic Power Relations (EPR) data (ETH Zürich)
Output indicator type and format	Dataset, with possibility to export as csv and shapefile
Spatial and temporal resolutions obtainable	Spatial resolution: Aggregated estimate at admin1 or admin2 level Temporal resolution: Monthly or quarterly observations
Thematic area covered	Water and food security
Workflow schema and brief steps description	Step 1: assigning geospatial and temporal coordinates to input data, if not already included (e.g. in the case of media data) Step 2: join data with table containing relevant units of analysis (e.g. admin1 by month) Step 3: aggregate data by unit of analysis to create indicators (e.g. average sentiment towards government officials score in admin1 in a month) Step 4: create composite indices, if necessary, by combining different indicators For the general workflow schema and prototypical workflow for media-based indicators, see ID-11.

WFS-ID-24: Dispute resolution mechanisms

Name of Indicator	Dispute resolution mechanisms
Brief Description	Presence of trusted formal and informal mechanisms (e.g. legal recourse, inter- and intra-community dialogue) to address disputes, for e.g. over access to and usage of resources.
Gap(s) addressed	Frequently mentioned in qualitative climate-security literature but rarely included in predictive models, with some exceptions.[306]
List of input data required with relative sources (where are available)	Data from CENTAUR partners: ➢ Media data, including mentions of dysfunctional courts; ineffective enforcement of laws; contradictory rules; sentiment (trust) in courts and legal system; informal dispute resolution bodies (e.g. village council, elders); etc. Available data potentially useful for validating and calibrating the above: ➢ Afrobarometer ➢ Ethnic Power Relations (EPR) data (ETH)

[305] See for e.g.: Detges (2017). Droughts, state-citizen relations and support for political violence in Sub-Saharan Africa: A micro-level analysis. Political Geography, 61, 88-98.

[306] See for e.g.: Linke et al. (2015). Rainfall variability and violence in rural Kenya: Investigating the effects of drought and the role of local institutions with survey data. Global Environmental Change, 34, 35-47.

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Name of Indicator	Dispute resolution mechanisms
Output indicator type and format	Dataset, with possibility to export as csv and shapefile
Spatial and temporal resolutions obtainable	Spatial resolution: Aggregated estimate at admin1 or admin2 level Temporal resolution: Monthly or quarterly observations
Thematic area covered	Water and food security
Workflow schema and brief steps description	Step 1: assigning geospatial and temporal coordinates to input data, if not already included (e.g. in the case of media data) Step 2: join data with table containing relevant units of analysis (e.g. admin1 by month) Step 3: aggregate data by unit of analysis to create indicators (e.g. average sentiment towards courts score in admin1 in a month) Step 4: create composite indices, if necessary, by combining different indicators For the general workflow schema and prototypical workflow for media-based indicators, see ID-11.

WFS-ID-25: Social cohesion

Name of Indicator	Social cohesion
Brief Description	Degree to which people feel connected and eager to stick together in the face of major challenges. (Perceived) social (in)equality might be a sub-component or a separate indicator.
Gap(s) addressed	Frequently mentioned in qualitative climate-security literature but to our knowledge not yet included in predictive models for conflict.
List of input data required with relative sources (where are available)	Data from CENTAUR partners: ➢ Media data, including mentions of social inequalities; (perceived) discriminations (in particular with regards to access to land, subsidies, food aid); sentiment (trust) in neighbours, members of other ethnic/religious communities, etc.; attitudes towards migrants and minority/marginalised groups Available data potentially useful for validating and calibrating the above: ➢ Afrobarometer
Output indicator type and format	Dataset, with possibility to export as csv and shapefile
Spatial and temporal resolutions obtainable	Spatial resolution: Aggregated estimate at admin1 or admin2 level Temporal resolution: Monthly or quarterly observations
Thematic area covered	Water and food security
Workflow schema and brief steps description	Step 1: assigning geospatial and temporal coordinates to input data, if not already included (e.g. in the case of media data) Step 2: join data with table containing relevant units of analysis (e.g. admin1 by month) Step 3: aggregate data by unit of analysis to create indicators (e.g. average trust in members of other ethnic groups in admin1 in a month) Step 4: create composite indices, if necessary, by combining different indicators For the general workflow schema and prototypical workflow for media-based indicators, see ID-11.

