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Feasibility assessment of an automated, global, satellite-based flood monitoring product for the Copernicus Emergency Management Service

Matgen, P.; Martinis, S.; Wagner, W.; Freeman, V.; Zeil, P.; McCormick, N.

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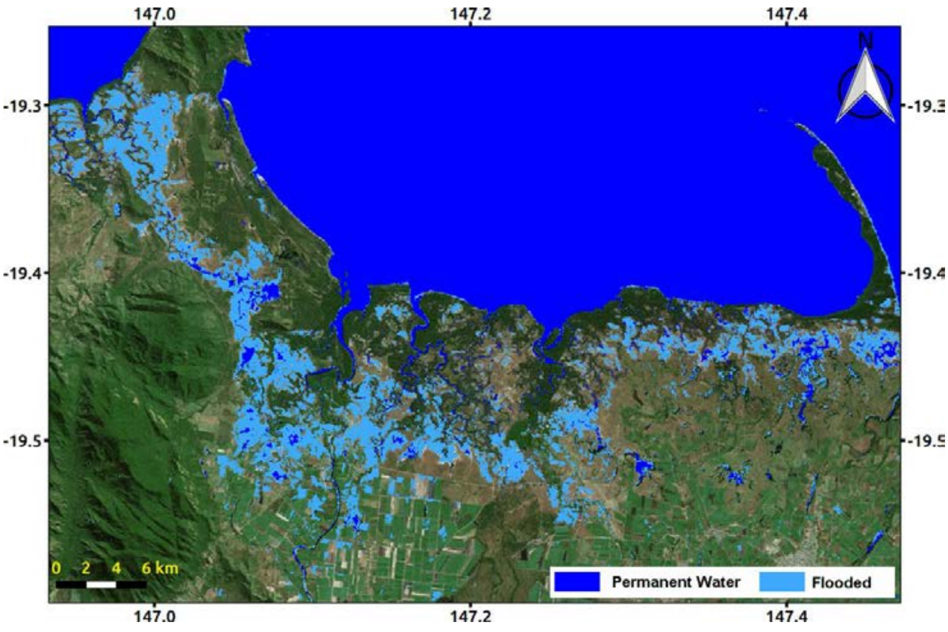

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Executive summary

Floods are the most frequent and costliest natural disasters worldwide. State-of-the-art, scientific methods for automatically detecting and identifying flood events, based on a global, continuous supply of all-weather, day-and-night satellite images, such as those provided by Europe's Copernicus Sentinel-1 satellites, are now mature and ready for operational implementation. This report presents the results of an Expert Group that was set up by the European Commission's Joint Research Centre (JRC), to assess the feasibility of an automated, global, satellite-based flood monitoring product, in order to complement and enhance the capabilities of the Copernicus Emergency Management Service (CEMS) for mapping and monitoring floods.

An analysis of potential end users shows that there is a wide range of actors - public and private - that would benefit from such a global flood monitoring product. These include the "classical" users of CEMS, such as civil protection authorities, hydrological and meteorological services, as well as other user groups, especially from the private sector (e.g. insurance, critical infrastructure, transport), and inter-governmental and non-governmental organisations, who currently only partially benefit from CEMS, due to its restricted user scheme. As the proposed product provides a unique record of flood events, it would also support EU Member States, for example, in relation to the reporting requirements of the Floods Directive and Sendai Framework for Disaster Risk Reduction. Due to its free provision of information on flooding around the world, the proposed flood monitoring product also represents added-value in the context of the actions of the EU (institutions and Member States) in international humanitarian aid and disaster risk reduction.

A global flood monitoring product, such as the one proposed in this report, would specifically complement the existing components of CEMS that provide flood early warnings (i.e. EFAS and GloFAS) and on-demand Rapid Mapping, by:

a) Enabling a continuous global, systematic monitoring of flood events.

b) Enhancing the timeliness of flood maps for emergency response, since no user activation request is required and the process is fully automated.

c) Improving the effectiveness of Rapid Mapping activation requests through a better identification of the area of interest, where additional information from contributing missions and / or a higher spatial resolution is required.

Experience from CEMS Rapid Mapping, in particular, has shown that activation requests often come after flood events have started, or after the peaks of flood events have occurred. To address this issue, CEMS flood early warnings (from EFAS and GloFAS) are currently used for "pre-tasking" satellite image data for Rapid Mapping, thus improving the timeliness of flood maps - though only for large flood events. Therefore, the proposed global flood monitoring product can fill this gap by providing systematic mapping throughout the flood cycle, for almost any flood around the world.

Currently, no existing operational product offers similar technical advantages as those provided by the proposed CEMS global flood monitoring product (see Table below) - particularly in terms of global coverage, spatial resolution, revisit frequency, level of flood information provided, or timeliness. Considering the unprecedented opportunities offered by the Copernicus Sentinel-1 mission, as well as other related recent scientific and technological developments, such as the Copernicus Data and Information Access Services (DIAS), it is clear that the capacities are now in place in Europe to develop and implement the unique product that is described in this report. This would represent a major advancement in monitoring flood disasters, and further consolidate Europe's position at the forefront of Earth observation applications for disaster risk management.

Quick reference guide summarising the basic technical characteristics of the proposed automated, global, satellite-based flood monitoring product for CEMS.

INPUT SATELLITE IMAGE DATA:	
Satellite sensor:	Sentinel-1 Synthetic Aperture Radar (SAR)[1].
Acquisition mode:	Interferometric Wide Swath (IW). (See Section 4.1).
Data product:	Level-1 - Ground Range Detected (GRD). (See Section 4.1).
Spatial resolution:	20 x 22 metres (full resolution).
Image swath width:	250 km.
Global revisit frequency:	Europe: ~1-3 days. Rest of the world: ~3-14 days, depending on location. (See Section 4.2).
SAR polarisation scheme:	VV + VH. (See Section 4.1).
OUTPUT LAYERS:	
1. Observed flood event:	Flooded areas, mapped as the difference between the observed water extent and the reference water mask (see below).
2. Observed water extent:	Open and calm water mapped using Sentinel-1 SAR backscatter intensity.
3. Reference water mask:	Normal (i.e. permanent, seasonal) water mapped using Sentinel-1 SAR backscatter intensity.
4. Exclusion mask:	Unclassified areas (e.g. urban areas; dense vegetation; flat and impervious areas; sandy surfaces; topographic effects).
5. Uncertainty values:	Estimated uncertainty of flood mapping, for all areas outside exclusion mask.
6. Advisory flags:	Flags indicating potential reduced quality of flood mapping, due to prevailing environmental conditions (e.g. wind, ice, snow, dry soil).
7. Sentinel-1 metadata:	Information on the acquisition parameters of the Sentinel-1 data used.
8. Sentinel-1 footprint:	Image boundaries of the Sentinel-1 data used.
9. Sentinel-1 schedule:	Next scheduled Sentinel-1 data acquisition.
PRODUCT TIMELINESS:	
Delivery time:	8-12 hours (after Sentinel-1 image acquisition). (See Sections 3.1.3 and 4.3).

[1] https://sentinel.esa.int/web/sentinel/user-guides/sentinel-1-sar

1 Introduction

Floods are the most frequent and costliest natural disasters worldwide. According to figures from the United Nations Office for Disaster Risk Reduction (UNISDR), in terms of occurrence floods accounted for 43% of all 7,255 disaster events recorded worldwide between 1998 and 2017 (Figure 1). Most studies of climate change agree that the frequency of floods will increase further. In its Special Report published in October 2018, the Intergovernmental Panel on Climate Change (IPCC) pointed out that our world has already warmed by one degree above pre-industrial levels, and warned of the likely disastrous global and regional impacts of global warming beyond 1.5°C. Without rapid, far-reaching and unprecedented changes in all aspects of society, the world's top climate scientists warned, our world will exceed 1.5°C much sooner than we think, and significantly impact the likelihood of floods, heatwaves and droughts.

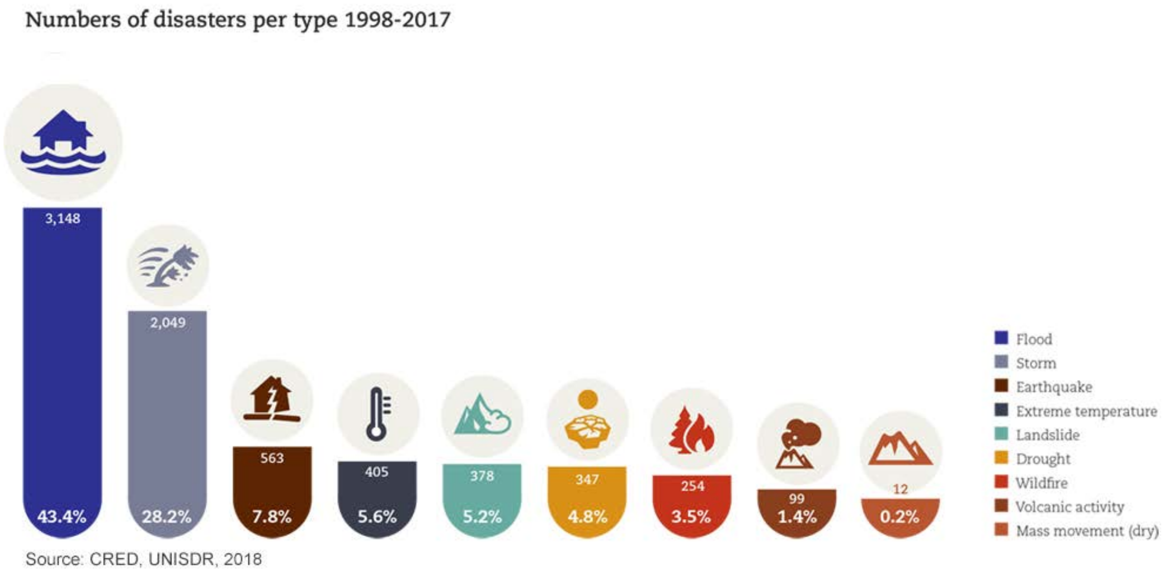

Figure 1: Infographic from the United Nations Office for Disaster Risk Reduction (UNISDR). See: www.preventionweb.net/knowledgebase/disaster-statistics

Economists are still trying to calculate the long-term effects of climate change in general, and floods in particular, on global trade networks, national gross domestic product (GDP), household income and inequality. Emerging research suggests that the human and financial costs of flooding are already much higher, and much longer-lasting, than ever suspected. One recent major study found that, without large-scale structural adaptations, the total economic losses from river flooding alone will increase by 17% globally, thanks to climate change, over the next twenty years (Willner et al., 2018).

Aside from the immediate damage, each flood has a series of long-lasting and far-reaching effects - what risk analysts refer to as "cascading costs" - that ripple outward through geographies, economies and lives. Some of the costs are tangible, and may be recovered in time, but the less tangible costs are often irretrievable. According to analysis by Munich RE, the global reinsurance company, based on its NatCatSERVICE global database on natural disasters, the frequency of "relevant loss events" (events causing loss of life or a certain threshold of property damage, adjusted to the country's income level) has increased by a factor of 3-4 since 1980, with 2017 being the second most expensive year on record (Figure 2). Increased urbanization, climate change and outdated infrastructure, have combined to make floods more severe and damaging. Much of man-made critical infrastructure was designed for a world before climate change. But even the systems built during the past half-century did not anticipate, for example, by how much or how quickly, global sea-levels would rise (Ciezadlo and Nallu, 2018).

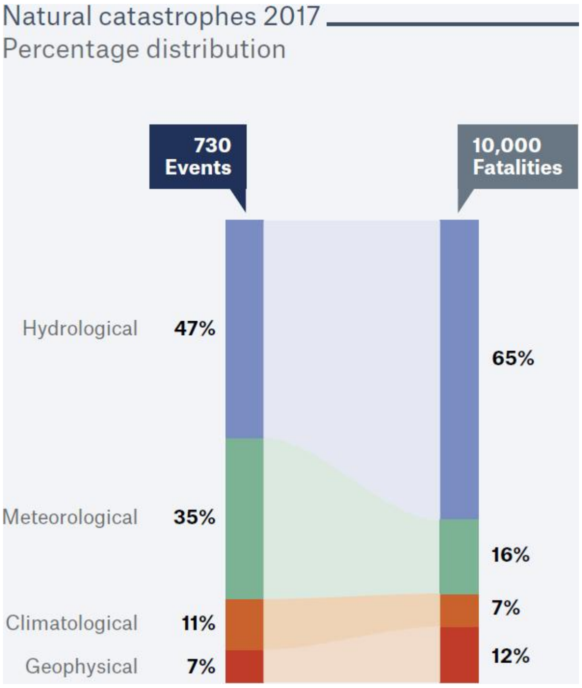

Figure 2: Infographic from Munich RE's on-line publication, Topics Geo 2017. See: *www.munichre.com/touch/naturalhazards/en/publications/topics-geo/2017/*

The Copernicus Emergency Management Service (CEMS)[2] currently addresses flood disasters through both of its two main components:

- Early warning and monitoring: This CEMS component includes the activities related to floods (the European and Global Flood Awareness Systems), wildfires (the European Forest Fire and Global Wildfire Information Systems), and droughts (the European and Global Drought Observatories).
- On-demand mapping: This CEMS component includes the activities of Rapid Mapping, Risk and Recovery Mapping, and Validation.

The CEMS European and Global Flood Awareness Systems (EFAS and GloFAS) provide complementary flood forecast information to relevant stakeholders, supporting flood risk management at national, regional and global level. The forecasts are derived using in-situ and satellite data and hydro-meteorological models, and are designed to support users through a wide range of added-value flood forecast products (e.g. medium-range lead-time, probabilistic, river basin-wide, flash flood indicators).

CEMS Rapid Mapping is an always available (24-hours-a-day, 365 days-a-year), on-demand service that provides geospatial information to support emergency activities, immediately after an event. The service can be triggered, on request, by Authorised Users in EU Member States and in most countries participating in the European Civil Protection Mechanism. CEMS Rapid Mapping provides two types of post-event maps derived from (mainly) satellite images, known as "delineation" and "grading" maps. Delineation maps outline both the extent of the area affected by an event and its evolution. Grading maps provide an assessment of the impact caused by the disaster, in terms of damage grade and its spatial extent, and can provide relevant and up-to-date information on affected population and assets, e.g. settlements, transport networks, industry and utilities. Since CEMS started in 2012, floods have been one of the most frequently mapped events: about 30% of all 344 Rapid Mapping activations were for flood events, and 70% of the products requested in these flood activations were flood masks (i.e. flood delineations).

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[2] https://emergency.copernicus.eu/

In the CEMS Risk and Recovery Mapping service, satellite-based maps of flood extent are commonly used to identify maximum flood extent, which is then used for further analyses, such as impact assessments (e.g. maximum water depth and duration, economic impact assessment), and to assess the potential risk of future events (mitigation measures). Since 2012, almost 18% of all CEMS Risk and Recovery Mapping activations were for floods.

As mentioned above, the CEMS on-demand mapping services (Rapid Mapping and Risk and Recovery Mapping) provide post-event flood maps based on Earth observation (EO) satellite imagery. Data from optical or microwave satellite-borne sensors are routinely used to detect and classify features on the Earth's surface, based on measurements of reflected (or emitted) electromagnetic radiation. As their names imply, optical and microwave satellite sensors make use of radiation from, respectively, the optical (i.e. visible and infrared) and microwave portions of the electromagnetic spectrum[3]. Because optical sensors rely on solar reflectance from the Earth's surface, they are only useful for cloud-free conditions, which is a major disadvantage in the context of mapping and monitoring flood events. On the other hand, microwave sensors - such as the state-of-the-art Synthetic Aperture Radar (SAR) instrument on board the two Copernicus Sentinel-1 satellites[4] - provide a global, continuous supply of all-weather, day-and-night image data of the Earth's surface, which are well suited for flood mapping and monitoring applications. Numerous scientific studies (e.g. Clement et al., 2018; Giustarini et al., 2017; Li et al., 2018; Schlaffer et al., 2017; Schlaffer et al., 2015; Martinis et al., 2018; Martinis and Rieke, 2015; Tsyganskaya et al., 2018; Twele et al., 2016; Westerhoff et al., 2013) have demonstrated that the fully automated flood mapping algorithms appropriate for, in particular, C-band SAR microwave imagery such as that provided by Sentinel-1, are now mature and ready for operational implementation.

Against the background outlined above, it is clear that a constant, automated, global flood monitoring product, based on microwave (SAR) satellite data, would potentially complement and enhance the CEMS portfolio - in particular the components for "Rapid Mapping" and "Flood early warning and monitoring" - by improving the timeliness of flood maps for emergency response, and providing a complete global coverage. Moreover, because the Sentinel-1 mission of the Copernicus programme systematically acquires SAR image data with an unprecedented spatio-temporal coverage, this would obviate the time-consuming step of tasking satellite data for flood mapping.

This report presents the results of the work carried out by an Expert Group, which was set up by the European Commission's Joint Research Centre (JRC), and composed of scientific experts and representatives from industry and the research community, complemented by experts from the Commission's JRC and DG GROW, with the aim of assessing the feasibility of an operational, global, automated, satellite-based flood monitoring product, within the CEMS framework. The specific objectives of the report are the following:

a) To evaluate the user requirements in relation to improving the preparedness, management and response to floods, taking into account already existing tools.
b) To analyse and evaluate the feasibility, and the scientific and technical issues that should be resolved, with regard to implementing an operational, global, automated, flood-monitoring product, based on Synthetic Aperture Radar (SAR) satellite data from the Copernicus Sentinel-1 mission.
c) To propose a feasible methodology for an automated, global, flood monitoring product, based on Sentinel-1 SAR satellite data, which would be suitable for inclusion as part of CEMS.

