Satellite-based flood mapping in the boreal region for improving situational awareness

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Abstract
Space-borne remote sensing techniques enable near real-time mapping of floods cost-efficiently. Synthetic aperture radar (SAR) and optical sensors are the most suitable for flood detection. However, SAR has become more popular, due to the independence of sunlight and weather conditions, and the increasing data availability. Typical spring floods occurred in northern Finland during 2018. Various remote sensing sources were utilised for monitoring and damage estimation of the flooding. Floods were mapped with the SAR-based Finnish Flood Centre’s Flood Detection Algorithm (FC-FloDA), a standard threshold-based approach applied to Sentinel-1, and a visual interpretation of Sentinel-2 images. In addition, flood maps from the Copernicus Emergency Management Service (EMS) and aerial photographs from the city of Tornio were ordered. The flood products and interpretations were compared, and a deeper accuracy assessment was conducted on the FC-FloDA maps. FC-FloDA was, in general, the most successful in detecting floods within the test areas. The EMS product and the Sentinel-1 interpretation worked well in open areas, but did not detect floods in forests. The superiority of Flood Centre’s product is mainly based on the adaptation of the algorithm to northern boreal environments and the selection of an optimal polarisation for detecting floods also under tree canopies.

KEYWORDS
boreal forest, Copernicus Emergency Management Service, flood monitoring, flood risk management, remote sensing, synthetic aperture radar (SAR)

INTRODUCTION
Floods during the snowmelt season are a well-known natural phenomenon experienced almost every spring in Finland, causing damages to, for example, agriculture, road network, and buildings. Changing climate increases floods in major central lakes and their outflow rivers due to increased precipitation (Veijalainen et al., 2010). The flood damages are likely to multiply if flood risk management measures are not continued and implemented as planned (Parjanne et al., 2018). Spring floods are typically caused by overflowing rivers, due to the combination of melting snow, low water infiltration in partly frozen soil, and packed ice along the rivers blocking the water flow (Beltaos et al., 2012; Flurchinger et al., 2005; Krasovskaia & Gottschalk, 2002; Lindenschmidt et al., 2018). Space-borne...
remote sensing techniques enable near real-time mapping of flooded areas cost efficiently. These flood maps can be beneficial to emergency personnel operating during a flood event, as well as to landowners and farmers when planning preventative and recovery actions. Flood maps can also be used by insurance companies when handling flood related claims, and by other private or public sectors for community, agriculture, land use, communication, and forestry planning. Flood maps also enable calibration and validation of hydraulic model-based (static) flood hazard maps, and flood maps of previous years yield more accurate prediction of flood progress.

Flood Centre, jointly run by the Finnish Environment Institute (SYKE) and the Finnish Meteorological Institute (FMI) maintains the flood situation awareness nationally. It provides many services and products, for example, forecasts, warnings, and flood maps, to the local authorities, such as the Regional Centres for Economic Development, Transport and Environment (ELY), municipalities, rescue services, and others. The past flood events in Finland have shown that a successful flood risk management relies on effective information systems, and up-to-date information is essential for emergency services. Therefore, in addition to the water system forecasts, flood warnings and static (modelled) flood maps, near-real time information about inundated areas and river ice conditions have a significant role in maintaining an overview of the flood situation. Especially, river ice jams can induce flooding in the boreal region. In addition to flood detection, SAR imagery can be used to define the locations of ice jams and to detect different types of river ice covers (Lindenschmidt & Li, 2019; Unterschultz et al., 2009). The knowledge of flood situation as well as river ice cover will assist the authorities to make correct and well-timed decisions.

Synthetic aperture radar (SAR) and optical sensors are the most suitable for flood detection. Recently, however, the use of SAR has gained popularity over the optical sensors, mainly due to the independence of sunlight and weather conditions, as well as due to the rapid increase in the availability of near real-time SAR data. Moreover, SAR sensors enable better detection accuracy in forests compared to optical sensors, because the microwave signal has a better penetration capability through the forest canopy. Existing methods and approaches for space-borne flood detection in general, and SAR-based flood mapping in particular, have been recently reviewed by Refice et al. (2018), Tsyganskaya et al. (2018), Shen et al. (2019), and Huang et al. (2018), and earlier by Klemas (2015) and Martinis et al. (2015). Recent advancements related to satellite-based flood mapping and monitoring have also been presented in a Special Issue by Domeneghetti et al. (2019).