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8 CONCLUSIONS

The **definition of user needs and requirements** is a multifaceted task that needs a continuous dialogue and interaction with the project's end-users, including the advisory board and other relevant stakeholders. Throughout the project's duration, this continuous engagement will be essential. Fortunately, during the initial stages, the users have already provided valuable feedback, ensuring that the project progresses in the right direction. Their input has been instrumental in shaping the project's development and ensuring alignment with their expectations and priorities.

Given that most users were coming from organizations whose main activities are related to Early Warning and Forecasting, and Emergency relief-response, and that users have high awareness about the security implications of climate change, the main expectations towards CENTAUR project are related to:

- **Early-warning system:** alerting every time a new event occurs.
- **Situational awareness at strategic and operational level**, to anticipate crisis to warn personnel deployed/EU citizens in the affected countries.

In the emergency domain, CENTAUR will address the flood-related threats to population, assets and infrastructures in urban areas. In the Security domain, CENTAUR will address water & food insecurity. The two work streams will be connected via a cross-cutting component focusing on exposure and vulnerability to climate change, as well as resilience and societal capacity for managing environmental risks and social conflict.

On one side, to address the needs for the improved **urban flood detection and monitoring**, the following points should be addressed, considering the state of the art and current user needs:

- Elaborate automated urban flood mapping using all-weather InSAR imagery;
- Set-up hydro-geomorphological urban flood modelling using EO inputs and ancillary data (VHR DTMs, social media, gauges, precipitation...);
- Access VHR DTMs for hydraulic modelling,
- Including VHR DTMs derived from InSAR compatible coverages and/or optical 3D compatible coverages (CO3D, Pléiades...),
- Hydrologically compatible VHR DTMs;
- Adapt modelling tools to handle VHR DTMs over larger areas;
- Receive high spatial and temporal resolution flood forecasts and potential flood modelling.

To meet these **urban flood mapping needs**, an initial set of **fourteen (14) innovative indicators** have been elaborated.

- UF-ID-1: Historical 6 hourly return period static precipitation maps (pre-event phase);
- UF-ID-2: ML Data Driven Forecast of return period based precipitation events in urban area (early warning-phase);
- UF-ID-3: Urban inundation probability maps and water depth for scenarios defined by return period at a spatial resolution in the order of <10 m;
- UF-ID-4: Inferred INSAR urban flood extent;
- UF-ID-5: Urban flooding map based on geomorphological and InSAR approach for an enhanced damage assessment;
- UF-ID-6: Social/Traditional media indicators for Urban Flooding Maps;

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- UF-ID-7: Hazard web sources indicator.
- UF-ID-8: Robustness and quality of the built environment
- UF-ID-9: Assets and financial resources
- UF-ID-10: Public services and government support
- UF-ID-11: Social networks and community support
- UF-ID-12: Timely access to information
- UF-ID-13: Ability to flee
- UF-ID-14: Economic impact of floods

On the other side, for the assessment of **water and food insecurity impacts**, according to the state of the art and in terms of current user needs, the following points need to be addressed to enhance the CSS-SEA on-demand component as well as to develop the CSS-SEA proactive component:

- Automatic access, processing, fusion and integration of social, economic & political indicators together with environmental degradation related indicators at regional level (e.g. admin 1, admin 2).
- Automatic access, processing, fusion and integration of social, economic & political indicators together with environmental degradation related indicators at local level.
- Development of a service to proactively monitor security challenges, such as conflict and fragility, associated with water and food insecurity at regional level (e.g. admin 1, admin 2), including the three different capabilities: improved understanding of climate security implications, risk assessment and early warning system, and foresight capabilities (e.g. "what if").
- Development of a service to proactively monitor security challenges, such as migration flows and displacement, associated with water and food insecurity at regional level (e.g. admin 1, admin 2), including the three above-mentioned capabilities.
- Development of a social media automated crawling capability for decision support in security challenges associated water and food insecurity.

To meet these **water and food insecurity needs**, an initial set of **twenty-five (25) innovative indicators** have been elaborated.