[3] http://sci.esa.int/education/50368-the-electromagnetic-spectrum/
[4] https://sentinel.esa.int/web/sentinel/missions/sentinel-1

2 User requirements

This chapter provides an overview of the different types of potential end users of the proposed automated, global satellite-based flood monitoring product, as part of the Copernicus Emergency Management Service (CEMS), and discusses the specific needs of the end users for relevant flood mapping and monitoring information. In order to illustrate how the proposed CEMS global flood monitoring product might be used in practice, some potential use cases are also presented.

The potential end users of the proposed CEMS global flood monitoring product, and their information needs, are derived based on various information sources, including a detailed literature review, the reports of several service-specific or thematic meetings (four of which are listed below), dedicated user consultations (e.g. during validation exercises) and feedback during CEMS Rapid Mapping activations, and flood-related findings and recommendations which have been collated, based on user feedback, both through the CEMS flood early warning component (EFAS), and the validation service of CEMS Mapping.

The latter source of information includes a summary of feedback specifically related to the following CEMS Rapid Mapping activations for flood disasters[5]: EMSR257 (November 2017, in the Region of Attika, Greece); EMSR199 (March 2017, in coastal Peru); EMSR176 (August 2016, in Louisiana, USA); EMSR166 (June 2016, in Bavaria, Germany); EMSR150 (December 2015, in Yorkshire, UK); EMSR149 (December 2015, in River Shannon catchment, Ireland); EMSR120 (February 2015, in north-eastern Spain); EMSR108 (November 2014, in Northern Italy).

Amongst the aforementioned thematic meetings which informed some of the material in this chapter, are the following:

- Copernicus GloFAS workshop: Hydrological Services for Business (8-9 May 2018)[6].
- Copernicus for Water Management workshop (29 May 2018)[7].
- Global Flood Partnership Annual Meeting (25-27 June 2018)[8].
- German workshop on flood monitoring using Copernicus (5-6 December 2018)[9].

One of the above four meetings - the Copernicus for Water Management workshop - was one of a series of workshops organised as part of the European Commission's "NextSpace" initiative, aimed at gathering user requirements for the Next Generation of the Copernicus Space Component.

2.1 Potential end users

In the present context, floods can be defined as hydrological disasters caused when a water-body (river, lake, etc.) overflows its normal banks or embankment due to rising water levels, or when (in the case of saturation or freezing of the soil) water discharges from the ground surface, or fills morphological depressions, due to heavy rain or melting snow or ice. Floods can also be caused by "backwater" effects (i.e. upstream flooding due to downstream conditions) or other special circumstances, such as the breaching of dams or extreme marine tides, storm surges or even tsunamis. Flash floods are sudden floods with short duration, typically associated with thunderstorms. Floods and flash floods are also a common result of severe storm and frontal systems, or cyclone landfall. Coastal lowlands are particularly vulnerable to storm surges which lead to coastal floods caused by rising seawater levels (IWG-SEM, 2016).

[5] https://emergency.copernicus.eu/mapping/list-of-activations-rapid
[6] www.globalfloods.eu/get-involved/workshop/hydrological-services
[7] https://copernicuswater.eventsite.be/file/19/Copernicus_for_Water_Management_Workshop_Report/
[8] https://gfp.jrc.ec.europa.eu/node/54
[9] www.bafg.de/DE/05_Wissen/02_Veranst/2018/2018_12_05.html?nn=169148

The EU Floods Directive (Directive 2007/60/EC) on the assessment and management of flood risks, requires that Member States address all elements of disaster risk management (i.e. prevention, preparedness, response, and recovery), in order to effectively reduce the socio-economic impact of floods. As shown in Figure 3, the Copernicus Emergency Management Service (CEMS) already includes components that provide data and information to address most aspects of flood risk management: the European and Global Flood Awareness Systems (for preparedness and response); Rapid Mapping (for response); Risk and Recovery Mapping (for prevention / risk reduction and recovery). However a constant, automated, global, flood monitoring product would significantly enhance the information base of CEMS for a wide range of users, due to the following specific benefits:

- Complete, global coverage of all major flood events (using Sentinel-1 satellite radar imagery).
- Continuous, near real-time monitoring of flood events.
- Improved timeliness of flood mapping, since no user activation is needed and the data processing is automatic and operational.
- Creation of a complete, global archive of past flood events, providing end users with a previously unimagined data source for creating flood hazard and risk maps, and long-term monitoring and trend analysis of flood impacts.

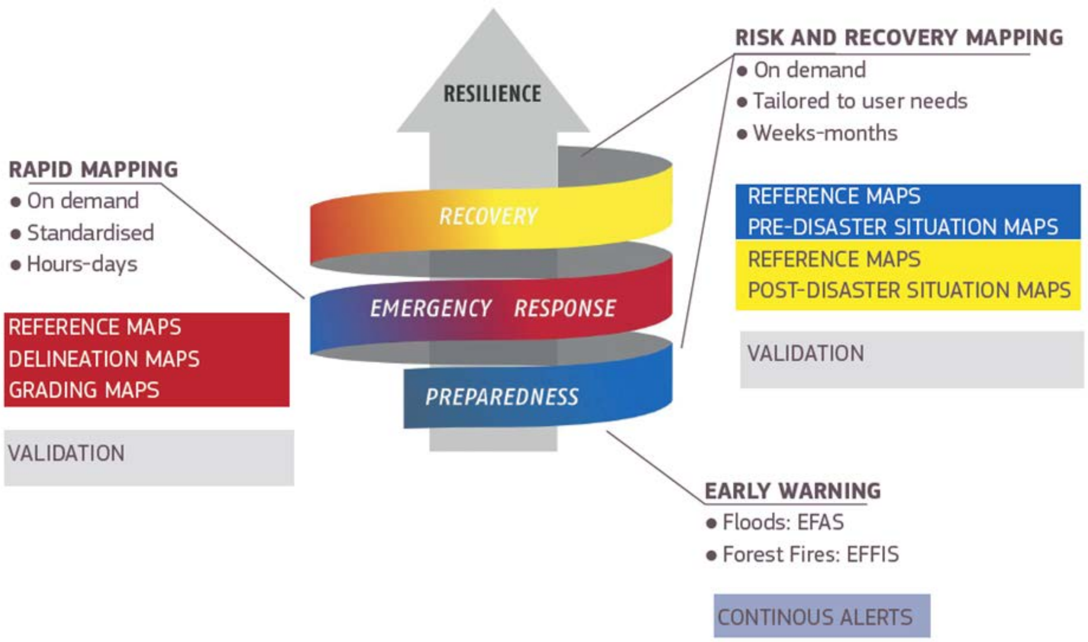

Figure 3: Role of the Copernicus Emergency Management Service (CEMS) in enhancing disaster resilience, through preparedness, response and recovery.

Some examples of potential end users of the proposed CEMS global flood monitoring product, are listed in Table 1. Although involved in diverse fields of activities, the potential end users are primarily concerned with assets which are at potential risk of flood damage, such as industrial complexes (reinsurance companies, energy authorities), road networks (logistics companies, local authorities), population (humanitarian organisations, district authorities), or refugee camps in conflict areas (security services, humanitarian actors).

Globally, aid organisations such as the UN Office for the Coordination of Humanitarian Affairs (OCHA), the World Food Programme (WFP), the International Federation of Red Cross and Red Crescent Societies (IFRC), as well as the European Commission’s Emergency

Response Coordination Centre (ERCC), need to monitor events in order to plan interventions and assess implementation options (e.g. access, mode of transport). Different units in the European External Action Service (EEAS) are concerned with situational awareness / a common operating picture, while activities of the Copernicus Service in Support to EU External Action (SEA) also relate to situational awareness, for monitoring critical infrastructure and crisis situations. In the commercial sector, there are big potential synergies with re-insurance companies, such as MunichRE[10] - who are particularly concerned with assessing natural hazard risks around the world - and service providers such as DHL - for whom managing risks to supply chains is a high priority[11]. With a global perspective, but acting locally, international NGOs such as Oxfam International, Médecins Sans Frontières, and SOS Children's Villages, increasingly use geospatial information for emergency response and preparedness / risk reduction measures.

Table 1: Non-exhaustive list of potential end users of the proposed CEMS global, satellite-based flood monitoring product (grouped according to the geographic scale of the application).

SCALE	*POTENTIAL END USERS*
Global:	- UN's Office for the Coordination of Humanitarian Affairs (OCHA). - UN's World Food Programme (WFP). - European Commission's Emergency Response Coordination Centre (ERCC). - EU's European External Action Service (EEAS). - Copernicus Service in Support to EU External Action (SEA). - Commercial companies in reinsurance (e.g. Munich RE) and logistics (e.g. DHL). - International Federation of Red Cross and Red Crescent Societies (IFRC). - Non-governmental organisations (NGOs), such as Oxfam International, Médecins Sans Frontières (MSF), and SOS Children's Villages. - Global Facility for Disaster Reduction and Recovery (GFDRR).
Regional:	- National water management authorities. - EU Civil Protection Mechanism (UCPM) participating states. - Development agencies including DG DEVCO. - River basin organisations (e.g. International Commission for the Protection of the Danube River / ICPDR). - European Commission's European Union Solidarity Fund (EUSF). - Universities and research institutions.
Local:	- NGOs dealing with social, humanitarian or environmental issues. - Watershed managers, regional planners, urban planners. - Disaster management agencies and public authorities responsible for managing floods and emergency operations (e.g. local fire fighters, civil protection agencies). - Owners and operators of critical infrastructures (e.g. hydropower plants, electricity grid operators, railway and waterway transports) at risk during floods. - Consulting engineers involved in flood risk management.

Particular users with a regional focus are national water management authorities, and actors of the EU Civil Protection Mechanism (UCPM), especially in case of trans-national events. Using flood forecasts from the CEMS European Flood Awareness System (EFAS), the Emergency Response Coordination Centre (ERCC) initiates timely interventions of the UCPM. River basin organisations monitor and support the implementation of river basin-wide flood risk management plans. The insurance sector use the information for estimation of claims, and regional organisations prepare needs assessments. Furthermore, the European Commission's department for regional and urban policy (DG REGIO) must assess Member State requests for assistance from the European Solidarity Fund (EUSF) after flood disasters, for which knowledge of the flood water extent is fundamental.

At the local level there is a wide range of local authorities (e.g. watershed managers, civil protection, and fire-fighters), NGOs, and private sector users (e.g. critical infrastructure operators, consulting engineers, insurance) that would benefit from such a product.

[10] www.munichre.com/en/reinsurance/business/non-life/nathan
[11] www.resilience360.dhl.com

2.2 Information needs of users

Thanks to early warning systems, such as the CEMS European Flood Awareness System (EFAS), users generally have timely knowledge about the imminent hazard. What they are often lacking, however, is information about the exposure in real-time, particularly information focussed on specific areas of infrastructure and population. In this context, a systematic global flood monitoring product would provide users with two major types of valuable additional information: (a) Real-time flood extent observations; (b) A systematic monitoring of flood-affected areas (with a revisit frequency as described in Section 4.2).

Information on real-time flood extent observations is needed in order, for example, to take decisions during a flood-related emergency situation, to activate evacuation plans, and / or to define evacuation routes. Local disaster management actors would then be better placed to decide when, and for which areas of interest, to activate the CEMS Rapid Mapping service, for example, which can provide complementary information such as a more detailed analysis and impact information. Experience from the CEMS Rapid Mapping in particular also shows that activation requests often come after the flood events have already started, or after the flood peaks have occurred, thus not always enabling Rapid Mapping to provide timely information. For this reason flood early warnings from EFAS and GloFAS are currently used for "pre-tasking" satellite image data for Rapid Mapping, thus improving the timeliness of flood maps (but only for large flood events). A systematic global flood monitoring would fill this gap by providing information right at the start of the flood. Rapid Mapping could then be used to complement this information, by covering time-steps, as needed. The critical phases of evolving or ongoing flood events that would be covered by the proposed CEMS flood monitoring product, compared with the relevant existing CEMS services (EFAS / GloFAS, and Rapid Mapping), are illustrated in Figure 4.

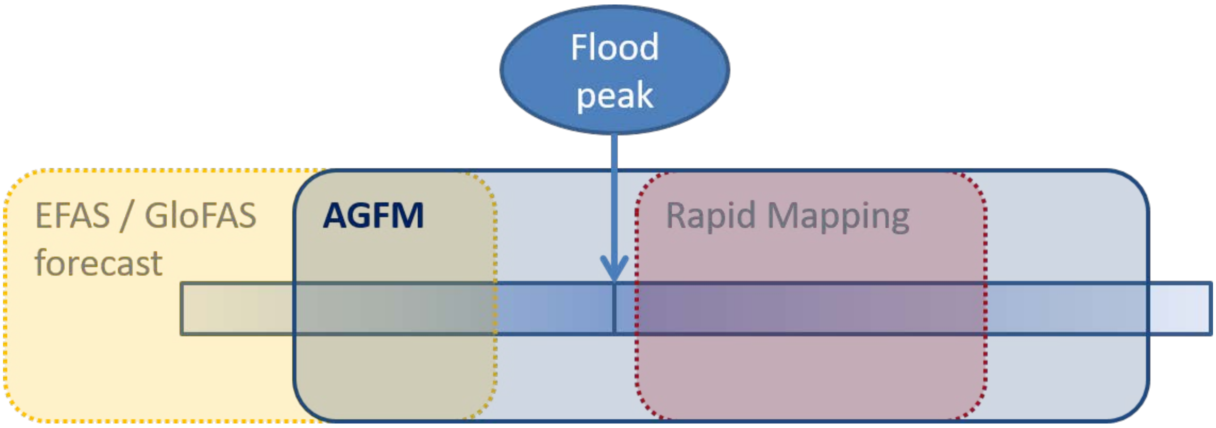

Figure 4: Conceptual comparison of the different phases of an evolving flood event (long narrow rectangle) covered by the proposed automated global flood monitoring (AGFM) product, and by the relevant existing CEMS components for flood early warnings (EFAS / GloFAS) and Rapid Mapping.

Regarding continuous monitoring of affected areas, based on extensive user feedback received via activations of CEMS Rapid Mapping, there is an ever increasing demand for a systematic monitoring of flood extent. This was particularly highlighted, for example, in relation to the flood disasters that triggered the following CEMS Rapid Mapping activations: EMSR265 (northern France, January 2018); EMSR293 (Romania, June 2018); EMSR324 (Aude, France, October 2018); and EMSR342 (city of Townsville, Australia, January 2019).

The monitoring of current hydrologic conditions and trends is essential for choosing the appropriate management actions, in a timely fashion, and for sharing critical information with users and stakeholders. This communication requires a focus on the potential impact: in other words, what might happen, when, and with what consequences. Using the information provided by the automated flood monitoring product, users would be in a good position to link the known vulnerability and exposure of their assets at risk, with the upcoming hazard, in order to estimate the probable impact. The users need to be able to assess whether or not certain thresholds that are important, for example, for the safe operation of critical infrastructures, will be reached during the upcoming flood event. Mandated users can then provide appropriate warnings and alarms to local communities and public authorities, to safeguard lives and prevent serious damage to critical infrastructures. Subsequently they will need to estimate the required personnel and technical equipment for flood mitigation and control, to identify for how long critical infrastructures or populations will eventually be exposed to the imminent flood wave, and to activate the CEMS Rapid Mapping for the most affected areas, if necessary.

In the long-term, the flood monitoring product will also, for example, provide input for reporting requirements, such as for the EU Flood Directive or Sendai Framework, provide essential information for analysing past flood events with a view to plan for future events (e.g. to update risk assessments, plan flood protection measures, and update and calibrate hydrological models), and can support climate change adaptation management plans (e.g. in relation to the Copernicus Climate Change Service).

2.3 Use cases

Considering the users' information needs discussed earlier, two key observations should be highlighted:

- Users need timely, frequent and systematic satellite-based flood maps. In CEMS user consultations and service validations, the timeliness and duration of the flood monitoring information are constantly mentioned as crucial requirements. Knowing the flood area extension and how the flooding evolves - ideally from day to day during the event - will be key benefits of the proposed product. Users have also agreed that the spatial resolution of the Sentinel-1 data product (i.e. 20 by 20 metres) is adequate for discriminating flooded areas at their working scale.

- As well as near real-time flood information, many users need access to historical flood maps derived from Sentinel-1, in order to differentiate floodwater from other water-bodies (permanent water, marshlands, etc.), to calibrate their flood models, or to assess the severity of flood events.

With this in mind, four potential use cases are summarised in Table 2, to demonstrate the feasibility and relevance of an automated flood monitoring product based on Sentinel-1 satellite radar imagery, which would complement the main flood-related components of CEMS (EFAS, GloFAS and Rapid Mapping).

Table 2: Potential use cases showing applications of a global satellite-based flood monitoring product.

USE CASE	*DESCRIPTION*	*INFORMATION / DATA NEEDED*
1. <u>High-frequency, detailed flood monitoring</u>	Inside EU: The disaster management agency at the town of Kozloduy in north-west Bulgaria (Figure 5), is monitoring the exposure of the local nuclear power plant (the largest in the region, 5 km from the Danube River) to approaching flood-waves.	- Flood extent in near real-time, at high spatial resolution. - Information is fed into a local information system (via API) containing vulnerability data.
2. <u>Flood impact assessment</u>	Outside EU: DG ECHO and UN OCHA are monitoring the impact of large-scale floods in Myanmar, to assess the required humanitarian action.	- Impact of flood on populations: flood monitoring product + global population and local census data. - Exposure to floods of access roads and human settlements: flood monitoring product + OpenStreetMap (OSM) and Global Human Settlement data.
3. <u>Flood impact assessment</u>	Inside EU: The Ebro River Basin authority in Spain is monitoring the possible impact of flooding on critical infrastructure and population.	- Impact on critical infrastructure: flood monitoring product + Basic European Assets Map (BEAM). - Impact on population: flood monitoring product + Spanish population data.
4. <u>Global flood risk assessment</u>	Outside EU: Strong storms with heavy rains have been registered during the last two days over the central US. Flooding is likely in north-east Oklahoma, north-west Arkansas, south-east Kansas and south-west Missouri. Early warnings have been issued by the US National Weather Services. A global re-insurance company (MunichRe) closely monitors the situation as it affects commercial complexes insured by its clients. Similarly, a global logistics company (DHL) is concerned about the possible flood impacts on their supply chains.	- Impact on built-up areas: flood monitoring product integrated via API / WMS in MunichRe's NATHAN system (see section 2.1). - Impact on supply routes and infrastructure: flood monitoring product integrated via API / WMS in DHL's Resilience360 system (see section 2.1).