The most popular methods used in SAR flood mapping are based on applying appropriate threshold values on the backscatter observations, classifying the pixels to flooded or non-flooded terrain. Floods in open treeless areas can be separated from non-flooded areas due to very low backscatter caused by specular reflection of the SAR signal over the water surface. In contrary, floods in forests can be separated from non-flooded areas due to relatively high backscatter caused by corner reflection of the radar signal between the water surface and the tree trunks (Engheta & Elachi, 1982; Hess et al., 1990; Martinis & Rieke, 2015; Refice et al., 2020; Richards et al., 1987; Townsend, 2001; Voormansik et al., 2014). HH- and VV-polarisations are generally preferable in flood mapping compared to HV and VH cross polarisations (Evans et al., 1986; Henry et al., 2006; Kuga et al., 1990; Wu & Sader, 1987). Yet, HH is the optimal polarisation for detecting floods in forests, due to better penetration of the forest canopy compared to VV-pol and cross-polarisations (Bourgeau-Chavez et al., 2001; Lang & Kasischke, 2008; Pierdicca et al., 2013; Townsend, 2002; Wang et al., 1995). Other factors, such as the signal frequency (Voormansik et al., 2014; Wang et al., 1995), incidence angle (Lang et al., 2008), forest density and tree height (TH; Cohen et al., 2016; Pulliainen et al., 1999), season (leaf-on, leaf-off), as well as soil moisture and surface roughness (French et al., 1996; Ulaby et al., 1981; Ulaby et al., 1982) affect the ability of SAR to detect floods (Henderson & Lewis, 2008), and therefore they need to be considered in a proper flood detection algorithm. In relatively high frequency SAR, such as X- or C-band, the signal is more sensitive to water and soil surface roughness and less penetrate tree canopies (Ulaby et al., 1982). On the other hand, low frequency SAR can more easily mix between water surfaces and other smooth surfaces. Nevertheless, the relatively high X-band frequency has been successfully used for flood mapping in many different regions (Cohen et al., 2016; Martinis & Rieke, 2015; Pierdicca et al., 2013; Pulvirenti et al., 2013; Voormansik et al., 2014).

In the boreal region, soil can in some occasions be still frozen at the time of spring floods, reducing the backscatter reflected from the ground surface (Cohen et al., 2019, 2021). Yet, this is not expected to considerably disrupt the flood detection, because backscatter from water surfaces is notably lower even when compared to frozen soil, and the major backscatter contributor in case of forest floods is the water-trunk corner reflection and not the ground backscatter (Cohen et al., 2016). The backscatter of wet snow is even weaker than of frozen ground (Luojus et al., 2007, 2009; Nagler et al., 2016; Nagler & Rott, 2000), thus getting closer to backscatter values of open water. Therefore, in SAR-based flood
mapping, wet snow could cause false flood indications in a higher probability than frozen soil. However, in the studied region, the snow in flood prone areas usually melts away before the peak of the spring floods.

Several flood events occurred in northern Finland during spring 2018. The main goal of this study was to assess the suitability of different sensors and methods for satellite-based flood detection in the boreal forest region, with a focus on the Finnish Flood Centre’s product, specifically tailored and adapted for the boreal forest environment. For this, we have examined and compared flood maps from different remote sensing sources in three representative sub-areas, and performed a deeper assessment of the flood maps generated by the Finnish Flood Centre in one sub-area, where SAR-based flood mapping is relatively challenging due the vegetation cover and land cover type. Flood maps were ordered from the Finnish Flood Centre and from the Copernicus Emergency Management Service (EMS) (EMS, 2020). In addition, flood maps were derived from Sentinel-1 data using a standard threshold-based approach. Due to favourable cloud conditions during the flood events, flooded areas were also visible in optical high-resolution Sentinel-2 data. Aerial photographs collected by the city of Tornio were used for validation in specific locations. In this article, Section 2 introduces the test areas and the datasets used. Section 3 explains the SAR Flood Detection Algorithm developed by the Finnish Flood Centre (FC-FloDA), the methods used for extracting flooded areas from Sentinel-1 images, and the methods used for assessing the flood detection accuracies. Section 4 presents and discusses the flood detection assessment results for the different products and sensors, and Section 5 concludes the study and the results.