- WFS-ID-1: Meteorological drought indicator (Monitoring)
- WFS-ID-2: Meteorological drought indicator (Forecast)
- WFS-ID-3: Meteorological drought indicator (calibrated in danger levels)
- WFS-ID-4: Agricultural drought monitoring (near real-time)
- WFS-ID-5: Agricultural drought forecast
- WFS-ID-6: Risk zone map
- WFS-ID-7: People movement indicator
- WFS-ID-8: Indicators of exposure to resource shortages: food (in)security
- WFS-ID-9: Indicators of exposure to resource shortages: water (in)security
- WFS-ID-10: Number of people living in conflict-affected areas
- WFS-ID-11: Food security
- WFS-ID-12: Economic security
- WFS-ID-13: Displaced persons
- WFS-ID-14: Crime and illicit activities
- WFS-ID-15: Radicalisation and polarisation

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- WFS-ID-16: Disruptions in food supply chains
- WFS-ID-17: Humanitarian aid
- WFS-ID-18: Resource capture
- WFS-ID-19: Climate sensitivity of agri-food systems
- WFS-ID-20: Obstacles to mobility
- WFS-ID-21: Public services and infrastructures
- WFS-ID-22: Strength of armed groups
- WFS-ID-23: State-citizen relations
- WFS-ID-24: Dispute resolution mechanisms
- WFS-ID-25: Social cohesion and trust

This document will serve as a reference document to undertake *Task 1.3 - Cross-cutting analysis, Use Cases and Crisis Indexes definition* according to CEMS and CSEA needs. In addition, the document serves as the foundation for *WP2 – Thematic product engineering* that will put in place workflows for collecting necessary data for the development of risk indicators and crisis indexes, as well as for their implementation.

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ANNEX I: CENTAUR USER REQUIREMENTS QUESTIONNAIRE

CENTAUR User Requirements Questionnaire

Fields marked with * are mandatory.

1 Personal information

I hereby declare my informed consent to the treatment of my personal data with the modalities indicated in the privacy statement for the following purposes:

* (1) Collect information related to the CENTAUR project user consultation process and communicate important information related to the user consultation process.
- Yes
- No

* (2) Dispatch of communications on important information regarding the consultation processes, invitations to CENTAUR events/meetings and other notifications.
- Yes
- No

* (3) Processing of data for statistical and management purposes.
- Yes
- No

CENTAUR Privacy Statement
CENTAUR_Privacy_Statement_v3.pdf

Complex Table

Name of your organization	*
Group/ Area/ Division	*
Point of Contact (optional)	
Complete name	
Position within your organization	

1

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Contact details (email and/or phone)

2 Background information

* Please select the field of activitity(ies) your department/unit is involved or interested in.

  at least 1 choice(s)
  - [ ] Rule of law
  - [ ] Humanitarian actions
  - [ ] Foreign affairs
  - [ ] Migration management
  - [ ] Climate change
  - [ ] Environmental protection
  - [ ] Conflict prevention/ Peacekeeping
  - [ ] Early warning and forecasting
  - [ ] Emergency relief-response

* Please select the option(s) that better summarizes the nature of the activity(ies) your department/unit undertakes.

  at least 1 choice(s)
  - [ ] Strategy and policy development
  - [ ] Risk assessment
  - [ ] Preparedness and planning
  - [ ] Decision making
  - [ ] Field operations
  - [ ] Programme and project management

* What is the level of awareness of your organization about the security implications of climate change?
  - ○ High awareness: Our organization has a good understanding of the security implications of climate change, and we have implemented some measures to address these risks.
  - ○ Moderate awareness: Our organization has a basic understanding of the security implications of climate change, but I need to know more to integrate it into my work.
  - ○ Low awareness: Our organization has limited knowledge about the security implications of climate change, and we have not taken any action to address these risks.
  - ○ No awareness: Our organization has no knowledge about the security implications of climate change.

In case your organization is already undertaking or participating in any type of study or activity related with water and food insecurity, could you please specify it?

* What are your expectations towards the CENTAUR project?

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Does your organization work with any people involved in field activities? If yes, please tell us more about your collaboration activities.