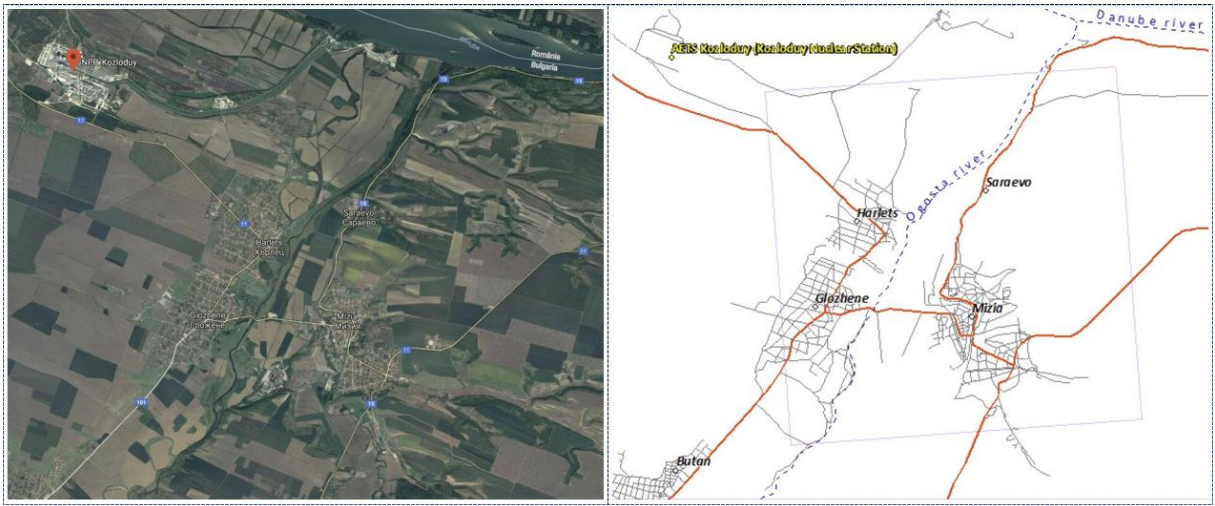

Figure 5: Location of Kozloduy nuclear power plant (the largest in the region) in Bulgaria, 5 km east of the town of Kozloduy on the Danube River, near the border with Romania. This area was the subject of an activation (EMSN022) of CEMS Risk and Recovery Mapping, including a post-disaster risk assessment after devastating flooding affected the nearby town of Mizia on 1-2 August 2014.

3 Product output specifications and validation

In this chapter, the different output layers (i.e. thematic maps) that should be provided by the proposed CEMS global flood monitoring product are described in detail, and the approaches that should be used for the validation both of the output layers and of the processing system itself, are outlined.

3.1 Product output layers

The output layers that should be generated from the processing system of the CEMS global, automated Sentinel-1 SAR-based flood monitoring product, in order to satisfy the user requirements, are summarised in Table 3. In the following sub-sections, the technical specifications related to the production of the output layers listed in Table 3 - including auxiliary datasets required, output data formats, and product timeliness and dissemination - are specified. Note that a technical overview of Sentinel-1 SAR satellite data is provided in Section 4.1 of this report, while the state-of-the-art data processing strategies and methods that are used for the systematic, automated delineation of flooded areas and water-bodies, based on Sentinel-1 data, are described in Section 5.2.

Table 3: Output layers of the proposed CEMS global flood monitoring product.

#	*OUTPUT LAYER*	*THEMATIC CONTENTS OF LAYER*
1	*Observed flood event*	Flooded areas extracted by subtracting the reference water mask (output layer 3) from the observed water extent (output layer 2).
2	*Observed water extent*	Open and calm water-bodies, mapped using Sentinel-1 SAR data.
3	*Reference water mask*	Normal water extent (i.e. permanent and seasonal water-bodies), considering seasonal effects, mapped using a consistent time-series of Earth Observation (preferably Sentinel-1) data.
4	*Exclusion mask*	Unclassified areas, including urban areas, dense vegetation, permanent low backscatter areas (e.g. flat and impervious areas, and sandy surfaces), and topographic effects.
5	*Uncertainty values*	Estimated uncertainty (integer values between 0-100) related to the classification algorithm, for all areas not covered by the exclusion mask.
6	*Advisory flags*	Flags indicating potential reduced quality of the flood mapping due to prevailing (i.e. dynamic) environmental factors such as wind, temperature (for freezing conditions), snow, and dry soil.
7	*Sentinel-1 metadata*	Information on the acquisition parameters of the Sentinel-1 data used.
8	*Sentinel-1 footprint*	Image boundaries of the Sentinel-1 data used.
9	*Sentinel-1 schedule*	Next scheduled Sentinel-1 data acquisition.

3.1.1 Auxiliary datasets

The production of output layers 3, 4 and 6 (i.e. reference water mask, exclusion mask, and advisory flags), listed in Table 3, requires the use of global, homogeneous and up-to-date auxiliary datasets. These auxiliary datasets may well be available in higher spatial resolution for Europe than for elsewhere. For European countries, the higher resolution datasets should be used in preference to globally available homogeneous datasets of lower spatial resolution.

Production of the reference water mask should preferably be done based on Sentinel-1 data, updated on a monthly basis (in order to consider seasonal effects), using a sufficiently long time-series of data (e.g. the three-year period prior to acquisition of the Sentinel-1 data set to be analysed). So, for example, if the Sentinel-1 scene currently being processed is acquired in March 2019, the reference period for the reference water mask is the month of March in years 2016, 2017, and 2018. For each month, the reference water mask could be computed on the basis of surface water occurrence (the number of water detections divided by the number of valid observations for each pixel) considering all Sentinel-1 data acquired within the corresponding month of the considered time-series.

It should be mentioned that the JRC's Global Surface Water Explorer[12], which is derived from a 32-year time-series of optical (i.e. Landsat) satellite imagery, also provides information on global permanent water-bodies. While in theory either the "Surface Water Occurrence" or "Water Seasonality" layer of this dataset could be used, in areas of high dynamics of river extents (e.g. braided rivers), the use of "Surface Water Occurrence" might be difficult, as in this layer the position of rivers, for example, changes over time. Up-to-date "Water Seasonality" (i.e. 12-month water-covered pixels) derived from data of only one year, may make more sense as a permanent water mask. At the time of writing, only "Water Seasonality" for years 2014-2015 is available on the Global Surface Water Explorer. For some areas, this could be reliably used as a permanent water mask. However, for areas where computation is based only on Landsat-7 data, it may not be suitable due to "striping" effects in the data (and therefore also in the water products). Finally, although consideration of seasonality is important in defining a reference water mask, "Surface Water Occurrence" does not consider which period of the year an area is usually water-covered, which users might be interested in (e.g. in order to compare the current water extent with a reference period in the past). In summary, deriving the reference water mask from a time-series of Sentinel-1 SAR data is the optimal solution, from a scientific point of view, in order to ensure consistency with the proposed CEMS flood monitoring product.

The exclusion mask shows regions where automatic water mapping is not reliable with the Sentinel-1 data (due to system and environmental parameters), which are mainly related to urban areas, dense vegetation, permanent low backscatter areas (e.g. flat and impervious areas, and sandy surfaces), and topographic effects. Areas which are reliably identified as flooded within both urban areas (mainly large open spaces between buildings) and vegetated areas, should be included within output layer 1 (observed flood event). However, other urban areas and densely vegetated areas, where no flooding is identified using Sentinel-1 data, should be marked as regions where water detection is not possible.

For example, in the case of urban areas, such cases could be excluded using databases such as DLR's Global Urban Footprint[13] (GUF) or the JRC's Global Human Settlement Layer[14] (GHSL), while densely vegetated areas (e.g. forest areas) - where water detection is impeded by high radar backscatter due to volume scattering or multi-bounce effects - could be excluded either by using land cover databases or Sentinel-1 time-series data. Sentinel-1 time-series data could also be used to exclude permanent low backscattering areas, such as smooth anthropogenic features (e.g. streets, air-strips) and sand surfaces, as well as areas affected by topography-related shadowing effects (based on Sentinel-1 data acquired with similar orbit parameters). Topographic effects such as shadowing or layover could also be excluded by applying modelling approaches to digital elevation data, taking account of Sentinel-1 acquisition parameters.

The advisory flags indicate where there may be reduced quality of the flood mapping result, due to prevailing environmental parameters such as wind, frozen conditions, snow and dry soil. The main purpose of advisory flags is to raise the awareness of users that adverse environmental conditions may impact the product quality, and to help them identify potential misclassifications. The advisory flags can be derived using weather forecasts (e.g. wind-speed above 5 metres per second, air temperature below 1°C) and operational satellite data services, such as the Copernicus Global Land Service[15], for snow extent, and the EUMETSAT Satellite Application Facility on Support to Operational Hydrology and Water Management[16] (H-SAF), for dry soil. In the case of wind, Sentinel-1 scenes where water extent might be under-estimated due to wind-roughened water surfaces, could also be identified for example based on the statistical distributions of backscatter values over reference water surfaces within the Sentinel-1 scene.

[12] https://global-surface-water.appspot.com/
[13] www.dlr.de/guf
[14] https://ghsl.jrc.ec.europa.eu
[15] https://land.copernicus.eu/global/
[16] http://hsaf.meteoam.it/

3.1.2 Output data formats

Output layers 1, 2, and 3 (i.e. observed flood event, observed water extent, and reference water mask) should be provided in both raster (GeoTIFF) and vector (Shapefile) format. Output layers 4 (exclusion mask), 5 (uncertainty values), and 6 (advisory flags), should be provided in raster format, with the different regions separable in output layer 4. Output layer 8 (Sentinel-1 footprint) should be provided in vector format. Output layer 9 (Sentinel-1 schedule), showing the next scheduled Sentinel-1 acquisition segments for an area of interest, are available from ESA as KML files[17].

3.1.3 Product timeliness

The proposed global flood monitoring product shall provide the output layers of flood information to users within 4-6 hours after the Sentinel-1 Ground Range Detected / GRD data product (see Section 4.1), first becomes available on either the Sentinel-1 "Fast-24h" or "NRT-3h" data streams (see Section 4.3). The target should be to provide the Sentinel-1 flood product output layers to users within eight to twelve hours after sensing. (By comparison, for the on-demand CEMS Rapid Mapping service, from March 2019 the target delivery times for the flood mask are seven hours (for the vector file) and nine hours (for the raster file). One issue affecting product timeliness concerns the possible pre-processing (on the service side) of the Sentinel-1 GRD data product to a coarser spatial resolution (e.g. 40x40 metres, at a 20 metres sampling), resulting in products of higher radiometric resolution, and less affected by backscatter "speckle" (due to a stronger multi-looking of the data, at the cost of spatial detail). While smaller rivers and inundation areas would be partly missed, this could further reduce the computational time required to generate the flood monitoring product output layers, while the storage capacities would also be improved compared with using the full-resolution product.

3.1.4 Product dissemination

While many authorized users still request disaster impact maps - such as those provided by CEMS as static raster- and vector-based delineation or grading maps and associated crisis vector data layers - there is an emerging demand for standardised web-services or advanced programming interfaces (API), which users can integrate into their working environment and existing information systems.

Dissemination of the proposed CEMS global flood monitoring results via web-services or an API can be accomplished following thematic processing of the Sentinel-1 SAR data, which would speed up the current delivery of flood crisis information within the CEMS. The web-services should be compliant with the standards, such those of Open Geospatial Consortium (OGC) - WMS (Web Map Server) and WFS (Web Feature Service), and INSPIRE (e.g. view and download services and data specifications). Users could be informed about new products by GeoRSS web feeds, ensuring that the information on the flood event is delivered and received as fast as possible.

The web-mapping client (an example of which is shown in Figure 6) should allow the rapid visualization and screening of the product layers in full resolution, using the following functionalities:

- A spatial filter should provide the capability to constrain the search of the products according to the geographic location by creating a bounding box.
- A temporal filter should provide the capability to restrict the query to a user-defined time period.
- A "slider functionality" should be implemented to facilitate the interactive visualization of the generated products of different time-stamps.

[17] From: https://sentinel.esa.int/web/sentinel/missions/sentinel-1/observation-scenario/acquisition-segments

- The functionality to retrieve attributes of vector features highlighted in pop-up boxes, for example.
- The user should be able to make a request to receive relevant products for a specified area of interest and time period.

In addition, the interface should provide the capability for downloading the product layers in both raster (GeoTIFF) and vector (Shapefile) format.

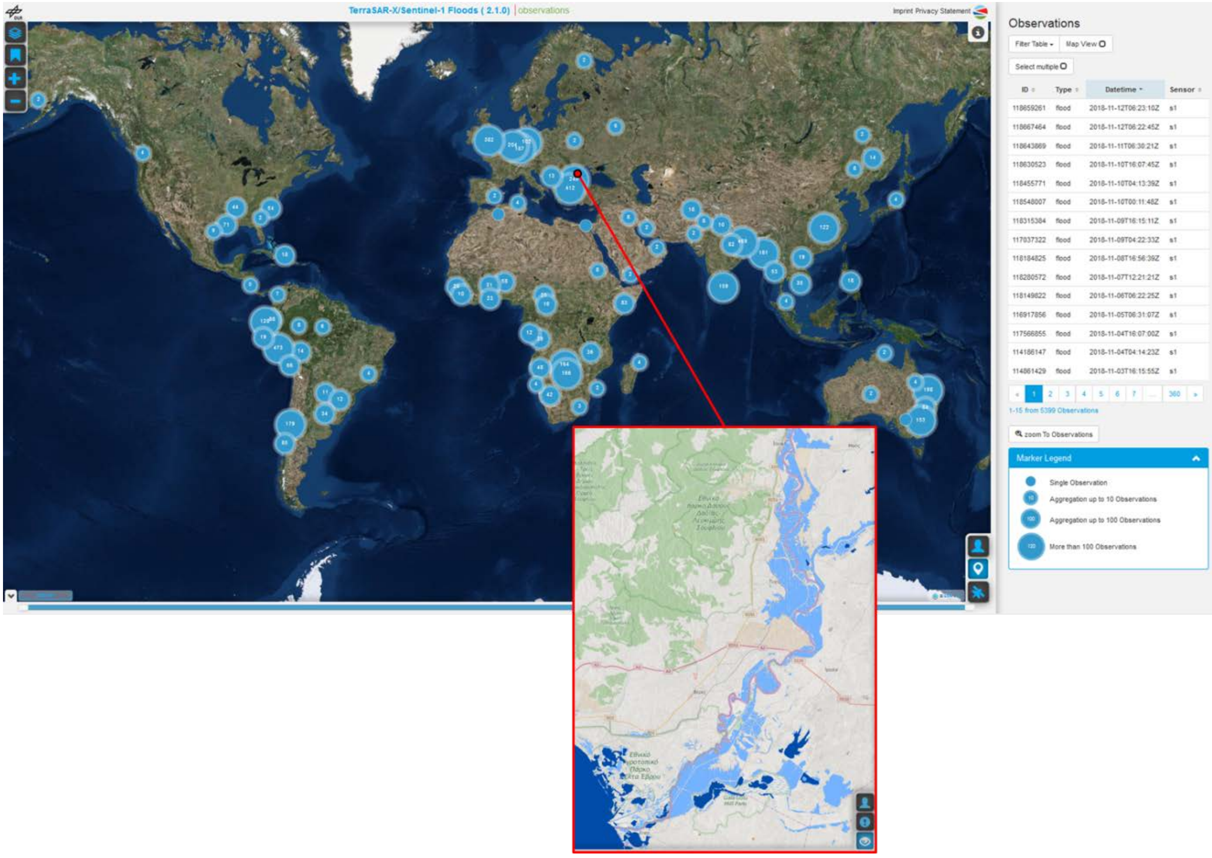

Figure 6: Example of the German Aerospace Centre (DLR) web-client for visualizing and disseminating flood extent products as part of DLR's flood service using Sentinel-1 and TerraSAR-X.

3.2 Validation of output layers and processing system

The Copernicus Emergency Management Service (CEMS) includes a validation methodology which is used for the verification of a sample of service outputs produced by the CEMS Rapid Mapping or Risk and Recovery Mapping components[18]. The proposed CEMS global flood monitoring product, and the derived output layers of flood information, should be extensively validated against defined criteria of the CEMS, with a focus on product accuracy and timeliness.

In order to validate the output layers of the proposed flood monitoring product, a quantitative evaluation of the products should be performed, whereby selected Sentinel-1 Ground Range Detected (GRD) datasets should be classified, in an off-line environment, based on a visual inspection and manual digitization of flood extent by experienced image interpreters. The manually digitized product should then be compared with the automatically generated flood mask. The flood product validation should be performed for various Sentinel-1 datasets acquired in different environments and various geographic locations throughout the world, during both flood as well as non-flood conditions.

[18] https://emergency.copernicus.eu/mapping/ems/quality-control-feedback

For a subset of the flood product validation areas, a further scientific validation based on in-situ or other space-based information (e.g. very high resolution optical satellite imagery) should be accomplished. This would inform users about the flood information content of Sentinel 1 data compared with other sources (but not quantifying the quality of the Sentinel-1 data per se).