2 | TEST AREAS AND DATA

Flood mapping was performed in two test areas in northern Finland; Tornio and Kittilä (Figure 1). The size of the test areas was approximately 20 × 30 km. In both test areas, flooding occurred mainly alongside the major rivers; Tornionjoki in Tornio and Ounasjoki in Kittilä. Tornionjoki is the national border between Finland and Sweden, and it flows southwards between the cities of Tornio on the Finnish side and Haparanda on the Swedish side, before discharging into the Gulf of Bothnia. Ounasjoki flows through the town of Kittilä and continues southwards until it merges with Kemijoki and finally reaches the Gulf of Bothnia near the town of Kemi. Both test areas represent typical boreal environments, including mainly forests, open bogs, and agricultural fields, as well as some populated areas.

Two Cosmo-SkyMed Stripmap HH-polarisation SAR images acquired on 17 May 2018, one from Tornio and one from Kittilä, were used in FC-FloDA. Flood maps for the Tornio test area were ordered from Copernicus EMS. The EMS flood maps have been derived from one Sentinel-1 image acquired on 17, and two Radarsat-2 images acquired on 17 and 18 May 2018. In addition, flood mapping was performed with Sentinel-1 Ground Range Detected (GRD) Interferometric Wide (IW) VV-polarisation SAR data and Sentinel-2 optical images. The Sentinel-1 and Sentinel-2 images from Tornio were acquired on 17 and 16 May 2018, and from Kittilä on 18 and 16 May 2018, respectively. Drone aerial images collected by the city of Tornio on 15 May 2018 were used for visual validation of the flood maps in Tornio.

As ancillary information, FC-FloDA uses forest canopy cover (CC) and TH maps generated from LiDAR data collected by the National Land Survey (NLS) of Finland, a digital elevation model (DEM) with a spatial resolution of 2 m (KM2) from NLS, and the Finnish Corine Land Cover (CLC) produced by SYKE. Additional information about how the LiDAR-based CC and TH data were generated can be found in Pulliainen et al. (2014) and Cohen et al. (2015).

A network of automatic water level measurement stations coordinated by SYKE is spread across Finland. River measurements near the test areas showing the flood evolution during the examined time period are presented in Table 1. The water level in Tornio region was very stable, with a variation of up to 6 cm between 15 and 18 May. In
Kittilä, the water level variation was higher; a decrease of 50 cm in the water level was observed from 16 to 18 May. This was accounted when comparing the flood maps in Kittilä based on Sentinel-2, Cosmo-SkyMed, and Sentinel-1, acquired on 16–18 May, respectively. The return period of floods in the same magnitude as observed in spring 2018 in Tornio and Kittilä has been estimated to occur approximately once in 10 years.

3 | METHODS

In this section, FC-FloDA, the flood detection algorithm developed by the Finnish Flood Centre for mapping floods in open areas and forested boreal environments, is first introduced. A diagram showing the structure of FC-FloDA is presented in Figure 2. The actual satellite data processing is done in FMI National Satellite Data Centre, Tähtelä, Sodankylä. Pre-processing of the SAR data, including calibration, terrain correction and speckle filtering, is done with the SNAP (Sentinel Application Platform) software. The algorithm can be roughly divided into three parts: (1) Detection of flood extent by analysing the SAR backscatter ($\sigma^0$) image (see Section 3.1), (2) estimation of flood depth by assimilating a high-resolution DEM with the SAR detected flood areas (see Section 3.2), and (3) correction of the flood extent by using the retrieved flood depth (see Section 3.3). After processing, the flood maps are disseminated through Flood Centre’s user interface, as described in Section 3.4. Section 3.5 explains the methods used for extracting flood maps from Sentinel-1 images, and finally, Section 3.6 describes how the accuracy of the flood maps was assessed.

### 3.1 | Flood extent

Floods are separated from non-flooded terrain by applying two threshold values on the sigma naught backscatter ($\sigma^0$) image: A lower threshold value ($thr1$) and a higher threshold value ($thr2$) are used to separate open-area floods and forest floods from non-flooded areas, respectively. To define the optimal threshold values, training areas representing open-area floods, forest floods, and non-flooded areas are first digitised over the SAR backscatter images. The selection of these training areas is the only manual step in the FC-FloDA process. Spring floods are typically located next to rivers and lakes. Open-area floods are recognised by the lower backscatter, while floods in forested areas by the stronger backscatter compared to the surrounding non-flooded areas. Especially when using HH-pol SAR data, floods in both open and forested areas are well distinguished in the SAR backscatter image. The optimal lower threshold value ($thr1$) is calculated by the algorithm based on the observations inside the digitised open-area flood (OF) and the non-flooded (NF) training areas, by finding the minimum of the error function:

$$\min[W_{OF} \cdot \sigma^0 > thr1 + W_{NF} \cdot \sigma^0 < thr1],$$

where $W$ is a weight factor controlling the relation between omission (floods not detected) and commission (falsely detected floods) errors. $OF_{\sigma^0 > thr1}$ is the number of open-area flood observations inside the OF training areas where $\sigma^0$ is higher than $thr1$, $OF$ is the total number of open-area flood observations, $NF_{\sigma^0 < thr1}$ is the number of non-flooded observations inside the NF training areas where $\sigma^0$ is lower than $thr1$, and $NF$ is the total number of non-flooded observations. The optimal higher threshold value ($thr2$) is calculated as in Equation (1), but based on the observations inside the digitised forest flood (FF) and the NF training areas:

$$\min[W_{FF} \cdot \sigma^0 < thr2 + W_{NF} \cdot \sigma^0 > thr2],$$

where $FF_{\sigma^0 < thr2}$ is the number of forest flood observations inside the FF training areas where $\sigma^0$ is lower than $thr2$, $FF$ is the total number of forest flood observations and $NF_{\sigma^0 > thr2}$ is the number of non-flooded observations inside the NF training areas where $\sigma^0$ is higher than $thr2$. The weight factor ($W$) was set to 2, to classify more areas as flooded at the expense of higher false commission error rate. This was preferred, because in the following steps of FC-FloDA, small flood polygons are removed.
and therefore the commissions errors are more likely to be corrected than omission errors.

Using the LiDAR-based CC and TH forest maps, the area is classified into three forest categories: (1) open treeless areas, where CC < 5% and TH < 1.5 m, (2) sparse or low tree forests, where CC is between 5 and 15%, and TH between 1.5 and 4 m, hereafter referred to as semi-forested areas, and (3) dense forests, where CC > 15%
and TH > 4 m. These threshold values were found to be optimal in forest flood detection by Cohen et al. (2016). After defining the $\sigma_0$ threshold values (Equations (1) and (2)) and the forest classes, all pixels with values below $thr_1$ or above $thr_2$ are classified as water/flood, and the rest as non-flooded areas. Areas identified as non-flooded in semi-forested areas are classified as uncertain, because in those areas SAR flood detection is problematic (Cohen et al., 2016). Smooth surfaces such as airport runways or roads are often falsely interpreted as water due to specular reflection causing low $\sigma_0$, and some built-up areas are often falsely classified as forest floods due to strong corner reflection from buildings. Hence, a detected flood pool was removed if more than 30% of it was over roads, airports or other urban areas, according to the CLC data. Detected forest floods (values above $thr_2$) were accepted only if the area was forested according to the LiDAR forest data. Also, detected small flood pools (less than 0.5 hectares) were removed. Finally, permanent water bodies were masked from the water/flood map using CLC data.

### 3.2 Estimation of flood depth

To estimate the flood depth, the outer borders of the SAR detected inundated areas (including permanent water bodies such as rivers and lakes) are first located. This is done first by filling small gaps inside flooded areas, that is, completely surrounded by floods (hereinafter referred to as flood gaps), and then, identifying the flood borders by applying a Laplace (first derivative) filter on the binary flood map. The ground elevation in the outer borders of the flood areas is then extracted from a high-resolution DEM (KM2). The elevation of the flood water level for each flood cell is then estimated by finding the elevation of the nearest flood border, ignoring borders in uncertain flood areas (detected floods in semi-forested forest category) and borders where the ground slope was more than 10%. The flood depth of each pixel is then calculated by subtracting the DEM from the flood water level grid.

### 3.3 Correction of flood gaps

A flood gap correction was applied on the SAR detected flood extent map by using the derived flood depth. A flood gap in the SAR interpretation (an area detected as non-flooded, but completely surrounded by detected floods) was corrected to flooded, if the derived flood depth was over zero. As seen in Figure 3, there are typically many small flood gaps inside the detected flood areas. Some of these gaps are in fact flooded, but they

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**Figure 3** Flood gap correction. Blue areas show forest and open flood areas detected from the synthetic aperture radar (SAR) image after filtering and removal of permanent water bodies, before the flood gap correction. Green-yellow-red graduated colours show flood gaps not detected by SAR and corrected using the flood depth map. SAR backscatter image is shown on the background, where lakes appear as large black areas.
have not been detected by the SAR due to backscattering similar to non-flooded terrain.