* As you know this is an evolution project for both the Copernicus Emergency and the Copernicus SEA services. Please select the category(ies) that better describes your involvement.

between 1 and 2 choices

- [ ] Copernicus Emergency Authorized User
- [ ] Copernicus Emergency Potential Future User
- [ ] Copernicus SEA Authorized User
- [ ] Copernicus SEA Potential Future User

3 Current data and operational tools available

* Based on you experience and needs, is there enough up-to-date data/information available to assess the effect of climate change on different dimensions of human security (e.g. food and water security, displacement, political instability, violent conflict etc.)?

* Based on your experience and needs, are the flood models accurate enough?

* Are you using any portals or information systems to access conflict risk or food/water security indexes?

- Yes
- No

Please specify

What are you missing? Please describe any limitations or obstacles in accessing, processing or analyzing climate security data you may have faced during your daily work.

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What is your previous experience with CEMS? Please explain how are the CEMS products included in your workflow.

What are the limitations that you have encountered while using the CEMS products?

Do you use another portal for risk assessment using those deriving from CEMS as products?

How familiar are you with the use of geospatial data?
- Extensive technical knowledge
- Good general knowledge
- Little knowledge
- No knowledge

How familiar are you with the use of (social) media data?
- Extensive technical knowledge
- Good general knowledge
- Little knowledge
- No knowledge

4 CENTAUR Value Proposition - Food and water insecurity

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Are the following anticipative and operational tools to assess climate change effects on security issues relevant to your organization? Please score from 1 to 5 it according to your priorities.

A) A catalog of datasets on water and food insecurity and its relation with political instability and conflict.	
B) A situational awareness portal providing continuous monitoring of climate security risk indicators and indexes	
C) An early-warning system, alerting when pre-defined triggers and drivers for crises are met	
D) Simulation and predictive analysis allowing to launch "what if" analysis	

Considering the tool A) (catalog of datasets), in which datasets are you interested in? (score from 1 to 5)

Crop production monitoring	
Food prices	
Water availability (e.g. surface and groundwater)	
Other biophysical parameters (e.g. soil moisture, vegetation health)	
Climate and meteorological data	
Political instability and violent events (e.g. ACLED data, social media)	
Changes in land use	
Population distribution and evolution	
Migration (e.g. border restrictions, flows)	
Other socio-economic variables (e.g. hunger/malnutrition, incomes)	

Considering B) (situational awareness portal) and C) (early-warning system) tools, what would be your preference in terms of:

Scale analysis

- Local
- Regional
- National
- Supranational

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Information format	☐ Notifications alerting of changes ☐ Disaggregated datasets visualization ☐ Indexes and indicators visualization ☐ Statistical analysis over data (e.g. graphs) ☐ In-depth analysis and reports prepared by analysts
Delivery	☐ Alert notification by email ☐ Online information access (e.g. geoportal) ☐ Data download ☐ IT interface (e.g. API, webservice) for ingestion in end-user system
Reasonable delivery time	○ 1 day ○ 3 days ○ 1 week

When using predictive analysis tool (tool D), which time horizon do you prefer for forecasting? Please select the option that best fits your preference

- ○ Monthly
- ○ Quarterly
- ○ Semestrial
- ○ 1 year
- ○ 3 years

5 CENTAUR Value Proposition - Urban flooding

What are your needs in terms of forecasting and operational tools to evaluate the effects of climate change, due to the increase in the number of extreme events, on the population? Please rank it according to your priorities.

A) Early-warning sytem, alerting when pre-defined triggers and drivers for crises are met	☆☆☆☆☆
B) Early warning system based on more precise meteorological data	☆☆☆☆☆
C) CEMS pre-tasking success (75%), in terms of number of pre-tasking alert, timeliness and improvement in the definition of the AOI for crisis-time satellite acquisitions	☆☆☆☆☆
D) Increase of the accuracy of urban flood mapping (>75%) using SAR and InSAR processing combined with urban flood modelling	☆☆☆☆☆

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E) Reduction of the temporal or spatial resolution of the current datasets, products or services delivered by a Copernicus operational service by 50%.	
F) Improvement of other more traditional map quality indicators owing to a more integrated and accurate input information and to more effective AI/ML modelling (thematic accuracy, speed of delivery, resolution, etc.).	