A validation of the processing system used by the flood monitoring product, should also be carried out, based on an evaluation of the delivery times, system availability and other key parameters required for generating the output layers of flood information. As an example, the time until product delivery, both from Sentinel-1 data acquisition, and the data's availability on the Copernicus Services Data Hub, should be monitored. In addition, the timeliness of the proposed flood monitoring product should be compared with existing products generated in the frame of the CEMS - Rapid Mapping service, based on the same Sentinel-1 datasets.

4 System architecture and data processing methods

The overall system architecture of a fully automated, worldwide Sentinel-1 flood monitoring product, is determined on the one hand by the requirements of users (described in Chapter 2), and on the other hand by the data acquisition system and the Ground Segment of the Sentinel-1 mission. In this Chapter, the main characteristics of Sentinel-1 satellite imagery are first summarised, the geographic coverage and data distribution system of Sentinel-1 data products are described, and the system architecture and data processing methods for the proposed automated, global flood monitoring product, are outlined.

4.1 Technical overview of Sentinel-1 SAR imagery

The EU's two Copernicus Sentinel-1 (S-1) satellites, operated by the European Space Agency (ESA), provide a global, continuous, all-weather, day-and-night supply of Synthetic Aperture Radar (SAR) imagery of the Earth's surface, which is acquired within the microwave part of the electromagnetic spectrum, in the C-band frequency range (3.75 to 7.5 cm wavelength).

The SAR instrument on board the two S-1 satellites (S-1A and S-1B) emits microwaves and measures the "amplitude" (i.e. signal strength or magnitude) and "phase" (i.e. fraction of the full wavelength) of the microwaves which are "backscattered" (reflected) by the surface features contained in each grid cell on the ground. An S-1 SAR image, therefore, can be seen as a two-dimensional array of image columns (i.e. the across-track or "range" direction) and image rows (i.e. the along-track or "azimuth" direction), where each pixel value is recorded as a complex number that carries information on both the amplitude and phase of the microwave signal backscattered for that pixel. Backscattered amplitude depends primarily on the roughness of the imaged surface features. Typically, exposed rocks and urban areas show strong amplitudes, while smooth flat surfaces, such as water bodies, show low amplitudes, since the microwaves are mainly mirrored away from the radar sensor. Backscattered phase, on the other hand, represents the (two-way) travel distance between the radar and the surface features. The phase of a single SAR image is of no practical use. However, phase differences between two SAR images of the same scene are closely dependent on terrain height, and form the basis for SAR interferometry (see below).

The S-1 SAR instrument acquires data in four different modes, one of which - "Interferometric Wide Swath" (IW) - is the primary mode over land. S-1 data products are distributed by ESA at three levels of processing, of which "Level-1" is the one intended for most data users. S-1 Level-1 data are provided as either "Single Look Complex" (SLC) or "Ground Range Detected" (GRD) products. In SLC products, range (across-track) coordinates are in the natural geometry (i.e. "slant-range") of the SAR imaging system, and information on backscatter phase is preserved. In GRD products, on the other hand, range coordinates are projected to normal geometry (i.e. "ground range"), while pixel values represent only the detected amplitude of the backscatter, which has been "multi-looked" to reduce the "speckle" (granular noise) that is inherent in SAR imagery. Some basic parameters (e.g. ground resolution, re-visit frequency) of S-1 Level-1 GRD data products, in IW mode, are shown in Table 4.

Table 4: Basic parameters of the Sentinel-1 (S-1A / S-1B) Level-1 GRD high-resolution product, in IW mode. (Adapted from: https://sentinels.copernicus.eu/web/sentinel/technical-guides/sentinel-1-sar/products-algorithms/level-1-algorithms/products).

GROUND RESOLUTION (RANGE BY AZIMUTH)	*PIXEL SPACING (RANGE BY AZIMUTH)*	*NUMBER OF LOOKS (RANGE BY AZIMUTH)*	*COMBINED S-1A / S-1B RE-VISIT FREQUENCY*
20 x 22 metres	10 x 10 metres	5 x 1	6 days at the equator, shorter at higher latitudes (both hemispheres)[19].

[19] https://sentinel.esa.int/web/sentinel/user-guides/sentinel-1-sar/revisit-and-coverage

The S-1 C-band SAR antenna can transmit and receive microwaves that are oriented in one of two orthogonal planes or “polarisations”, namely horizontal (H) and vertical (V). Hence there are four possible polarisation combinations: horizontal transmit and horizontal receive (HH); vertical transmit and vertical receive (VV); horizontal transmit and vertical receive (HV); vertical transmit and horizontal receive (VH). (The first two are called “co-polarised” or “single-polarised”, while the second two are called “cross-polarised”). In IW acquisition mode, a dual polarisation scheme (i.e. VV+VH or HH+HV) is available, as well as single polarisation (HH or VV). C-band SAR images that are acquired under different polarisation combinations will obtain different backscatter responses, depending on the surface features imaged, thereby improving the SAR data’s discrimination potential. Co-polarised (HH or VV) SAR data are generally considered more suitable for flood mapping.

SAR interferometry is a technique that uses the “interferometric phase” (i.e. phase differences) between two SAR images to (a) construct local topography (DEMs), if the images are acquired simultaneously from two different angles, or (b) measure surface deformation and subsidence (e.g. due to earthquakes or volcanoes), if the images are acquired at different times. Another key parameter produced by SAR interferometry is “coherence”, which measures the correlation of the interferometric phase between two SAR images. Coherence values range from 0 (interferometric phase is just noise) to 1 (complete absence of phase noise). Water bodies, for example, have low coherence, because their surfaces are constantly moving, so they appear black in coherence images.

4.2 Geographic coverage of Sentinel-1 SAR imagery

In the past, spaceborne SAR missions - such as ESA’s ENVISAT - Advanced Synthetic Aperture Radar (ASAR), Japan’s Advanced Land Observing Satellite (ALOS) - Phased Array type L-band Synthetic Aperture Radar (PALSAR), or the Canadian Space Agency’s RADARSAT - acquired data over land mostly on demand, whereby users could select from a number of diverse acquisition modes. This resulted in an uneven coverage of land surfaces and hindered a systematic exploitation of the data at larger scales. Recognising this deficiency, ESA’s Sentinel-1 mission has been designed to provide systematic coverage in a limited number of acquisition modes that meet most user requirements.

Over land, Sentinel-1 has been acquiring data almost exclusively in Interferometric Wide Swath (IW) mode (250 km swath width, and VV and VH polarisations) in pre-defined coverage patterns. A key advantage of this systemic approach is that data processing chains can be streamlined and made fully automatic. Therefore, it becomes possible to set up near real-time processing chains to convert the raw Sentinel-1 Level 0 data stepwise into higher level data products in a matter of a few hours after acquisition. Another important advantage is, as already stated in Chapter 2, that coverage is maximised, becoming de facto only limited by the maximum duty cycle of the SAR instrument.

Nevertheless, since the Sentinel-1 SAR instrument is designed to operate in IW mode for a maximum duty cycle of 25 minutes per orbit, Sentinel-1 data acquisition has been prioritized according to region. This was done based on requirements from the Copernicus services and Member / Participating States. As is shown in Figure 7, the two Sentinel-1 satellites (S-1A and S-1B) cover Europe exceptionally well, providing SAR measurements every two to five days, depending on geographic location. Over the World’s other continents, tectonic zones and agricultural areas are also usually well covered, with new measurements taken every five to ten days. Lowest priority regions - which typically are situated in arid and cold environments - are covered every ten to fifteen days on average.

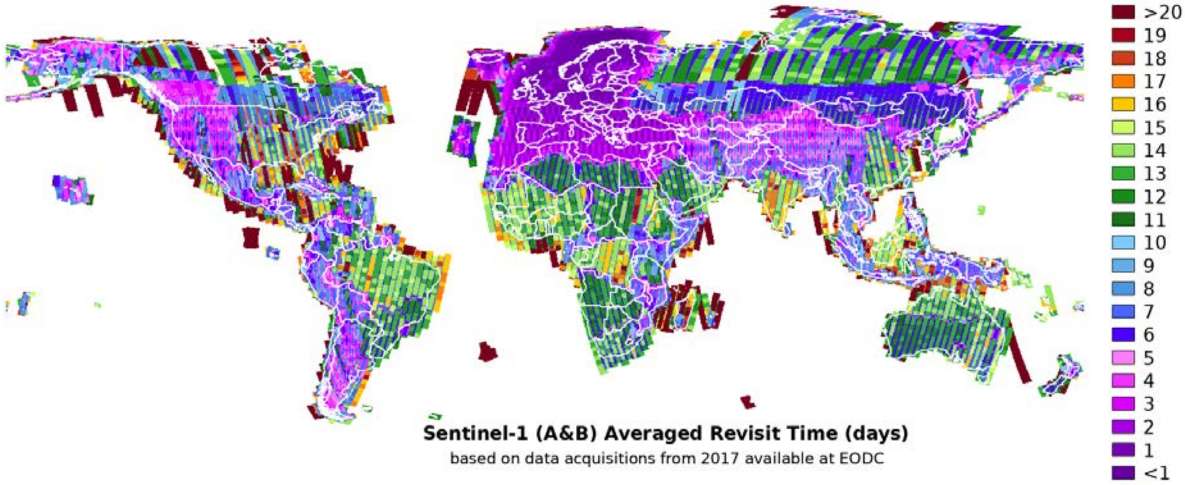

Figure 7: Averaged revisit time of the Sentinel-1A and 1B constellation in Interferometric Wide Swath (IW) mode, based on 2017 data acquisitions (available at the Earth Observation Data Centre / EODC).

4.3 Data reception of Sentinel-1 SAR imagery

As with most Copernicus data and information, Sentinel-1 imagery is available to any citizen and organisation around the world, on a free, full and open access basis, for example through a conventional data access hub or the European Commission's Data and Information Access Services (DIAS)[20]. The Copernicus Services Data Hub[21], which is restricted for use by the Copernicus Service Projects, also provides a dedicated access to Sentinels user products.

As a result, the Sentinel-1 global flood monitoring product can receive near real-time (NRT) Sentinel-1 data from a variety of sources. Short data latencies (time delays) can be achieved by receiving and pre-processing Sentinel-1 data at local ground stations. For flood mapping in Europe using Sentinel-1 data received in such a rapid mode, existing local ground stations, such as that operated by the German Aerospace Centre (DLR) at its Neustrelitz site (Figure 8), could be used. This would allow the automatic generation of the latest flood maps within one to two hours after data acquisition. However, coverage would be limited to regions centred on the location of the ground station (see Figure 8).

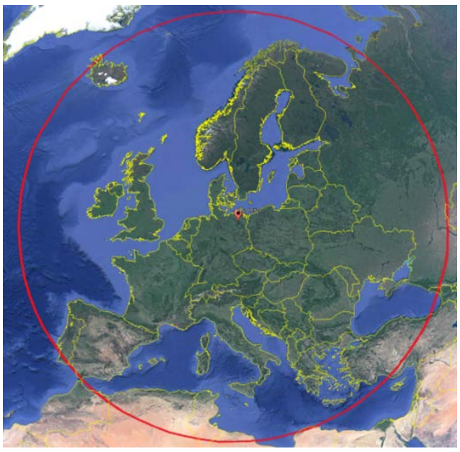

Figure 8: Receiving mask of the DLR ground station in Neustrelitz, Germany.

[20] www.copernicus.eu/en/access-data/
[21] https://cophub.copernicus.eu/

Table 5 lists the different Sentinel-1 data access points, and their characteristics. As can be seen, to receive worldwide Sentinel-1 Level-1 data in NRT (defined as within 3 hours of sensing), one can obtain the data from one of the existing Copernicus data hubs. While NRT generation (for land areas) is mainly for Europe, non-time critical (NTC) data - so-called "Fast24h" - are in practice made available rapidly. For the proposed new CEMS product, Sentinel-1 NRT (or NTC) data would be obtained from the Copernicus Services Data Hub, or as a potential fall-back option from the Copernicus Collaborative Nodes. The Copernicus Data and Information Access Services (DIAS) are also an option, if a DIAS provider offers access to worldwide NRT or NTC Sentinel-1 data as a service.

Table 5: The different Sentinel-1 data access points. NRT = near real-time; NTC = non time-critical. Modified from: https://sentinel.esa.int/web/sentinel/sentinel-data-access/typologies-and-services.

DATA ACCESS POINT	*USE TYPOLOGY*	*S1 DATA OFFER*	*SERVICE LEVEL*
Copernicus Services Data Hub	Copernicus Services.	Full archive of NTC and NRT products.	Max 10 concurrent downloads. Access via public internet and GÉANT network, with committed reliability and performance.
Copernicus Collaborative Nodes	Collaborative Ground Segments. ESA / EU Member States, National Use.	Rolling archive of NTC and NRT products (30 days on Node 1, 14 days on Node 2).	Max 10 concurrent downloads. Access via public internet and GÉANT network (node 1 only), with committed reliability and performance.
Copernicus Open Access Hub	Scientific and other use (e.g. commercial, outreach, public).	Full archive of NTC products.	Max 2 concurrent downloads. Access via public internet and GÉANT network. Free and Open Access following Self Registration.
Sentinels International Access Hub	International Agreements.	3-week rolling archive of NTC products.	Max 10 concurrent downloads. Access via public internet and GÉANT network, with committed reliability and performance.

Because Sentinel-1 (S-1) Ground Range Detected (GRD) NRT data come in different "flavours" regarding timeliness, the situation is slightly more complicated than shown in Table 5. The S-1 GRD "NRT-3h" data stream is disseminated to all users in under 3 hours, and is currently available for Europe and some specific regions (i.e. orbits). The S-1 GRD "Fast-24h" data stream is regularly disseminated on a world-wide basis within about 6 hours, on average, both on the Copernicus Open Access and Services Data hubs, with 90% of products being available on the Open Access hub within 3 hours[22]. (This is very relevant for the proposed flood monitoring product). A statistical analysis of Fast-24h data from January 2019, shows a mean latency (time from sensing to end of processing) of just 3.7 hours. However, S-1 data from orbits that neither pass ground stations nor dump data via the European Data Relay System (EDRS), arrive much later (closer to the 20 hours target).

In the context of the considered flood mapping service, it should be borne in mind that, originally, there were no plans to provide Sentinel-1 data over land in near real-time, except in case of emergency to support CEMS Rapid Mapping. Despite this, the service quality of the Copernicus Services Data Hub is already quite good in terms of data availability, latency, and quality. Furthermore, ESA might conceivably improve data latencies in the future, through implementation of more Core Ground Stations (CGS) and / or enhanced use of the EDRS (though only outside Europe).

[22] https://sentinel.esa.int/web/sentinel/news/-/article/sentinel-data-access-annual-report-2017

In summary, a timeliness target of Sentinel-1 data being available on the Copernicus Services Data Hub, within 4-6 hours after acquisition, seems realistic. Once the data are on the hub they can be downloaded and transferred (e.g. using ESA software) to the facility creating the flood monitoring product. Once the flood monitoring product is ready, the final step is to transfer it to the CEMS Data Distribution system, from where users can access the data (see Figure 9). Assuming that the latter two steps take 1-2 and 2-4 hours respectively, an overall timeliness of about 8-12 hours - i.e. from S-1 data acquisition to making the flood monitoring product available to users via CEMS - can be achieved.

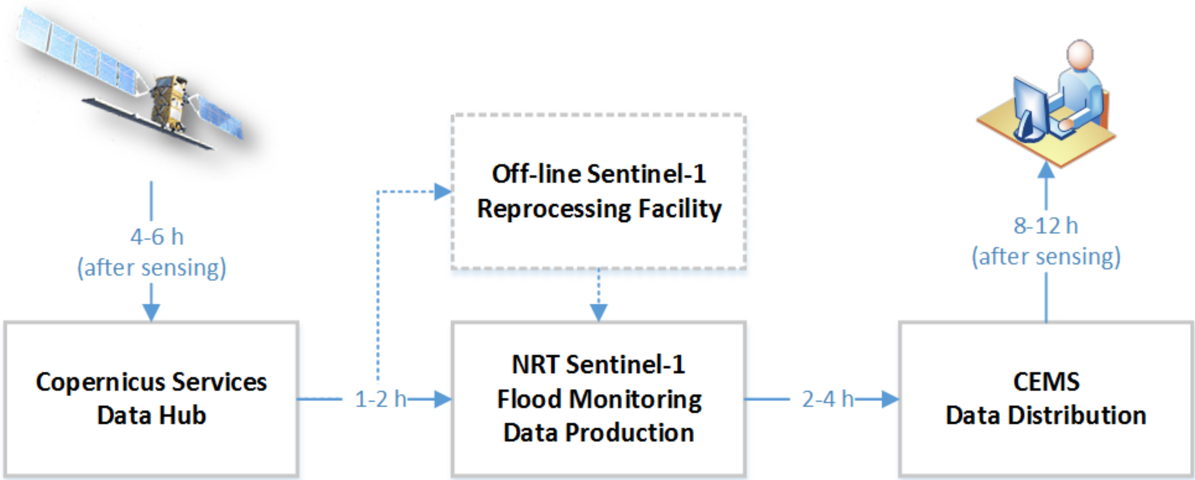

Figure 9: Data flow and envisaged data latencies (time delays) from the Copernicus Service Data Hub to the CEMS data distribution facilities. Note that the indicated timeliness of 8-12 hours represents the total time from Sentinel-1 data acquisition to flood monitoring product distribution to users.