3.4 | Dissemination

After the generation of the flood maps, they are automatically transferred and published in the situation awareness map developed by SYKE. The map brings together the essential information on floods under a single graphical user interface. The application includes an array of flood-related information that serves the duty officer managing the flood event, such as remote sensing-based detection, damage estimations, live cameras, situ observations and photographs, road traffic incidents caused by the floods, and georeferenced social media. In addition, the flood extent is published as a part of the national public flood map service (Figure 4) (Sane et al., 2014).

3.5 | Sentinel-1 SAR-based flood detection

The usability of flood interpretation based on Sentinel-1 SAR images was investigated in the same areas; in Tornio, where FC-FloDA and EMS flood maps were available, and in Kittilä, where FC-FloDA was available. Sentinel-1 provides SAR data free-of-charge with regular operational availability, but only using VV and VH (vertical-horizontal) polarisations in the IW Swath acquisition mode over land areas. The flood mapping procedure followed ESA guidelines. First, the backscatter coefficient values of Level-1 GRD IW images were calibrated. The images were filtered using Lee filter with window size of $7 \times 7$ and georectified using KM10 DEM of NLS. In both study areas, Kittilä and Tornio, the $\sigma^0$ threshold was set to $-14$ dB (0.04 in power units) to extract pixels covered by water. Permanent water bodies were then removed using CLC data, leaving only flooded areas.

3.6 | Flood map accuracy assessment

A rough assessment was first done for the different flood products and derived flood maps by a visual comparison between FC-FloDA, EMS, and Sentinel-1-based flood maps, as well as HH-polarisation Cosmo-SkyMed SAR backscatter images, Sentinel-2 optical false colour images, drone photographs, and forest density maps. After the visual accuracy assessment, the FC-FloDA flood maps were further assessed for the Kittilä test area using a quantitative analysis against flood reference areas.
representing the true flood conditions, forest maps and land cover classification data. These flood reference areas were manually digitised over a Sentinel-2 false colour RGB image with a combination of $R = \text{NIR}$ (near infrared), $G = \text{Green}$, and the $B = \text{Red}$ channels. The reference areas were then further inspected, and if needed, corrected using a high-resolution DEM (KM2). The total size of the reference flood areas was 16.4 km$^2$, including land cover classes and forests typical for the test region.

4 | RESULTS AND DISCUSSION

Two representative flooded sites near Tornio are visually analysed; Papinsaari (Figure 5) and Napinpää (Figure 6). Floods detected by FC-FloDA, EMS, and Sentinel-1 are marked with green, yellow, and magenta orthogonal lines, respectively, over a Cosmo-SkyMed HH-polarisation backscatter image. Optical false colour Sentinel-2 images are also shown for the same sites. The Papinsaari site shown in Figure 5 is from a river confluence where the Keskijoki and Järvijoki rivers merge with Liakanjoki river. The Napinpää site shown in Figure 6 is located on the Finnish side of on the Tornionjoki river.

The flooded area detected by FC-FloDA, marked with green orthogonal lines, is significantly wider than the flooded area according to the EMS product marked with yellow and the Sentinel-1 detected floods marked with magenta orthogonal lines (Figure 5(b)). As seen in the drone images (Figure 5(d,e)), all three SAR-based maps recognised the open-area floods, but only FC-FloDA managed to identify floods under tree canopies. Moreover, the Sentinel-2 RGB image from Papinsaari (Figure 5(c)) supports the FC-FloDA detection, especially in the eastern side of the flooded area, where the Heinijänkäntie (the road seen in the drone images) forms

![Figure 5](image-url)

**Figure 5** Flood mapping in Papinsaari, Tornio, during 15–18 May 2018. (a) The location of the Papinsaari site shown in images (b–e) is marked with a red square. The location of the automatic water level measurement stations of Tornio, Liakanjoki and Tornio City (Table 1), marked with orange dots. (b) Image shows floods detected by Flood Centre’s Flood Detection Algorithm (FC-FloDA) on 17 May with green, floods detected by Emergency Management Service (EMS) on 17 (Sentinel-1) and 18 (RadarSat-2) May with yellow, and floods extracted from Sentinel-1 on 17 May with magenta orthogonal lines, over a Cosmo-SkyMed backscatter image. (c) RGB false colour image of Sentinel-2 from 16 May, with the combination of $R = \text{NIR}$, $G = \text{green}$, and $B = \text{red}$ channels. (d,e) True colour drone images collected by the city of Tornio on 15 May.
a clear border between flooded and non-flooded terrain. Darker areas west to Heinijärvi represent flooded, and brighter areas east to the road, non-flooded terrain. The Sentinel-2 image clearly shows that most of the areas west to the road are flooded, as classified by FC-FloDA.