Considering A), B), C), D), E) and F) product output, what would be your preference in terms of:

Scale analysis *
- Local
- Regional
- National
- Supranational

Information format *
- Notifications alerting of changes
- Disaggregated datasets visualization
- Indexes and indicators visualization
- Statistical analysis over data (e.g. graphs)
- In-depth analysis and reports prepared by analysts

Delivery *
- Alert notification by email
- Online information access (e.g. geoportal)
- Data download
- IT interface (e.g. API, webservice) for ingestion in end-user system

Reasonable delivery time *
- 1 day
- 3 days
- 1 week

* For predictive analysis (tool D)), what is you preferred time-horizon?
- Monthly
- Quarterly
- Semestrial
- 1 year
- 3 years

6 Use Cases - Food and water insecurity

Mali: Lies between the most arid and the rainy equatorial regions, water is seasonally scarce and precipitations increasingly unpredictable, often marked by low and high extremes. Climate change effects are intensifying conflict between communities, increasing poverty and weakening traditional means of survival. The recent increase of farmer-herder conflicts in the western Sahel is exacerbated by violent

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extremists and other armed groups operating in the area. This model may also be applied to other regions of the Sahel.

Somalia: Below average rainfall during the rainy season led to worsening droughts in different parts of the country. This situation forced tens of thousands of people to leave their homes, in search of water, food and work, mostly to urban areas. These climate impacts are usually used by armed groups (i.e. Al Shabaab) to position themselves as aid providers after severe impacts of droughts and floods. Outputs of this demonstrator could also be exported and applied to other countries in the Horn of Africa.

Mozambique: Composed mostly of coastal lowlands, Mozambique is highly exposed and vulnerable to temperature increases, cyclones and tropical storms. Over 80% of the population depend on agriculture for their livelihoods. Much food storage, fisheries infrastructure and livestock assets are washed away and thousands of hectares of crops are destroyed due to flooding. In addition, since 2017, an Islamic group has staged a destabilizing insurgency in the predominantly Muslim Northern Province of Cabo Delgado.

Could you please score them according to your interests?

Mali	☆☆☆☆☆
Somalia	☆☆☆☆☆
Mozambique	☆☆☆☆☆

Considering these 3 pre-defined Use Cases,

Is there any climatic, geographic or social aspect you are particularly interested in? *

Any region with highest interest?

Do you have any input data that could be used as input to the system (such as census data, population distribution, violent events, etc)? If yes, please specify of what type

- ☐ Meteorological data
- ☐ Hydrological data
- ☐ In-situ data
- ☐ Reference geospatial data for land-use
- ☐ Reference geopatial data for elevation
- ☐ Demographic-census data
- ☐ Conflict/violent events data

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Do you have any data that could be used for validation purposes? If yes, please specify of what type	☐ Meteorological data ☐ Hydrological data ☐ In-situ data ☐ Reference geospatial data for land-use ☐ Reference geopatial data for elevation ☐ Demographic-census data ☐ Conflict/violent events data
Would it be possible to share it with the CENTAUR project or do you have any sensitivity concern?	
Is there any organization or local agent working in the field you would like to involve?	

Is there any other geographical location you may be interested in? (to be considerd out of the scope of this project)

7 Use Cases - Urban flooding

EBRO BASIN: Given its morphology and location, floods are common in the Ebro basin. Among the most relevant past episodes are the floods of extraordinary intensity that occurred in 2015, 2018 and 2021. Due to a combination of heavy rains and fast melting snow, severe effects on agriculture, population and infrastructures were observed. CEMS RM monitored these events in EMSR118, EMSR120, EMSR279, and EMSR555 activations. In the Navarra Region of the Ebro basin an extensive repository of information exists including cadaster, land cover, soils, infrastructure, edaphology and hydrography, amongst others 18. Complete meteorological data acquired by the Government of Navarra and the National Meteorological Agency (Agencia Estatal de Meteorología, AEMET) and up-to-date hydrological data provided by the Ebro Hydrographic Confederation (CHE) are also available. In addition, the LiDAR coverages of Navarre 2017 and the urban area of Pamplona 2021 are especially noteworthy, acquired at a minimum density of 14 point /m2 and 50 point/m2, respectively. These combined cold case datasets enable model training, preparing for a highly likely upand-coming hot spot during the project where the system can be validated.