4.4 System architecture using Sentinel-1 SAR imagery

The system architecture for the flood monitoring data production, is primarily driven by the data processing algorithms applied to the Sentinel-1 (S-1) imagery, which are themselves driven by the user requirements. Considering the various algorithms published in the scientific literature, one can distinguish three broad categories of data processing architectures (illustrated in Figure 10 to Figure 12):

- Single-image processing architecture.
- Dual-image processing architecture.
- Data cube (or time series) processing architecture.

In the first, most basic single-image processing architecture (Figure 10), the water mapping algorithm is applied to a single S-1 image, using some ancillary data, such as a digital elevation model, and maps of land cover and historical water extent. In this case, the data flow is simplistic, whereby incoming S-1 SAR Level-1 data are converted, step-by-step, to geo-coded imagery and the flood mapping product. The algorithms should be designed to work with single SAR images, typically relying on processing techniques that, for example, combine thresholding with region-growing and noise reduction. From an engineering point of view, the single-image processing architecture is easily implemented. Drawbacks are: (a) It is difficult to deal with spatial heterogeneity of the land surface, due to the limited information content of single SAR images; (b) Training and calibration of algorithms is not naturally built into the processing architecture, and so is usually done only for a limited number of flood events.

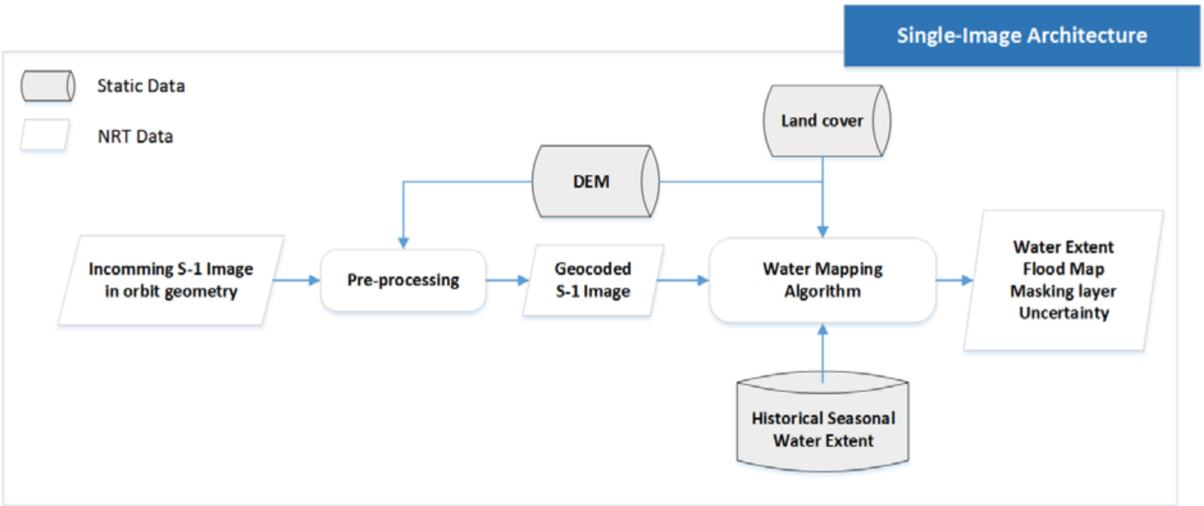

Figure 10: Single-image processing architecture for global flood monitoring using S-1 SAR image data.

Change detection approaches, which are based on a comparison of flooded and non-flooded S-1 SAR images, enable the detection of flooded areas more reliably than single-image approaches. In the simplest case, change detection algorithms can be implemented using a dual-image processing architecture (Figure 11), which allows the comparison of the incoming SAR image to an historic SAR image extracted from the S-1 data archive. This architecture is somewhat more difficult and costly to implement than the single-image processing architecture, for example due to the need to maintain an S-1 data archive, and provide fast access to it. However, this architecture has the important advantage that change detection algorithms are better able to handle the spatial heterogeneity of the land surface, than single-image methods. This simply reflects the fact that two custom-selected SAR images hold more information than a single image. Additionally, change detection algorithms are more easily applied to different geographic regions. Nonetheless, a dual-image processing architecture does not fully solve the training and calibration problem, since region-specific thresholds and / or model parameterisations are still required.

The most sophisticated data processing architecture is based on the "data cube" concept, whereby incoming SAR images are geocoded and added to an existing SAR data cube (Figure 12). By using a data cube processing architecture, each incoming S-1 image can be compared with the entire backscatter history, in a straightforward manner. The entire backscatter time series for each pixel can then be analysed, in order to derive pixel-specific backscatter statistics, which can then be used for example to derive pixel-specific thresholds and model parameterisations. Using this architecture, the S-1 SAR information content is maximised (by providing the entire backscatter history), and model training and calibration may be carried out systematically for each pixel. Advantages are: (a) Algorithms are better able to handle land surface heterogeneity; (b) Uncertainties can be better specified; (c) Regions where open water cannot be detected for physical reasons (e.g. dense vegetation, urban areas, deserts), can be determined "a priori". Additionally, historic water extent maps are produced, essentially as a by-product of the model calibration, which may serve as a reference for distinguishing between floods and the normal seasonal water extent.

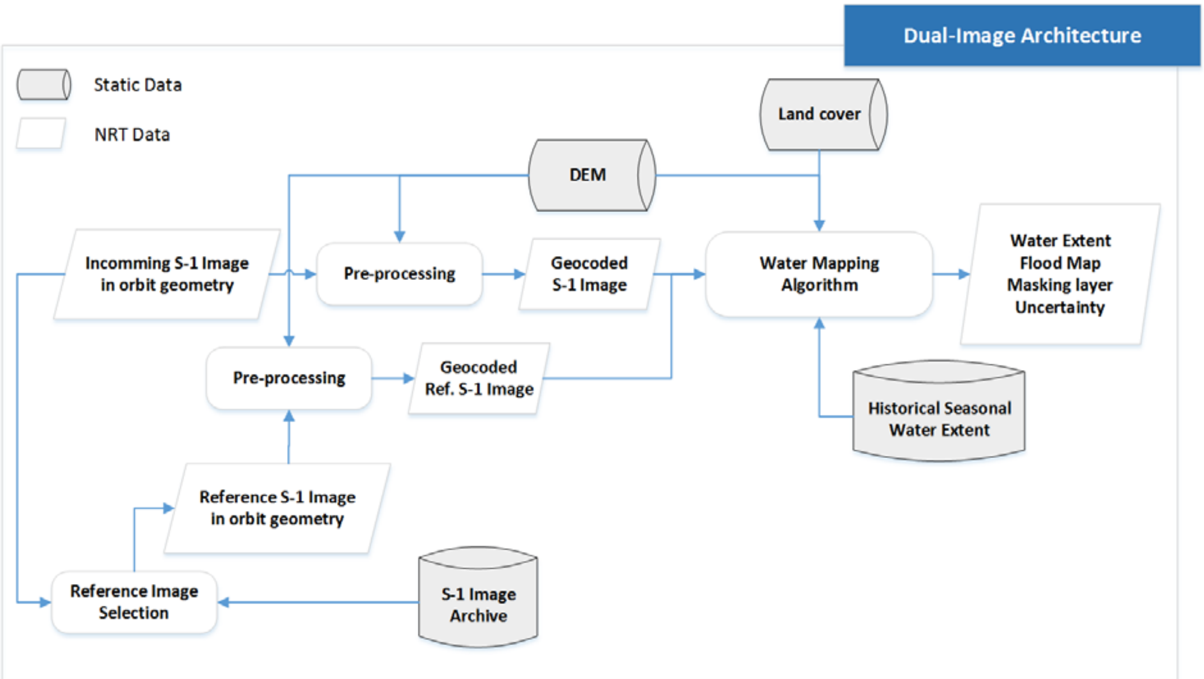

Figure 11: Dual-image processing architecture for global flood monitoring using S-1 SAR image data, based on change detection approaches using individual historic S-1 images as a reference.

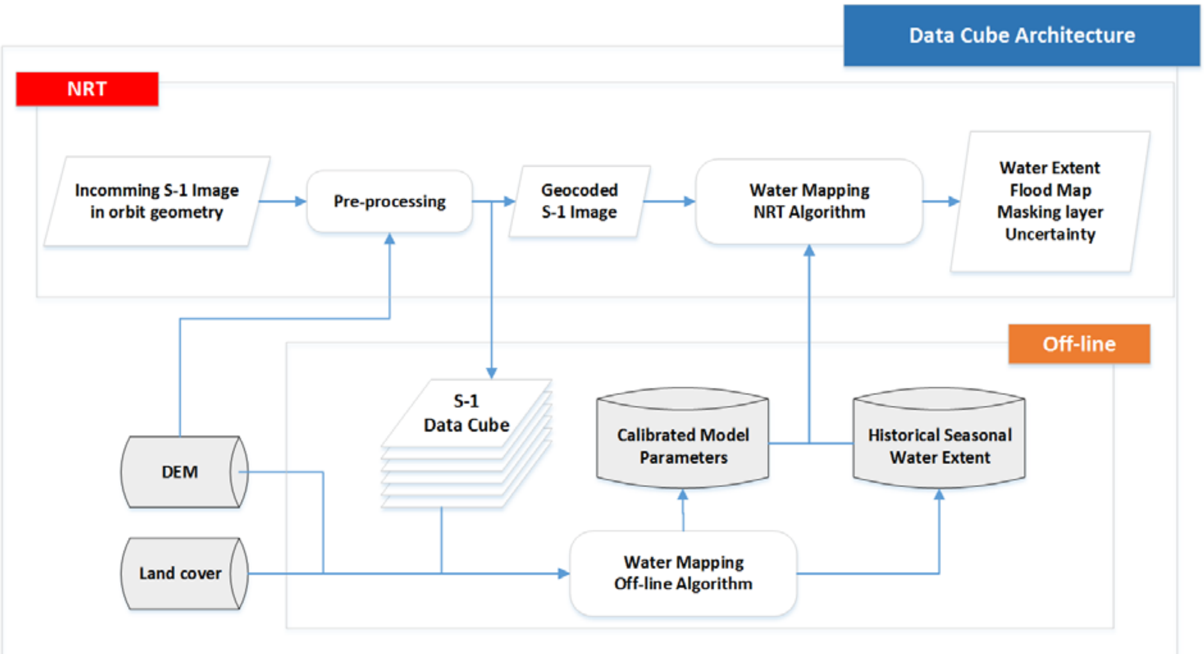

Figure 12: Data cube processing architecture for global flood monitoring using S-1 SAR image data, consisting of an NRT data flow and off-line components.

4.5 Data processing methods using Sentinel-1 SAR imagery

In the following section, the key technical issues in the derivation of flood maps, starting from the incoming Sentinel-1 Level 1 data, are briefly addressed. A more detailed discussion of the scientific algorithms used for the flood mapping, and their principal limitations, is provided in Chapter 5.

4.5.1 SAR pre-processing methods

As mentioned earlier, the Sentinel-1 (S-1) Level 1 Ground Range Detected (GRD) product consists of focused S-1 SAR data that have been detected, multi-looked, and projected to ground range using an Earth ellipsoid model. Only backscatter amplitude is preserved, with the phase information lost. The resulting product has approximately square pixels and spacing, with reduced speckle (at the cost of spatial resolution). Despite all processing steps involved from Level 0 to Level 1, there is still further pre-processing that needs to be applied, before Level 2 data production. This pre-processing includes data calibration, radiometric correction (e.g. thermal noise removal), image-edge noise removal, orbit corrections using external orbit files (if not already applied), georeferencing and terrain correction using an external digital elevation model, data encoding and compression, re-projection, resampling and tiling. Implementation of quality control procedures are also needed to ensure data consistency and correctness.

Figure 13 shows an example of a pre-processing workflow, using ESA's Sentinel Application Platform (SNAP) software for calibration and geocoding. Processing high-resolution S-1 images requires a large amount of system memory (RAM) for calculations, and storage of intermediate results. The required size of RAM and storage depends on input data file size and geographic location (latitude). The pre-processing chain should be optimized to use the memory effectively for numeric calculations. Memory management and input-output volume controlling becomes very critical in parallel processing, and requires careful configuration and set-up, according to the specifications of the computer cluster.

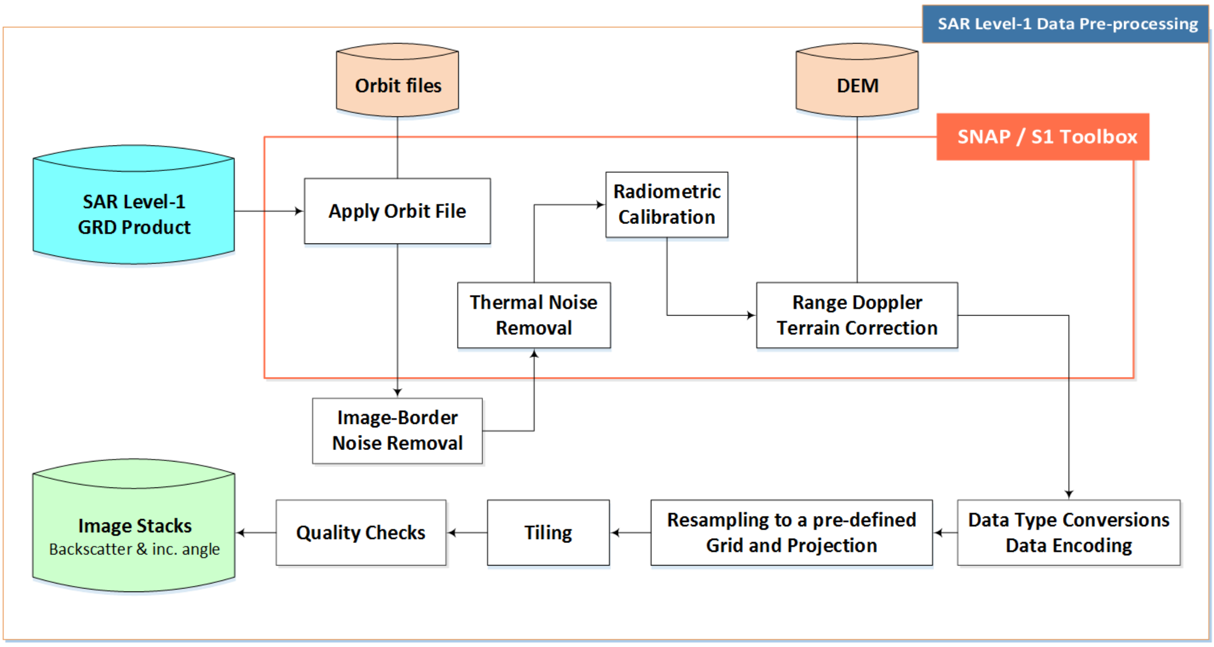

Figure 13: Typical pre-processing steps required for the Sentinel-1 Level-1 GRD data product.

4.5.2 Cartographic projection

High-resolution S-1 SAR image data must be resampled to regular grids defined by map projections. Working with re-projected and terrain-corrected images is the most practical approach, and enables time series analysis and change detection procedures. However, if map projections are not well chosen, re-projection of data with global coverage can lead to significant geometric distortions, and data over-sampling. The additional data introduced by projecting satellite images to a regular raster grid becomes critical for processing facilities in terms of storage and processing capacities, in particular when working with data cubes that span the entire time series of Sentinel-1 data. Therefore, use of a well-defined spatial grid and tiling system, with an efficient cartographic projection, is highly important for S-1 data processing. One such global grid and tiling system, illustrated in Figure 14, is the open source "Equi7 Grid", proposed by Bauer-Marschallinger et al. (2014).

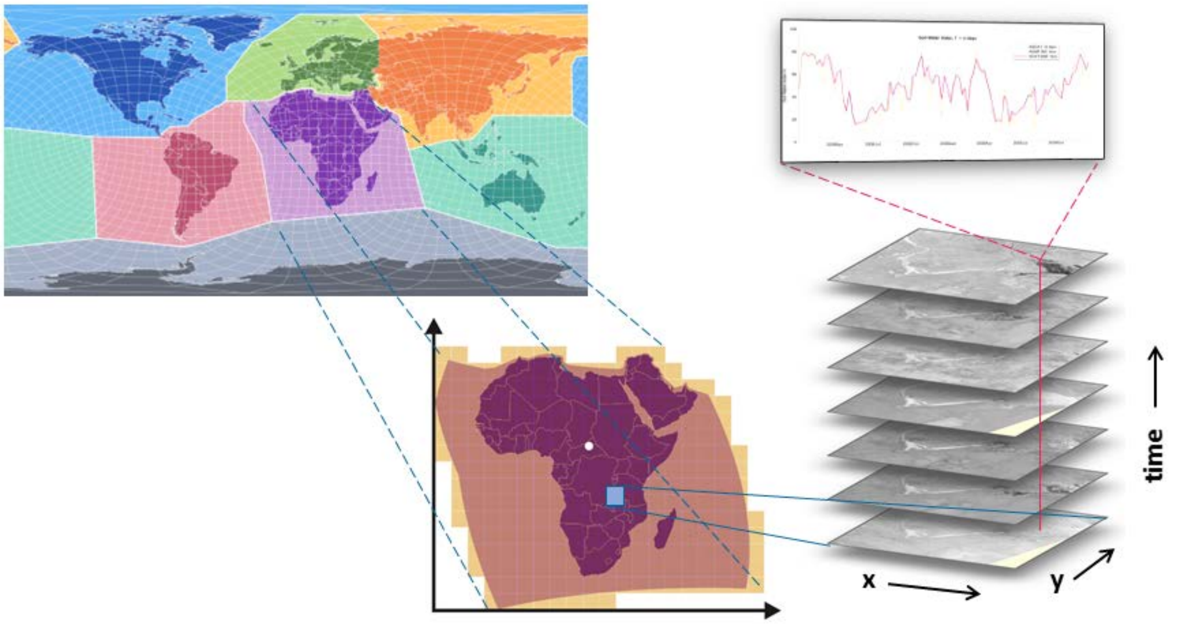

Figure 14: A global grid and tiling system for building Sentinel-1 data cubes. From: Bauer-Marschallinger et al., 2014. See: https://github.com/TUW-GEO/Equi7Grid

4.5.3 Sentinel-1 SAR water mapping algorithm

To set up a fully automated operational water mapping system on a global scale, a mature scientific algorithm must be available. The algorithm must furthermore be suited to perform intensive computations and to extract the desired information from the Sentinel-1 Level 1 data in near real-time. In principle, microwave backscatter signals from smooth open water are low, due to the "specular" (i.e. mirror-like) reflection from the water surface, especially at far range incidence angles. This characteristic is used to detect water on ground surfaces, with a good level of accuracy but under limited conditions. The incidence angle dependency of backscatter makes it difficult to use a unique threshold for classifying water pixels. In addition, many environmental factors such as rain, wind, turbulence or emergent vegetation, may roughen the water surface, causing significant increases in radar backscatter, which makes water mapping very challenging. Furthermore, backscatter from smooth and dry soil surfaces, or some types of vegetation, could be very low, emulating the backscatter level of surface water. The influence of the above-mentioned issues varies, depending on the spatial resolution and the frequency of the microwaves. Existing SAR-based techniques for water mapping are mainly based on thresholding of single or multi-temporal backscatter images. However, the retrieval functions differ in the parametrization and the statistical methods that are used for setting the thresholds, refinement and post processing. More details on the state-of-the-art scientific algorithms for water mapping are provided in Chapter 5.