Also in Napinpinä (Figure 6), flooded areas detected by FC-FloDA are remarkably wider than the floods detected by EMS and Sentinel-1. When comparing the SAR-based flood maps (Figure 6(b)) with the CC map (Figure 6(c)), it can be seen that floods detected by FC-FloDA, but not by EMS and Sentinel-1, are located in forested areas. Also here, as in Papinsaari (Figure 5), the Sentinel-2 RGB image is in-hand with the FC-FloDA detection, showing clear borders between flooded and non-flooded terrain.
non-flooded areas that match the FC-FloDA detection. Although the flood borders are well visible in the Sentinel-2 RGB images (Figures 5(c) and 6(d)), it appears that the separation between flooded and non-flooded terrain is more distinct in open areas compared to forested areas. Especially the red colour representing the NIR band is strong in both flooded and non-flooded forests, due to the tree canopies visible also on top of the flood water surface.

Figure 7 shows the results from the Kittilä test area. The town of Kittilä is located in the riverbanks of the Ounasjoki river, which is often flooded during the spring. Floods detected by FC-FloDA and Sentinel-1 are marked with green and magenta orthogonal lines, respectively, over a Cosmo-SkyMed HH-polarisation backscatter image. A partly clouded optical false colour Sentinel-2 image is also shown. An EMS product was not ordered to Kittilä. However, based on the similarity of the EMS and the Sentinel-1 interpretations observed in Tornio Pappinsaari (Figure 5) and Näpinpää (Figure 6), we can assume that EMS flood detection in Kittilä would have been similar to the interpretation of Sentinel-1, that is, open-area floods would have been detected, but not floods under tree canopies. For easier interpretation, the CC map in Figure 7(c) shows the forest density only in areas detected as flooded by FC-FloDA. Also in Kittilä, floods detected by FC-FloDA include forested and open-area floods, but Sentinel-1 detected only open-area floods. Within the open flooded areas, floods detected by Sentinel-1 are somewhat suppressed compared to

**FIGURE 7** Flood mapping in Kittilä during 16–18 May 2018. (a) The location of the test area shown in images (b–d) is marked with a red square. The automatic water level measurement station of Kittilä, Ounasjoki (Table 1), located in the town of Kittilä, is marked with an orange dot. (b) Image shows floods detected by Flood Centre’s Flood Detection Algorithm (FC-FloDA) on 17 May with green, and floods detected with Sentinel-1 on 18 May with magenta orthogonal lines, over a Cosmo-SkyMed backscatter image. (c) Canopy cover map of the test area (only areas detected by FC-FloDA). (d) RGB false colour image of Sentinel-2 from 16 May, with the combination of R = NIR, G = green, and B = red channels
FC-FloDA detection. Yet, this can be explained by a retreat of the flood border following a decrease of ~30 cm in the Ounasjoki water level from 17 to 18 May (Table 1). By a visual inspection of the optical Sentinel-2 image (Figure 7(d)), floods in open areas can easily be distinguished because they appear darker than the surrounding non-flooded areas. Floods under tree canopy are also somewhat darker compared to non-flooded forests, but the contrast between flooded and non-flooded forests was smaller than the contrast between flooded and non-flooded open areas. According to the Sentinel-2 data, some small patches of snow were still present in Kittilä region, but most of them were located in higher altitudes, far from the flooded areas, approximately 4 km west and 13 km north from the town of Kittilä. These snow patches are not visible in Figure 7(d). Instead, the white areas seen in the optical RGB image are clouds or bright urban targets in the town of Kittilä. Overall, like in the Tornio test sites, also in the case of Kittilä, Sentinel-2

**FIGURE 8** The coverage percentage of the main land cover classes in the whole test region of Kittilä, in the chosen reference flooded areas, and in the undetected floods inside the reference areas. Land cover classes are derived from Corine Land Cover (CLC) 2018 data

**FIGURE 9** All chosen reference areas over an optical false colour image from Kittilä test area (a) and a comparison between reference areas and detected floods over a high-resolution digital elevation model (DEM) (b–e). The edges of the reference areas are marked with green and the detected floods by Flood Centre's Flood Detection Algorithm (FC-FloDA) are marked with magenta partly transparent (image b) or diagonal lines (images c, d, and e). As seen in image (b), most of the floods were detected by FC-FloDA. Image (b) shows the location of the three sub-areas (c–e), where the detection was relatively poor. The height in m.a.s.l. according to the NLS DEM with 2 m spatial resolution (KM2) is shown next to each sub-image
interpretation supports the flood mapping results of FC-FloDA.

