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I. Olthof[1], S. Tolszczuk-Leclerc[1], B. Lehrbass[1], Y. Shelat[1], V. Neufeld[1], and V. Decker[1]

[1] Canada Centre for Mapping and Earth Observation, 560 Rochester Street, Ottawa, Ontario K1S 5K2

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ABSTRACT

Spring 2017 flooding in eastern Ontario and southern Quebec was caused by a number of consecutive record-setting rain events combined with melting snow between April 5 and mid-May. In Quebec, the event caused more than 5000 residences to flood in 261 municipalities, forcing mass evacuations and declaration of a state of emergency. The International Disasters Charter was activated shortly after, providing near-real time earth observation data from a range of sensors through Charter member agencies. Upon activation, the Emergency Geomatics Services (EGS) at the Canada Centre for Mapping and Earth Observation (CCMEO), Natural Resources Canada (NRCan), produced flood maps from RADARSAT-2 and Charter satellite imagery to provide up-to-date situational awareness. Previous methodologies to extract flood information were not adequate to map open water and flooded vegetation from all data received through the Charter, while work was ongoing in the previous year to develop reliable flood extraction methods from multiple sensors for floodplain characterization. These new methods were quickly adapted and put into operations during the activation, enabling rapid flood map production from RADARSAT-2, Sentinel-1 and TerraSar-X, among other sensors. This document describes the methodology and presents successes and challenges of the 2017 EGS activation for flooding in eastern Ontario and southern Quebec. From lessons learned during the 2017 activation, we also present a way forward to improve subsequent flood activations.

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1. INTRODUCTION

The 2017 EGS flood activation in eastern Ontario and southern Quebec began due to severe flooding in Rigaud, a community located on the Ottawa River between the Quebec / Ontario border and Lake of Two Mountains on April 5, 2017. As record amounts of precipitation continued to fall into May 2017, the activation area expanded to include the Ottawa River from west of Ottawa to east of Montreal, as well as Lac St-Pierre further downstream to the east (Figure 1).