4.5.4 Identification of historical permanent, seasonal water extent

Information on the historical permanent water extent is needed, to distinguish flood events from permanent water bodies and seasonal water fluctuations, such as those due to pronounced dry-wet seasons, water management or agricultural practices (see Figure 15). This reference or baseline information is best obtained from historical Sentinel-1 time series, in order to ensure high consistency with the NRT data product. The use of other global datasets, such as those derived from optical satellite imagery - e.g. the Global Surface Water Explorer[23], developed by Pekel et al. (2016) - would be problematic for this purpose, given that surface water areas seen by optical sensors are not identical to those

[23] https://global-surface-water.appspot.com/

seen by Sentinel-1 SAR. This also applies to datasets derived from other SAR sensors, operating at different wavelengths, polarisations or spatial resolutions from Sentinel-1.

The proposed near real-time flood-mapping algorithm could also benefit from historical information on water extent, provided at an annual or seasonal scale. Prior information on permanent water, and frequent and intermittent floodplains, helps to reduce misclassification by optimizing the water mapping algorithm, for example by using dynamic thresholds or masking areas not prone to flooding. Such information, combined also with hydrological modelling, can be used to refine the final flood monitoring products, for example by applying targeted morphological operations and flood region-growing methods.

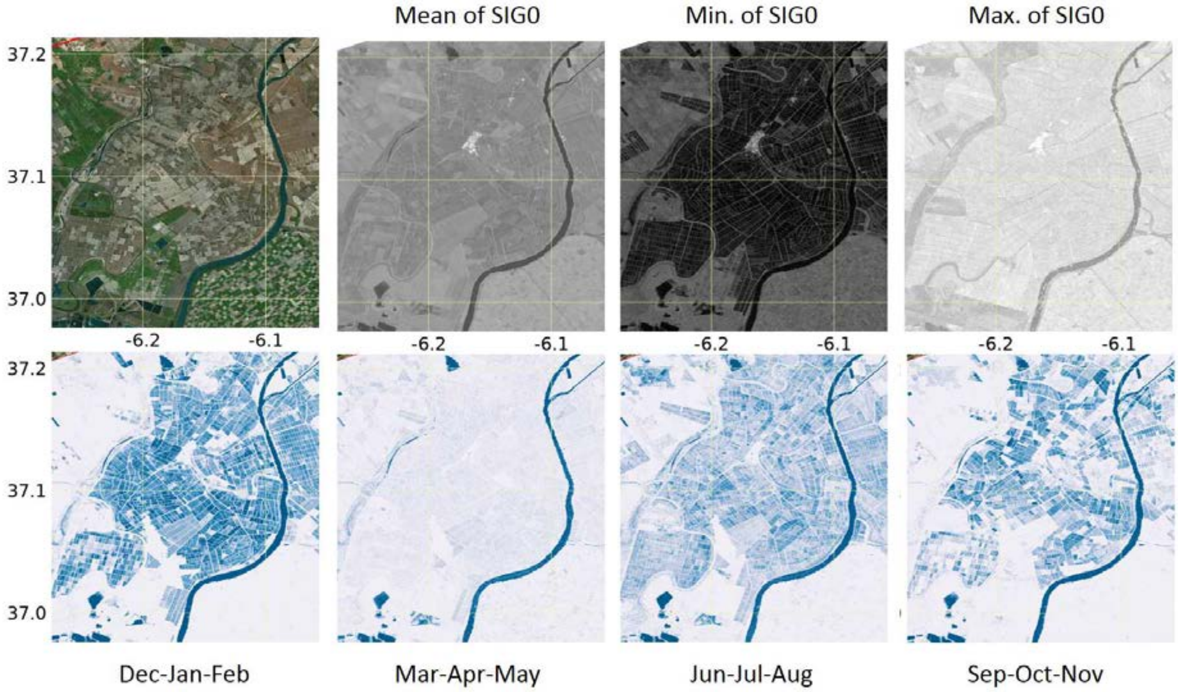

Figure 15: Satellite-based water mapping of a rice-growing region near Seville, Spain. Top row: Optical satellite image of the area (left), and backscatter statistics (mean, minimum, and maximum) derived from the Sentinel-1 data cube. Bottom row: Seasonal water fluctuations measured using Sentinel-1.

5 Scientific challenges

Spaceborne Synthetic Aperture Radar (SAR) imaging systems provide a powerful tool for flood monitoring, due to their all-weather, day-and-night capability, the high spatial resolution of the new generation of instruments, and the short revisit time of current SAR satellite constellations. The systematic, fully automated, large-scale mapping of flooded areas nonetheless, represents a challenging problem. In the first part of this Chapter, the scientific challenges that must be addressed when using microwave remote sensing imagery for the rapid, systematic, and automated production and dissemination of accurate flood maps, are reviewed. The potential effects on radar data of specific surface features, and the difficulties that may arise when classifying flooded and non-flooded terrain - particularly considering the technical characteristics of the Copernicus Sentinel-1 (S-1) satellites - are also discussed. The second part of the Chapter provides an overview of state-of-the-art strategies and methods for the systematic, automated delineation of flooded areas based on SAR amplitude data, at large scale. Methods for identifying areas where flood mapping based on S-1 amplitude data is usually not possible, and for assessing the uncertainties of SAR-based flood mapping, are also reviewed.

5.1 Radar response of flooded land - general principles and challenges

As mentioned in Chapter 4, the main physical mechanism behind the high contrast in radar imagery between flooded and non-flooded terrain, is the "specular" (mirror-like) reflection of SAR signals from standing water, leading to very low backscattered "amplitude". This property renders the mapping of open, calm water using SAR observations, rather straightforward, and many processing algorithms have been proposed for accurately mapping water-bodies at large scale, in a fully automated way. However, the radar "signatures" of the Earth's surface can become ambiguous due to several factors (such as the target structure and geometry, presence and type of vegetation, meteorological conditions at time of acquisition) which are often not well known. For example, SAR-based flood mapping of vegetated and urban areas remains a challenging problem. Other difficulties may be related to surface topography (e.g. false alarms due to shadows), particular surface types (e.g. wet snow, very dry soils), and atmospheric conditions (e.g. high winds, or - especially for X-band SAR data - heavy precipitation). In this section, we briefly review these challenging scenarios, and explain the scattering mechanisms affecting the radar response.

The capability to detect and monitor floods using microwave sensors, arises from the very high sensitivity of microwaves to the presence of water in natural media. Liquid water is a highly dissipative medium with large values of dielectric constant (also called relative permittivity). Water thus modifies the dielectric (or electrically insulating) properties of the Earth's surface, as well as its geometric characteristics - as seen for example when comparing surface roughness in the presence of standing water with that of non-flooded soil. In contrast with the diffuse (or scattered) reflection from rough and dry soil, the predominant specular (or mirror-like) reflection from a smooth water surface (having high permittivity) results in a high contrast in radar imagery between flooded and non-flooded areas. Although a smooth water surface covering the terrain reflects incident radar signals mainly in a specular fashion, in practice there is always a mixture of specular and diffuse reflection, as even standing water is not perfectly smooth. The specular and diffuse reflection properties that are exhibited respectively by flat and rough surfaces, are illustrated in Figure 16.

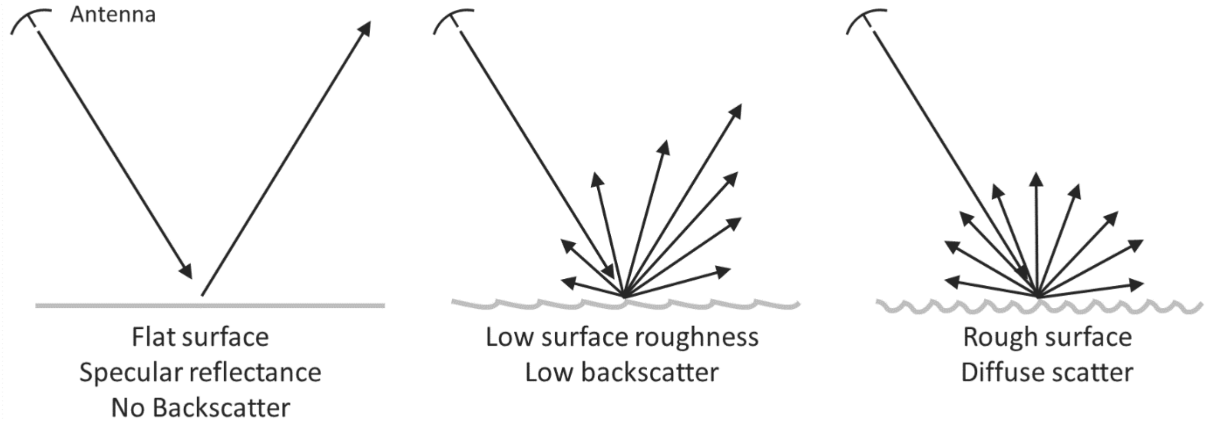

Figure 16: Illustration of the microwave backscattering mechanism for flat and rough surfaces.

It is worth adding that, as the SAR incidence angle increases, scattering (i.e. diffuse reflection) decreases more sharply from smooth than from rough surfaces. As a result, the contrast between flooded areas and rough bare soil, for example, is generally higher for larger incidence angles, whereas, when observed at steep angles, water-bodies appear brighter (and thus less contrasted with respect to the surrounding terrain) in SAR images. It should also be borne in mind that, at constant surface roughness, SAR backscatter increases with soil moisture, and so the contrast between flooded and non-flooded terrain is generally higher for moist soils. (The latter point is because volumetric soil moisture content increases soil permittivity, implying an increased contrast between the electromagnetic impedances of air and terrain).

5.1.1 Influence of wind on SAR-based water mapping

In the presence of strong wind that roughens the water surface, the contrast between flooded and non-flooded soil in SAR images, can be significantly reduced. This is an ongoing problem for SAR-based flood mapping, since significant investigations of increased backscatter from wind-roughened water surfaces have mainly focused on the open ocean. In flooded land, many different and unknown situations - such as different water depths, or obstacles obstructing wind flow - can arise, where it is difficult to measure the effect on the SAR signal, even if meteorological conditions are accurately known. In extreme cases (very high winds), the contrast between flooded and dry surfaces may even disappear completely. For flood monitoring using SAR, options to account for wind effects include collecting accurate data on wind speed and direction for the area of interest, or using SAR-based monitoring of permanent water-bodies to detect wind-related anomalies. When potentially affected areas are identified, attempts can be made to refine the classification, for example using topography data or flood inundation models by data assimilation.

5.1.2 Influence of vegetation on SAR-based water mapping

Due to the weak (or totally absent) backscatter contrast between flooded and non-flooded vegetation, the detection of water-bodies under vegetated canopies is challenging. Here, the main mechanism is related to double-bounce, due to multiple reflection from the horizontal surface and vertical structures (e.g. tree trunks, crop stems), which complements (or may even exceed) the contributions from single scattering from vegetation, attenuated scattering from the surface, and multiple interactions between the various scattering elements. The double bounce mechanism can be highly enhanced by the presence of water under the vegetation, since specular reflection increases in flooded conditions, which can make the backscatter for flooded vegetated areas higher than for non-flooded conditions.

However, backscatter contrast between flooded and non-flooded vegetation strongly depends on the characteristics of the vegetation and the observing system. A major factor is that the radar signal can penetrate into the vegetation, as in the case of low vegetation biomass, low frequency, small incidence angle, or proper polarization. At higher microwave frequency (i.e. C-band of Sentinel-1), flooded vegetation can be detected only for relatively transparent agricultural crops with small elements and low Leaf Area Index, or (occasionally) leafless deciduous forests. Moreover, one can exploit the fact that for volume scattering, “cross-polarized” SAR is more sensitive than “co-polarized” SAR, while for double-bounce scattering it is vice versa. In fact, considering the two polarisations of Sentinel-1 (see Section 4.1), flood-induced double-bounce scattering in vegetated area may become detectable (Chini et al., 2016).

5.1.3 Influence of topography on SAR-based water mapping

The terms foreshortening, layover, and shadowing refer to the effects of topography on the geometry (i.e. image deformation) and radiometry (i.e. change of backscattered values) of SAR data. In the context of flood mapping, the main effects are false alarms due to the presence of shadow. In fact, low backscatter from slopes inclined away from the incident SAR signal, can be confused with smooth and dark water. Bright pixels on the slope facing the SAR signal do not produce such errors. These effects can be predicted, and false alarms avoided, by using an accurate DEM for image orthorectification, computing the local incidence angle for each pixel, and mapping areas in shadow. An alternative is to apply change detection, using a reference image from the same orbit. If the data are acquired from the same orbit, the backscatter response from shadow areas will not change between image acquisitions, thereby enabling the distinction between low responses due to shadow and those due to flooding. To avoid false alarms, shadow areas thus need to be recognized and masked, prior to water mapping.

5.1.4 Influence of urban areas on SAR-based water mapping

In general, SAR imaging of urban areas is very complex, especially when radar resolution is not very high and many scattering components are included in the same resolution cell. Therefore, it is currently very difficult to delineate floods in urban areas. Single buildings produce very high backscatter, due to the double bounce arising from the combined reflection of the horizontal ground and vertical walls facing the radar (similarly to the case of trees). The very bright pixels - in some cases almost saturating the image - are those at the side of the building “footprint” closest to the radar. The building causes additional scattering components. For instance, the layover of the roof return and the ground, which is located at the nearest range with respect to the building footprint, can also produce a high signal partially superimposed on that due to the double bounce. Some studies have exploited the "dihedral corner reflection" of building walls to assist flood detection in urban areas. The complexity of the problem - which includes mutual shadowing between buildings in dense urban settlements, higher-order bounces (triple bounces can be very likely), specular reflection from gable roofs, and scattering from other elements like windows - renders SAR-based flood mapping in urban areas very unreliable. Some studies have shown that flooded areas within urban settlements can be detected due to the fact that such settlements comprise very steady targets with high “interferometric coherence” (see Section 4.1), even for large temporal baselines. The presence of flooding may thus imply a significant decrease of coherence, which can be exploited for flood mapping in urban areas. Recent studies have shown that in the vicinity of double-bounce features such as buildings, the drop in coherence between consecutive pairs of images is typically due to the presence of floodwater at the acquisition time of one of the two images (Chini et al., 2018).

5.1.5 Influence of snow, ice and other surfaces on SAR-based water mapping

Smooth surfaces such as asphalt roads and flat rock exhibit low backscatter, which may lead to confusion with flooded areas. Another potential false alarm that can arise is due to attenuation of the radar signal by atmospheric conditions, such as heavy precipitation (which can easily occur during a flood event). At higher microwave frequencies, there is higher absorption and backscattering of the SAR signal due to water drops. Therefore, in SAR images collected at higher microwave frequency (e.g. X-band), high signal attenuation from heavy rain can produce very low backscatter, and possible confusion with flooding. At lower microwave frequencies (e.g. C-band and especially L-band) this problem is not severe, but can occur occasionally. Another potential false alarm is attenuation of the SAR signal by wet snow. Ice is not particularly dissipative, so when the snowpack is dry it is quite transparent in the microwave range. However when snow is wet - similar to the case of rain - it becomes a very absorbing material, producing very low backscatter, and possible confusion with flooding. In this case, ancillary information is required to avoid a significant number of false alarms. For example, information on terrain slope and local incidence angles can be used to mask areas where very low backscatter is unlikely to indicate flooding. Alternatively, snow-related simulations of large-scale land surface models can be used to reduce misclassification. Finally, in some arid regions, sand surfaces are characterized as water-like areas. SAR backscatter over sand is affected mainly by the size of the grain, and its distribution and moisture. Times series of backscatter measurements can be used to identify such dry areas with permanent low backscatter.

5.2 Methods of flood detection using Sentinel-1 SAR data

Advanced SAR processors and ancillary data are now available that enable the systematic and reliable monitoring of calm and open water-bodies, at a large scale. In the context of the proposed automated, global, Sentinel-1 (S-1) flood monitoring product for CEMS, however, special attention must be paid to the situations where reliable mapping of water-bodies remains difficult, if not impossible. As discussed in the previous section, in order to address some of these challenging situations, a limited number of advanced SAR processing algorithms are currently available. In many cases, however, the methods are not yet at the level of maturity and readiness to be used within CEMS. Furthermore, some of the more advanced approaches for flood mapping in such situations, either would require SAR features (e.g. full polarimetry, low radar frequencies, very high spatial resolution) which are not offered by S-1, or would render the data processing too demanding (e.g. use of interferometric coherence).