According to an analysis of FC-FloDA results against the flood reference areas in Kittilä, 90% of the flooded areas were detected. As seen in Figure 8, most of the undetected floods were in semi-forested areas (sparse canopy) and in wetlands (marshes and open peatbogs). This supports the results obtained by Cohen et al. (2016), who found that flood detection with X-band HH-polarisation SAR is problematic in semi-forested sparse or low-tree forests.

Figure 9(a) shows all the chosen flood reference areas over an optical false colour image, and images (b–e) compare the reference areas with detected floods, with a high-resolution DEM in the background. As seen in Figure 9(b), vast majority of the floods were detected by FC-FloDA. The undetected flood areas, as seen in images (c–e) of Figure 9, were mostly located in the edges of the flooded areas, where the terrain is most likely partly covered by shallow flood pools and partly by exposed ground. The exposed patches, seen as bright lines in images (c–e) (Figure 9), cause an increase of the total backscatter, thus disrupting the SAR flood detection. Apart from these shallow floods with partially exposed ground, the flood detection accuracy is expected to increase close to 100%.

5 | CONCLUSIONS

Flood maps generated by the Flood Centre were, in general, the most successful in detecting floods in the Tornio and Kittilä test areas; 90% of the flooded areas, including forest floods, were detected by FC-FloDA. Most of the undetected floods were in the edges of the flooded areas, that is, in shallow waters, where the ground was most likely partially exposed. EMS flood product worked well in open, non-forested terrain, but did not recognise floods under tree canopy. Flooded areas were visually apparent in the optical Sentinel-2 images, but in some forested areas, the distinction of floods was less clear. Analysis of the Sentinel-1 VV-polarisation data showed that floods in open areas can be detected, but similarly to the EMS product, floods in forests were less visible. SAR sensors are generally preferable over optical, due to frequent cloud cover in the region.

The superiority of the Flood Centre product over the other SAR-based methods in boreal environments is mainly based on the adaptation of the algorithm to the boreal forest region: Selecting the optimal HH-polarisation band better penetrating the forest canopy (Bourgeau-Chavez et al., 2001; Henry et al., 2006; Pierdicca et al., 2013; Townsend, 2002; Wang et al., 1995), and adding a separate mechanism targeting forest flood detection, in addition to the more general case of detecting floods in open areas. For example, the VV-polarised Sentinel-1 data are less applicable for the detection of floods in forests. Nevertheless, our preliminary analysis found that when combined with VH-pol, it is possible to detect some of the forest floods also with VV-pol. This approach can therefore be used to support the flood monitoring in the possible absence of HH-pol. As these are only preliminary results, the investigation continues and will be reported further on.

The increasing amount of satellite sensors providing freely available and continuous observations has encouraged investigations assessing their suitability for flood monitoring (Clement et al., 2018; DeVries et al., 2017; Du et al., 2016; Kordelas et al., 2018; Notti et al., 2018; Reksten et al., 2019; Ruzza et al., 2019; Tsyganskaya et al., 2019; Twele et al., 2016; Uddin et al., 2019). Considering spatial and temporal resolution, Sentinel-1 and Sentinel-2 have the potential to significantly improve flood monitoring capabilities. In particular, the suitability of these data for detecting forest floods in the boreal region should be further studied. To improve flood risk management in the boreal region, the usability of Sentinel-1 for detecting existing ice jams, and Sentinel-2 for assessing the risk of ice jam formation along the river, should also be investigated. This information, in addition to flood maps, may be essential when measures to prevent flood damages during river ice break-up are planned.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request. As an exception, restrictions apply to the availability of the original Cosmo-SkyMed data used in FC-FloDA. These data were used under a license agreement between FMI and e-GEOS, and will be available from the authors with the permission of e-GEOS.

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