PIEDMONT: Piemonte Region has a rich history of frequent and important flood events occurred in the past due to intense precipitations that led to the fluvial flood of the Po river, one of the main watercourses of the Region (last event 2016, covered by CEMS RM activation EMSR192). For the city of Turin, located along this important fluvial channel, a high resolution aerial data acquisition with photogrammetric cameras has recently been performed. This not ordinary dataset will be used to produce a high definition 3D model of the

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urban area in order to test its integration within flood modelling. Beside Turin, another minor urban area located along a different river, but still characterized by high flood risk, e.g. the Tanaro river, will also be chosen for ad hoc acquisitions.

GERMAN: On the 13 July 2021 catastrophic rains led to devastating flood events destroying many areas, like the Ahr Valley, mostly in tributaries to the Rhine in the Saar, Rhineland Palatinate, North Rhine-Westphalia States. The German Joint Information and Situation Centre (GMLZ) triggered the CEMS Rapid Mapping (RM) Service to monitor the floods evolution20. At the time the Authorised User made aerial imagery available to CEMS RM to supplement the satellite data coverage. Now, this highly engaged user, in a joint effort with the Service Provider, is highly motivated to explore innovation in CEMS RM products and is willingly to make aerial imagery, pre and post LIDAR, differential LIDAR DEMs, river gauge measurements to help in the realization of detailed forecast and modelling enhanced products. These are to be combined with traditional and social media enrichment to provide enhanced products especially in and around urban areas.

MOZAMBIQUE: In these last years Mozambique has been hit several times by Tropical Cyclones. In 2019, Idai TC brought huge precipitations over the Beira hinterland badly affecting the lower oceanside parts of the city, including slums. Due to the urban context, the usual storm time SAR data such as Sentinel-1, COSMO-SkyMed and Radarsat-2 did not lead to good flood extent extraction within built-up areas (cf. Copernicus EMSR34821). Only VHR optical data acquired more than 10 days after the event provided the first insight on the remaining traces and impacts. CENTAUR proposes to replay this CEMS activation by integrating ICEYE VHR InSAR data combined with a 3D modelling of the city to better estimate the flood extent and associated potential impacts within the city. Considering the frequency of such events in this area, this cold case scenario could most likely become a hot case scenario within the projects' lifespan, supported by the recent integration of ICEYE data within Copernicus Space Component Data Access.

Could you please score them according to your insterests?

Ebro Basin, Spain	☆☆☆☆☆
Piemonte, Italy	☆☆☆☆☆
German floods	☆☆☆☆☆
Mozambique	☆☆☆☆☆

Considering these 4 pre-defined Use Cases,

Is there any climatic, geographic or social aspect you are particularly interested in? *

Any region with highest interest?

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Do you have any input data that could be used as input to the system (such as DTM, hydrological and hydraulic data deriving from gauge station, etc.)?	
Do you have any data that could be used for validation purposes? If yes, please specify of what type	☐ Meteorological data ☐ Hydrological data ☐ In-situ data ☐ Reference geospatial data for land-use ☐ Reference geopatial data for elevation ☐ Demographic-census data ☐ Conflict/violent events data
Would it be possible to share it with the CENTAUR project or do you have any sensitivity concern?	
Is there any organization or local agent working in the field you would like to involve?	

Any other geographical location you may be interested in? (to be considered out of the scope of this project)

8 Information delivery and way ahead

* How you would like this service to be delivered to you?

- ☐ Email - notification
- ☐ Data catalogue
- ☐ Online geoportal
- ☐ Web service - API
- ☐ Other format to be integrated within any of your systems (please specify):

Please specify:

* Do you have any information legacy systems in place in which you would like the information produced by CENTAUR to be ingested?

- ○ Yes
- ○ No

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If Yes, is there any data format requirement/preference that should be considered to ensure interoperability:

* Would you be interested in scaling up the CENTAUR general capabilities to other regions?
  - Yes (please describe)
  - No

Please describe:

* Identify the three most important water-related challenges in your region/country in which EO\CENTAUR could contribute to the solution

at least 3 choice(s)

- [ ] Mapping water bodies and floods
- [ ] Quantifying soil moisture
- [ ] Quantifying evaporation
- [ ] Defining groundwater level
- [ ] Volume of big basins
- [ ] Mapping rainfall distribution
- [ ] Hydrological forecast (droughts, floods, etc.)

Any additional comments you may have:

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