For all of these reasons, the proposed global S-1 flood monitoring product shall primarily focus on the mapping of floodwater in open areas, such as bare soils or low-canopy vegetation. In order to improve the reliability and usefulness of the flood monitoring product, it is important to identify and exclude areas where the flood mapping is not possible.

The remainder of this section reviews the state-of-the-art, mainstream algorithms (grouped according to the three processing architectures described in Section 4.4), which are routinely used for SAR-based flood mapping at a large scale. Although the focus is on the most responsive land use classes, accurate flood mapping using SAR data nonetheless requires an adequate strategy for image processing, coupled with the use of relevant ancillary data. The aim is to present the different options that make best use of the possibilities offered by the images systematically acquired by the S-1 mission, which are characterized by high spatial resolution, high sampling rate, and a wide spatial and temporal coverage. Finally, in addition to describing the various SAR image analysis approaches, details are also presented on methods (already touched on elsewhere in this report) for deriving an exclusion mask to improve classification results, and for characterising the uncertainty of the flood classification.

5.2.1 Flood mapping based on single-image processing architecture

Recently, a large variety of methods have been introduced for mapping water on bare soils and sparsely vegetated terrain, using SAR backscatter intensity (where backscatter intensity is computed as the square of backscatter amplitude). When favourable conditions prevail - in other words, where water-like response areas are limited in size and can be easily identified using external data sets - a single SAR image acquired during a flood can be sufficient to detect water-bodies, while limiting classification errors. In this configuration a digital elevation model of adequate spatial resolution and accuracy is required to estimate topographic effects on SAR geometry and radiometry, while other external databases are required to exclude at least some of the “water-like” response areas (to minimize false alarms).

This first group of algorithms are based on identifying those image pixels with low backscatter values in a single SAR image. Considering just one image reduces processing time, with no need for another satellite acquisition. This can be advantageous, especially when dealing with very high resolution (VHR) SAR satellites that are not routinely operating in a pre-programmed, conflict-free mode. In such cases, a reference image acquired under similar conditions is often not available.

When using only a single SAR image, with the flood mapping reduced to a classification between “water” and “non-water”, the fastest and most frequently applied technique is “histogram thresholding”. The threshold is generally selected as the maximum backscatter value associated with open water, and all pixels having an intensity value lower than the fixed threshold are classified as "water". Different approaches are used to automatically derive one threshold for the entire image, or to determine local thresholds for different image sub-regions. Parametric algorithms are used to automatically extract the best threshold value, although their efficiency is known to be strongly hampered when the respective fractions of the image occupied by the different classes are strongly unbalanced, or when the distribution functions significantly overlap due to the presence of backscatter speckle (granular noise).

To overcome these difficulties, "tiling" approaches with fixed or variable tile-sizes, are typically applied (e.g. Martinis and Twele, 2010). In this kind of classification, uncertainty is higher in the portion of the histogram where both distribution classes overlap. Indeed, a single-image thresholding algorithm inevitably produces a binary map with a number of misclassified pixels that depends on the extent of the overlapping distributions, as well as the presence of water look-alikes. Several approaches have been proposed to deal with these issues: (a) Combining the Otsu thresholding method on tails of fixed size with region-growing (Pulvirenti et al., 2014); (b) Using thresholding, tailing and fuzzy logic in the post-processing (Twele et al., 2016); (c) Integrating thresholding, change detection, and region-growing (Giustarini et al., 2012); (d) Hierarchical tiling and region-growing (Chini et al., 2017). Statistical approaches have also been directly applied to solve the two-class problem in the image difference, using an expectation-maximization algorithm with generalized Gaussian distributions, or a support vector machine and a similarity measure.

To improve the reliability of the flood classification, ancillary data are used to at least partially exclude non-water areas with low backscatter values (e.g. shadow, smooth tarmac, wet snow). Twele et al. (2016), for example, apply an exclusion mask by thresholding the globally available “Height above Nearest Drainage” index to remove many of the water-look-alikes. They further refine the initially derived flood map by excluding individual pixels with elevation vales significantly above the mean of other water pixels. In order to distinguish between permanent water-bodies and inundated areas, reference water masks are needed (e.g. SRTM Water-body data, Land Cover CCI permanent water-bodies layer, MODIS land-water mask).

5.2.2 Flood mapping based on dual-image processing architecture

To more fully exploit the characteristics of Sentinel 1 A/B it is useful to consider at least a pair of SAR images, i.e. the image acquired during the event and an adequate reference image (i.e. an image acquired in non-flooded conditions with the same acquisition parameters). Change detection tends to improve not only the classification accuracy via an arguably more robust identification of non-water areas with a consistently low backscatter over time (i.e. surface water-like response areas), but also helps to distinguish seasonal water-bodies from extraordinary floodwater.

Change detection approaches are used for the efficient removal of many of the “false positives” generated by single-image processing, as well as for distinguishing between permanent water and temporally inundated areas. Change detection takes advantage of the particularly short repeat cycle of Sentinel-1 A/B and its routine pre-programmed operational mode, enabling the frequent acquisition of images from the same orbit with identical look angles. Changes can be thus be directly ascribed to those occurring on the ground, rather to variations of the incidence angle. Using a pair of SAR images extends the flood mapping problem to a classification between change and non-change, which can complement the classification derived from a single image. Following the computation of the difference image (i.e. by subtracting grey-values in the flooded SAR image from those in the reference image), histogram thresholding is applied as a first step to generate a binary classification. The previously described thresholding approaches (often combined with tiling methods) can be used to solve the two-class problem in the difference image. These methods assume that one type of change (i.e. decreased backscatter due to specular reflection over water-bodies) dominates all others. For example, O'Grady et al. (2011) showed that misclassification of non-flooded pixels due to low backscatter over dry regions can be effectively reduced with the use of dual-image processing approaches. Martinis et al. (2018) use statistical information derived from a time-series of backscatter measurements, to compute an exclusion layer consisting of non-water areas with permanent low backscatter over time.

Change detection requires selection of an adequate reference image, which should satisfy a series of criteria. It should have the same viewing geometry as the image acquired during the flood, while also characterising the typical backscatter signature of the area of interest. Selection or computation of an adequate reference image leads to SAR-based change detection that reduces many of the false alerts generated by single-image processing and only partially removed using ancillary data sets. The following methods can be used to select or compute a suitable reference image:

- Picking the most adequate reference image from a sample of images acquired from the same orbit, for example by applying histogram analyses (e.g. Hostache et al., 2012; Li et al., 2018).
- Selection of the reference image, by default, as that closest in time and from the same orbit, and use of time-series analyses to evaluate its representativeness and presence of anomalies a priori.
- Synthetical generation of a reference image for each orbit, by computing the median or mean pixel values from a stack of images.

Use of a synthetically generated baseline map, ideally created for each orbit separately, or after normalizing all measurements to a common incidence angle a priori, for example using the harmonic model introduced by Schlaffer et al. (2015).

5.2.3 Flood mapping based on time-series analysis architecture

Ultimately, an approach taking advantage of a time-series of backscatter recordings derived from hundreds of SAR images acquired over a given area, provides all of the information required to understand fully a floodplain's backscatter response to changing water levels, delineate its floodwaters and contextualize the observed event (i.e. allow estimation of the magnitude of the event).

The acquisition mode of Sentinel-1 A/B ensures a consistent high-frequency data coverage and data archive. This SAR data record makes it possible to understand and model the seasonality of the backscattering that characterizes the climatology of soil moisture and the seasonal behaviour of land cover. The most straightforward way to extract water-bodies from a single image is to apply a (local or global) threshold to each pixel's backscatter value. Using the time-series approach, the thresholds are determined not using the statistics from a single image or a pair of images, but rather those from many SAR recordings over time. Sabel et al. (2015) applied a radiometric thresholding to a time-series of backscatter measurements normalized to a local incident angle of 30 degrees, in order to classify water-bodies for all images. Schlaffer et al. (2015) used harmonic analyses of a time-series of over 500 SAR scenes to account for and model the seasonality of backscatter under non-flooded conditions. In that study, pixels that were inundated during a flood event showed strong deviations from the seasonal trend inferred from the harmonic model. An automatic threshold optimization algorithm is applied on the residuals obtained for a single image, to produce a water-bodies map.

Time-series analyses of SAR data archives are also used to improve the characterization of permanent water-bodies (Santoro et al., 2015). A high density of observations enables generation of metrics of the SAR backscatter's temporal variability. Permanent water-bodies are typically characterized by a high standard deviation and low minimum SAR backscatter, with respect to other land cover types. Thresholding these two values thus enables a quite accurate detection of permanent water-bodies. Such an approach can be used for example to generate a monthly reference water mask.

The multi-temporal information of Sentinel-1 backscatter further helps the reliable identification of non-water areas with a permanent low backscatter over time, which could be mistaken as flooded areas. Martinis et al. (2018) used such an approach to compute offline an exclusion layer, which improves the classification results from single-image processing. Westerhoff et al. (2013) derived probability distributions of water and non-water backscatter from multi-temporal SAR imagery. Using these histograms, the probability of a single measurement belonging to either population is derived, to generate flood probability maps that can be converted into binary flood extent maps.

5.2.4 Creating an exclusion mask to improve SAR-based flood mapping results

To improve the reliability, usefulness and acceptability of SAR-based flood and water extent products for open and calm water surfaces, it is essential to apply an exclusion layer that masks all areas where measurements of radar backscatter do not carry information on the presence of surface water, with sufficiently high confidence. These include all areas that are not open and calm water, and where (for different reasons) the appearance of water on the ground does not significantly impact the radar backscatter. Such cases are mainly related to urban areas, dense vegetation, permanent low backscattering areas (e.g. flat impervious areas, sand surfaces), and effects related to topography.

The first category of methods for creating an appropriate exclusion mask, takes advantage of SAR theory in order to predict the response from different targets in the presence of surface water. This essentially entails using global-scale land cover products to mask areas expected to be non-responsive (e.g. urban areas, terrain with high vegetation canopies, dry sand, etc.). The second category of methods is based on analysing radar backscatter time-series, applied to a stack of SAR images acquired from the same orbit, or from different orbits but with all measurements normalized to a common incidence angle. Such techniques are commonly used to generate exclusion layers for SAR-derived soil moisture products. One method is to compute a dry (e.g. 10% percentile of radar backscatter over time) and wet (e.g. 90% percentile of radar backscatter over time) reference layer, and to threshold the difference of the two layers. Here, the rationale is that areas not responsive to SAR are characterized by a low temporal variability of SAR backscatter.

An alternative method is to apply a threshold to the correlation between individual pixel backscatter and regional backscatter (i.e. mean backscatter computed over a moving window), assuming that the latter is partly governed by soil moisture and vegetation changes. Pixel values that are only weakly correlated to this regional reference are considered non-informative regarding the presence of surface water. A similar approach applies a threshold to the correlation between individual pixel backscatter and soil moisture output from a land surface model. Martinis et al. (2018) introduced an approach for generating a "Sand Exclusion Layer", consisting of thresholding the relative frequency of each pixel with a backscatter lower than a predefined threshold in a time-series.

5.2.5 Characterizing the uncertainties of SAR-based flood mapping results

The information content of flood extent maps can be increased considerably by including the estimated uncertainty of the flood delineation. For example, the assimilation of such data sets into numerical models for improved flood forecasting and monitoring requires a quantification of the uncertainty.

There are different approaches for characterizing the uncertainties of SAR-based flood mapping, in order to generate a layer with the estimated uncertainty of the classifier (typically with values between 0-100), for all areas not covered by the exclusion layer. Computation of a “degree of belief” that a given pixel is flooded, is often the by-product of the classifier used to generate the flood maps. Methodologies have been proposed to estimate “uncertain flood maps”, based on fuzzy set theory (Pulvirenti et al., 2011; Martinis and Twele, 2010), and Bayesian statistics (Schlaffer et al., 2017, Giustarini et al., 2016, D’Addabbo et al., 2016). The most critical step in computing uncertain flood maps is estimation of the necessary function parameters, namely the class membership functions or class-conditional probability density functions (PDFs). For example, fuzzy membership functions have been estimated using the output of electromagnetic scattering models (Pulvirenti et al., 2011). Parameters of conditional PDFs can be estimated from the histograms derived from flood images, under the assumption that calm open water-bodies cause a multi-modal distribution.

The PDFs of flooded and non-flooded areas can also be obtained from time-series of backscatter data. Westerhoff et al. (2013) and Schlaffer et al. (2017) trained their probabilistic flood classifiers using full time-series of SAR data acquisitions. The PDF corresponding to open water-bodies is estimated based on observations over permanent open water-bodies, while the PDF of non-flooded areas can be estimated for each pixel separately, in order to take into account the backscatter signatures that the corresponding land surface would exhibit under non-flooded conditions.

6 Resource requirements

The computing resources required for a worldwide Sentinel-1 flood monitoring product, depend primarily on the volume of Sentinel-1 SAR data, the computationally demanding data processing, and the user requirements regarding product timeliness and availability. While the exact specifications of the flood monitoring product are important, probably the most important drivers of cost are the SAR data pre-processing efforts, the spatial sampling of the flood product, and the need to provide historic data that are consistent (e.g. regarding format, software version) with the near real-time (NRT) data stream. The selected data formats, data latencies (time delays), and system availability also play a role. In this Chapter, the critical resources needed for a fully automated, worldwide Sentinel-1 flood monitoring product, are discussed.

6.1 Sentinel-1 Data Access

A fundamental requirement for the NRT generation of products, is a fast, uninterrupted access to input data. In the present context, the lowest data latencies (i.e. 1-2 hours) would be achieved by receiving the Sentinel-1 data at local ground receiving stations. However, costs for running dedicated reception services at one or more ground receiving stations are probably large, and coverage would be limited to a few regions worldwide. Acceptable data latencies (i.e. 8-12 hours) should also be attainable by downloading the data from the Copernicus Service Data Hub and Collaborative Nodes (see Section 4.3). In this scenario for data access, costs arise due to high bandwidth internet access, to allow downloading several Terabytes per day, and dedicated efforts to ensure a fast, uninterrupted data stream for downloading. These costs might be reduced by accessing Sentinel-1 data at one of the Copernicus Data and Information Access Services (DIAS).

6.2 Storage Capacity

Depending on the product specifications and system set-up, the storage required for data processing and archiving can be substantial. The Sentinel-1 Ground Segment operations generate about 250 terabytes (TB) of Interferometric Wide Swath (IW) mode - Level 1 - Ground Range Detected (GRD) data per year (i.e. about 0.7 TB per day). For NRT processing of incoming Sentinel-1 data, at its most basic level it is sufficient to have storage capacity for processing only one day of Sentinel-1 data (e.g. a few TB to store Levels 1, 2, and intermediate data products). In practice however, such minimalistic requirements are not realistic, as users wish to have access to historical data, which implies keeping at least one copy of the derived flood maps and ancillary internal data - leading to a requirement of a few tens of TB per year. In the event that users want the NRT and historical data to be consistent (in terms of data format or software versions used along the entire processing chain), storage needs to be large enough to hold also the Level 1 data, in order to allow for regular re-analysis efforts (which ensures that algorithmic updates can also be applied to historic data). In such a scenario, the required storage space to store all data (Levels 1, 2 and intermediate data) is about two to four times that of the Level 1 data volume. Hence, the required storage capacity would be about 0.5 to 1 petabytes (PB) per year.

6.3 NRT Data Processing

The NRT data processing system must have the capability to handle all daily acquisitions of Sentinel-1 data. A typical flood mapping processing chain includes pre-processing of SAR scenes (calibration, noise removal, terrain correction, geo-referencing), and water mapping. Computational performance solely for the Sentinel-1 pre-processing (i.e. to generate geometrically and radiometrically corrected images on a 10x10 metres raster-grid), based on evaluations done with ESA's Sentinel-1 Toolbox, is about 5 megabits (Mbit) per second - equivalent to 1.6 seconds per megabyte (MB) - using a high performance computing node (i.e. two processors of Intel Xeon 2.6 GHz each having 8 cores). For example, for pre-processing 0.7 TB of daily Sentinel-1 data, based on a performance factor of 5 Mbit per second, 311 node-hours are required (e.g. 20 nodes running for 16 hours daily). The computation effort required for flood mapping (which varies depending on the selected algorithm) is added to this estimate. Typically, it will be (much) less than that needed for the pre-processing. Therefore, a conservative estimate of the computing resources needed to run the NRT service is 30-40 computing nodes. (A certain overhead is needed to handle fluctuations in the incoming Sentinel-1 data stream).

6.4 Offline data processing

In order either to allow a regular re-processing of the historic flood maps, or to support a Data Cube processing architecture (see Section 4.4), an off-line high performance computing (HPC) environment is needed in parallel to the NRT system. Data processing in such an environment is not as time-critical as in NRT, in that the requirements for hardware availability are not stringent. However, sufficient HPC resources are required to perform analysis over several tens to hundreds of TB of historical Sentinel-1 data. Hence, the HPC facilities must be large enough to be capable of providing in the order of millions of core hours per month in order to complete re-processing efforts in reasonable time periods (i.e. a few weeks to months per re-analysis cycle). For example, when using “compute nodes” with 2 processors, each with 8 cores, then 87 compute nodes are needed to provide 1 million core hours per month. In practice, re-processing jobs should be run on 200-500 compute nodes, so the HPC system must consist of several hundred to a few thousand compute nodes to provide sufficient resources when needed. Considering these data processing requirements, the Copernicus Data and Information Access Services (DIAS) offer a European capacity that could meet these high processing demands.

6.5 Bandwidth for data transfer

An important characteristic of any Sentinel-1 data processing environment - whether on-line or off-line - is the bandwidth between the processing components and the storage. High bandwidth is needed, as data transfer rate must be high in order to parallelize the computations of the Sentinel-1 data. In view of the Sentinel-1 data volume acquired per day, the network bandwidth capacity between the computation units and storage must be several tens of gigabits (Gbits) per second, in order to generate flood maps seamlessly, with no input / output restriction. Similarly, a high bandwidth is crucial when re-processing historical Sentinel-1 data.

6.6 Metadatabase

Metadata contain information for understanding and interpreting data, which is needed for effective data processing. For any system capable of the automated processing of global Sentinel-1 data, the availability of an active metadatabase, suitable for steering processing efforts, is a prerequisite. Throughout the data processing chain, different kinds of information must be gathered to set up configurations for accessing and processing various data sources. A fast and reliable querying of both input and output data products, should be available, based on region of interest, acquisition time, and satellite data specifications (acquisition mode, polarization, orbit, etc.). The query results are used to make decisions, select the right model parameters, and read relevant information from auxiliary data sources (e.g. land cover, historical flood maps, advisory flags, and masking layers). The metadatabase should be automatically updated as soon as a data product is generated, in order to keep track of processed and non-processed data-files in near real-time.

6.7 System redundancy and product availability

Timely and reliable delivery of data products is an essential aspect of the NRT system. The system should be reliable enough to provide a non-stop (24 hours per day, seven days a week) service operation, with a high product availability. Therefore, a monitoring system must be in place, to automatically detect failures and to recover data processing instances, using redundant system components, including the following:

- Access node redundancy: In the event of failing to access input data or auxiliary data, Sentinel-1 data should be accessed from alternative data hubs or cloud platforms.
- NRT hardware redundancy: In the event of any failure of the storage or computing nodes needed for the NRT processor, a redundant NRT processor should take over
- Software redundancy: The processing chain should be implemented in redundant environments ready for running identical code.

7 Links and synergies with other systems

This chapter firstly presents a brief comparison of the proposed automated, global, satellite-based flood monitoring product with three existing systems for carrying out satellite-based flood monitoring. In doing so, the aim is to evaluate the relevance of the proposed system, not just with regard to fulfilling the user requirements outline in chapter 2, but also in relation to two important questions: (a) Has this work already been addressed by other initiatives, and does it interfere with commercial interests? (b) What does this new product add to comparable existing systems? The second part of the chapter explores how the proposed flood monitoring product might usefully contribute to selected existing flood-related emergency management systems and initiatives.

7.1 Comparison with existing systems

In this section, the proposed flood monitoring product that has been described in this report, is compared with three existing satellite-based systems, specifically in relation to the following main characteristics of the proposed product:

- Output: observed flood event; observed water extent; reference water mask; exclusion mask.
- Spatial resolution of 20 metres, average repetition rate of 1-3 days (Europe) and 3-14 days (globally), and product timeliness of 8-12 hours (after reception of satellite data).
- Fully operational system, and providing continuous global monitoring.

While a few companies worldwide provide flood monitoring products on-demand for specific regions, to our knowledge there is only one existing fully operational system that provides continuous satellite-based global flood monitoring. The "FloodScan" system, run by the US commercial company Atmospheric and Environmental Research (AER), provides near real-time flood monitoring using microwave (radar) satellite image data, for Africa, South America, and North America, at spatial resolutions up to 90 metres. (AER is part of the Verisk Analytics Family of Companies in the US). FloodScan provides satellite-based daily maps of flooding from 1992 to the present, monitoring all land areas for flooding in clear and cloudy conditions from day and night satellite passes. When the system detects flooding, it derives flooded fraction at lower-resolution microwave data scales (22 km or coarser) and applies physical downscaling to produce flood maps at higher-resolution (90 metres). FloodScan is more likely to detect larger and longer lasting flood events (e.g. large river floods) than smaller and shorter duration events (e.g. flash floods).

On a technical level, Floodscan is based on a "passive" radar (microwave) system, unlike for example the Sentinel-1's state-of-the art Synthetic Aperture Radar (SAR) instrument, which is an "active" system. Without going into details, active radars such as Sentinel-1 offer several advantages over passive radars, for example by providing more control of how ground targets are illuminated.

According to a FloodScan performance document[24] its algorithm works well when flooding covers significant parts of more than one microwave data footprint (22 km for AMSRX, 50 km for SSM/I). This means that floods need to be very large (ideally more than 450 km^2) to be detected with high confidence by FloodScan. In addition, it is limited in its ability to depict floods precisely, due to uncertainties in microwave flooded fraction estimates and the downscaling process. One of the performance document's recommendations to improve FloodScan is the combined use of its passive microwave data with conventional (i.e. active) microwave data, such as that provided by Sentinel-1, as well as with optical satellite remote sensing data. This indicates that the CEMS Sentinel-1 flood monitoring product assessed in this report, could be used to complement and improve FloodScan.

[24] http://product.aer.com/images/FloodScan/afm_algo_perf_doc_v05r00_r00.pdf

In addition to the FloodScan operational system, NASA has developed an experimental global flood monitoring and detection system called Near Real-Time Global Flood Monitoring[25] that uses the optical Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Terra and Aqua satellites, to provide flood extent maps at 250 metres resolution. Water is detected by applying an algorithm, developed at the Dartmouth Flood Observatory, which uses a ratio of MODIS Bands 1 and 2, and a threshold on Band 7 to identify pixels provisionally as water. If a pixel is identified as water over several (2 or more) observations during the product window, it is then definitively marked as water, and output in the MODIS Surface Water (MSW) product. Two or more observations are required because cloud shadow can be spectrally similar to water. In cases where cloud shadow occurs in the same spot in two observations, the product may incorrectly flag such areas as water. A third observation helps further, but also increases product time-delay. At the moment, the service uses the two-observation requirement as a balance between accuracy and timeliness. Finally, the detected water is compared to a reference water layer that shows "normal" water extent, and any pixels found outside the normal water extent are marked as flood, and output in the MFW ("MODIS Flood Water") products. The product is updated every 2-3 days, once cloud-free data are available.

Besides being an experimental product, the use of optical satellite data restricts observations to cloud-free, day-time conditions, and significantly reduces the product timeliness. Furthermore, flooded features smaller than 250 metres are not reliably detected. Interestingly, NASA is also recommending to add radar data into the system to provide more timely products, hence suggesting that a Sentinel-1 based global flood monitoring product could also complement the NASA flood monitoring system.

Finally, some systems provide global flood monitoring using real-time satellite-based precipitation products as input into a hydrologic / hydraulic model. For example, the Global Flood Monitoring System (GFMS)[26] is a NASA-funded experimental system that uses "real-time TRMM Multi-satellite Precipitation Analysis (TMPA) and Global Precipitation Measurement (GPM) Integrated Multi-Satellite Retrievals for GPM (IMERG) precipitation information as input to a quasi-global (50°N - 50°S) hydrological runoff and routing model running on a 1/8th degree latitude/longitude grid". Flood detection / intensity estimates are based on 13 years of retrospective model runs with TMPA input, with flood thresholds derived for each grid location using surface water storage statistics (95th percentile plus parameters related to basin hydrologic characteristics). Streamflow, surface water storage, and inundation variables are calculated at 1km resolution. Clearly, the quality of these systems is strongly limited by the quality in real-time satellite precipitation data and the uncertainties in the hydrologic / hydraulic models. Furthermore, the spatial resolution for inundated areas is 1km^2 or even coarser.

7.2 Synergies with existing systems

From the review in the previous section, it is clear that none of the existing systems provide products on an operational level which are comparable in terms of spatial resolution, timeliness and accuracy, with the proposed flood monitoring product. Moreover, most of the systems recommend adding or combining their products with a SAR-based flood monitoring product. A systematic, automated, global, satellite-based monitoring of floods derived from the Copernicus Sentinel-1 satellite constellation at a spatial resolution of 20 metres, will represent a significant advancement in the monitoring of floods from space, and will demonstrate Europe's leading role in space applications for disaster risk management. Furthermore, it will create synergies and benefits for Copernicus services and activities as well as for other major global mechanisms as briefly outlined below.

When incorporated into the Copernicus Emergency Management Service (CEMS), the flood mapping product would enable users to monitor the evolution of floods in their region of interest. Once alerted by forecasts from CEMS EFAS or GloFAS, emergency response actors

[25] https://floodmap.modaps.eosdis.nasa.gov/
[26] http://flood.umd.edu/

can better determine if and when to activate CEMS Rapid Mapping. This will make activation requests more effective, the selection of areas of interest more relevant, and reduce the number of activations if assessments at higher spatial resolution are not necessary. In addition, the continuous flood monitoring may already be sufficient for large areas (e.g. previous floods in Ireland and Eastern US), reducing the number of flood monitoring maps produced by CEMS Rapid Mapping.

For the CEMS Risk and Recover Mapping, the provided time-series of flood data offer valuable information for analysing emerging vulnerabilities, support the selection of effective measures to strengthen coping capacities, and contribute to recovery planning such as the Post-Disaster Needs Assessment (PDNA) process. Beyond the emergency situation, a time series of flood data are valuable input to the Copernicus Climate Change Service (C3S). This relates not only to the improvement of climate models, but also to investigations into the attribution of extreme weather events and its potential contribution to assessing loss and damage associated with climate change impacts.

The Support to External Action Service SEA (one of the three Copernicus Security Services) would greatly benefit from continuously updated flood mapping for a series of portfolio products, such as situational awareness in conflict areas, trafficability of roads, or refugee/ internally displaced person (IDP) camp monitoring.

Related to the Copernicus realm, the JRC's Global Surface Water Explorer (GSWE) quantifies changes in global surface water with the objective to map the spatial and temporal variability of global surface water at 30-metre resolution. Using optical satellite data as input, the GSW faces the challenge that seasonal water surfaces can show strong variability, moving between wet and dry years, even shifting geographically. Capturing such variability, especially for short-duration events, is challenging because cloud-free satellite observation must be concurrent with water occurrence. It seems evident that using SAR-derived information is highly complementary, especially in cloud-prone areas and at high latitudes. In addition to the complementary satellite data acquisitions provided by SAR when optical high resolution (HR) acquisitions are not possible (i.e. cloud-cover, northern winter, nighttime) the proposed flood mapping product will further complement the GSW by providing additional temporal coverage in all conditions – which for GSW is currently limited to HR optical acquisitions. In future, this could increase to HR-optical plus HR-SAR acquisitions.

On the other hand, the proposed global flood monitoring product will benefit from contributions from, for example, the Copernicus Global Land Service, by making use of the snow-layer product (for the exclusion mask) and soil moisture product. Furthermore, the Copernicus Data and Information Access Services (DIAS) represent a European alternative that could ease production of the flood monitoring output layers - which represents a significant challenge in terms of required computing resources (see Chapter 6).

The constant, automated, satellite-based global monitoring of floods will also greatly benefit the other mechanisms operating in satellite-based emergency mapping, in particular the International Charter Space and Major Disasters[27] and Sentinel Asia[28], in a similar way that it will contribute to improving CEMS. In future, the EU - African Union (AU) cooperation programme (GMES and Africa) will benefit from the proposed product for its planned disaster management and climate change services.

[27] https://disasterscharter.org/web/guest/home;jsessionid=0129604750511854D0A2D8ED7C1E221D.jvm1
[28] https://sentinel.tksc.jaxa.jp/sentinel2/topControl.jsp

8 Potential future evolution

This report has described a proposed automated, global, near real-time flood monitoring product, based on C-band Synthetic Aperture Radar (SAR) image data acquired by the EU's Copernicus Sentinel-1 satellite constellation, suitable for implementation within the framework of the Copernicus Emergency Management Service (EMS). In the preceding chapters, the main technical details of such a product - particularly regarding the user requirements, product output layers, system architecture, data processing methods, scientific challenges, and resource requirements - have been outlined. In this chapter, ways in which the proposed flood monitoring product might potentially be further developed in the future, are briefly described. These include:

- Possible enhancements to the quality of the flood monitoring product itself (e.g. by applying more advanced SAR-based flood detection methods).
- Additional sources for C-band SAR satellite data.
- Faster delivery times of the product output.
- Benefits related to any future evolution of the Copernicus Sentinel-1 mission's observation scenario.

The proposed global flood monitoring product that is described here, is primarily focused on detecting and mapping floods that appear as calm water surfaces occurring in open areas, such as bare soils or low-canopy vegetation. This is because, for certain land cover types such as urban areas and dense vegetation, as well as permanent low backscatter areas (e.g. flat and impervious areas, and sandy surfaces), standard methods for automatic water mapping based on C-band SAR data, such as those from Sentinel-1, are not very reliable, as is described in Chapter 5. Therefore, an exclusion mask is used to highlight such regions where water detection is generally not possible using Sentinel-1 data. However, two examples of advanced SAR processing algorithms which - though perhaps not yet at the level of maturity to be used in an automated, global product – have been shown to improve flood mapping results in such problematic areas, are mentioned here. Martinis et al. (2018) describe an approach for removing over-estimation of water extent due to permanent low-backscatter regions (i.e. sand surfaces), by excluding such surfaces based on their time-series statistics in Sentinel-1 data sets. Chini et al. (2019) describe an automatic algorithm that detects not only inundated bare soils, but also flood-water in urban areas, based on a method (developed by Chini et al., 2018) for automatically mapping buildings using multi-temporal Sentinel-1 coherence.

At present, the use of interferometric SAR coherence would not be appropriate for the proposed CEMS global flood monitoring product, as this would imply using Sentinel-1 Single-Look Complex (SLC) data products (for backscatter phase information), which would not be feasible in terms of data storage requirements, or data processing times. However such an approach could conceivably be used, for example, in an off-line environment, for more accurately delineating built-up areas, thereby improving the quality of the exclusion mask and (by extension) the flood mapping results.

Obvious benefits for a CEMS global flood monitoring product, in terms of geographic coverage, data reception, and product timeliness, will result from the planned expansion of the Copernicus Sentinel-1 programme, through the future launch of the Sentinel-1C and 1D satellites, as well as Sentinel-1's planned inter-operability with the Canadian Space Agency's three-satellite RADARSAT Constellation Mission (RCM), expected to be launched in May 2019. The proposed global flood monitoring product will also benefit from ongoing development of the European Data Relay System (EDRS), or "SpaceDataHighway", aimed at providing near real-time data downlinking for the Sentinel-1 satellites. The second EDRS geostationary laser communication satellite (EDRS-C) is planned for launch in 2019.

Finally, further improvements of the proposed CEMS global Sentinel-1 flood monitoring product may also arise from the regular revisions and adaptations of the Sentinel observation scenarios, which are planned in order to accommodate the evolution of the observation requirements of the Copernicus services, inter alia. Details of the pre-defined Sentinel-1 observation scenario, particularly regarding revisit and coverage frequency, acquisition mode, polarisation and observation geometry, are provided on the ESA web-site[29]. For instance, while the image acquisitions of the Sentinel-1A and -1B satellites are systematic, their geographical coverage over land has been prioritized for the Earth's major tectonic zones (e.g. mountainous areas) and agricultural regions. In the context of a CEMS global flood monitoring product, future adaptation of the acquisition pattern might be considered in order to improve coverage for major populated areas at high risk of flooding.

On a more technical level, in terms of the SAR polarisation scheme, while the main Sentinel-1 imaging mode over land (i.e. IW) provides VV (vertical transmit and vertical receive) co-polarised or VH (vertical transmit and horizontal receive) cross-polarised SAR data, the use of HH (horizontal transmit and horizontal receive) co-polarised SAR data has been shown to improve the discrimination of flooded areas. Therefore, the availability of HH polarisation SAR data for monitoring flood-prone areas, would in theory represent a potential future enhancement of the CEMS global Sentinel-1 flood monitoring product. In practice, however, selection of Sentinel-1's dual polarisation of VV+VH over land and seas (outside polar areas), was seen as the best compromise to support the various user requirements, and selecting HH+HV polarisation at this stage would break the time-series, and therefore would not be considered appropriate.

[29] https://sentinel.esa.int/web/sentinel/missions/sentinel-1/observation-scenario

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List of abbreviations and definitions

AFM	Automated Flood Monitoring
API	Advanced Programming Interface
C3S	Copernicus Climate Change Service
CEMS	Copernicus Emergency Management Service
CGS	Core Ground Stations
DEM	Digital Elevation Model
DIAS	Copernicus Data and Information Access Services
DLR	German Aerospace Center
EC	European Commission
ECHO	European Civil Protection and Humanitarian Aid Operations
EDO	European Drought Observatory
EDRS	European Data Relay System
EEAS	European External Action Service
EFAS	European Flood Awareness System
EFFIS	European Forest Fire Information System
ERCC	Emergency Response Coordination Centre
ESA	European Space Agency
EUSF	European Union Solidarity Fund
GDO	Global Drought Observatory
GDP	Gross Domestic Product
GHSL	Global Human Settlements Layer
GloFAS	Global Flood Awareness System
GRD	Ground Range Detected
GUF	Global Urban Footprint
GWIS	Global Wildfire Information System
ICPDR	International Commission for the Protection of the Danube River
IPCC	Intergovernmental Panel on Climate Change
IW	Interferometric Wide Swath
OCHA	Office for the Coordination of Humanitarian Affairs
NGO	Non-government organisation
NRT	Near real-time
REGIO	Regional and Urban Policy
RM	Rapid Mapping module of the CEMS-Mapping component
RRM	Risk & Recovery Mapping module of the CEMS-Mapping component
SAR	Synthetic Aperture Radar
SEA	Support to External Action
SNAP	Sentinel Application Platform
UCPM	Union Civil Protection Mechanism
UN	United Nations
UNISDR	United Nations Office for Disaster Risk Reduction
WFP	World Food Programme
WFS	Web Feature Service
WMS	Web Map Service

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