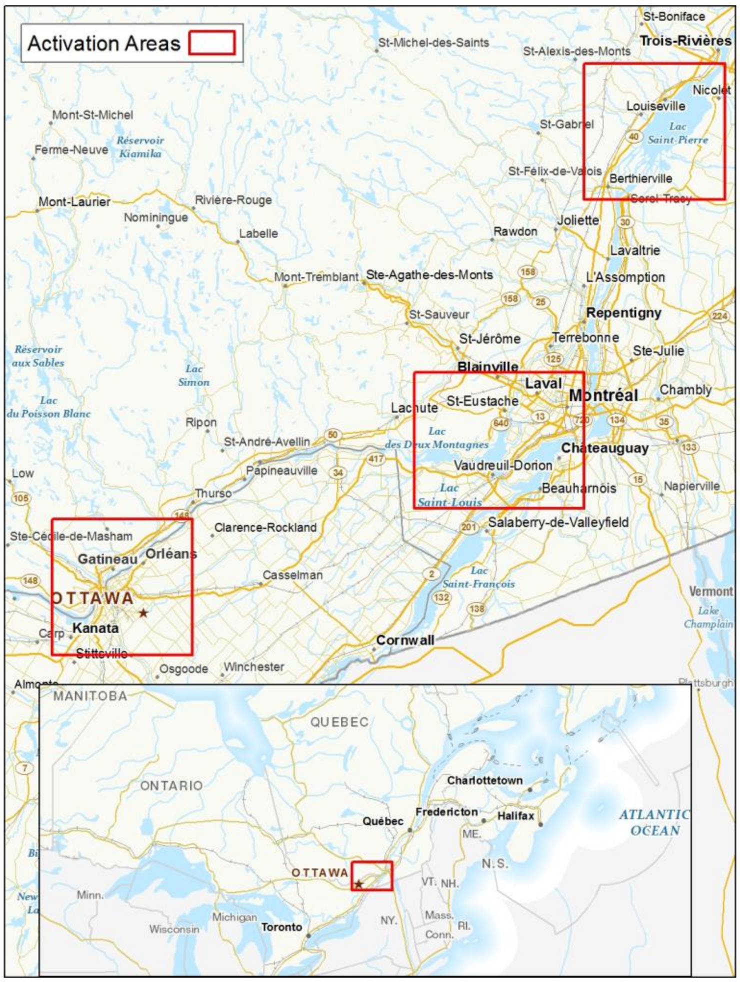

Figure 1. 2017 flood activation area from west of Ottawa to Lac St-Pierre

In the year prior to the 2017 activation, significant progress had been made on automated flood / water extent mapping from optical and radar satellite data. This work was ongoing within Public Safety's floodplain characterization program with the goal of generating historical flood maps for dynamic surface water mapping, including inundation frequency and trends. A methodology for automated flood mapping from historical Landsat data had been developed and published in

Olthof (2017), and Landsat inundation frequency products for three floodplains prone to annual springtime flooding including the Red (Man), the Richelieu (Que) and the Saint John (NB) Rivers were generated to demonstrate the new methodology.

The methodology was subsequently adapted to single and dual-polarization radar imagery from RADARSAT-1 and 2 and work began to generate historical flood maps over the Saint John River floodplain to compare with optical data with the eventual goal of multi-sensor integration. The overarching objective of this work is to produce a methodology that can be applied to generate flood maps from a range of sensors for both operational and historical flood mapping. Once the 2017 flooding triggered activation of the International Space Charter for Disasters, this new methodology was tested on data received through the charter in addition to RADARSAT-2; primarily from other radar satellites including Sentinel-1, TerraSAR-X, ALOS-2 and KOMPSAT5 due to radar's ability to penetrate the near continuous cloud cover that was present during the weeks of flooding. Fortunately, the methodology proved to be sufficiently reliable to be adapted to other sensors that include different radar wavelengths, polarizations and spatial resolutions, requiring specification of only three sensor-specific parameters to account for these differences. While clients had been critical of products generated by EGS during the 2011 flood activation over the Richelieu, these same individuals praised products generated from the new methodology during the 2017 activation and deferred production entirely to EGS acknowledging the fact that they could not generate better products themselves.

Previously, EGS operations mapped open water that is usually dark in radar due to single bounce using single polarization thresholding, even when multiple polarizations were available (Bolanos et al., 2016; Li and Wang, 2015). While thresholding has been shown to perform well for open water under ideal conditions, water surface roughness due to ice that is sometimes present during the spring flood season as well as wind-generated waves, can increase backscatter to a level where a single threshold value cannot reliably separate water from land (Henry et al., 2006). Automated methods used to determine optimal threshold values are compromised by these factors, while manual thresholding can better tune the value to minimize errors of omission and commission. Even still, a significant amount of post-processing is often required to reduce errors to an acceptable level (White et al., 2013).

One of the biggest improvements in the new flood extraction methodology is mapping flooded vegetation operationally for the first time (Figure 2). Previous methods mapped open water only; however, most flooding beyond baseline open water extents occurs in vegetated, and increasingly in residential areas, which is why research into flooded vegetation mapping from radar has been active in recent years. Flooded vegetated areas present a challenge to remote sensing because the signal needs to penetrate the vegetation layer to sense water below. While optical remote sensing has a very limited capability to detect flooding beneath vegetation and can do so only during leaf-off conditions in the early spring, radar is able to detect water beneath leaf-on canopies under certain conditions. Leaf size, wavelength, polarization and incidence angle are all factors that affect water detection beneath vegetation, with longer wavelengths relative to leaf size (Townshend and Walsh, 1998) and shallower incidence angles (White et al., 2015) generally providing greater signal penetration through the canopy. Radar is an active sensor that is side-looking, causing double-bounce of the incident beam first off of horizontal water surfaces beneath the canopy, and second off of vertical trunks and stems acting as corner reflectors before returning to the sensor.

Flooded vegetation acting as corner reflectors causes a high intensity return to the sensor, leading to a bright signal in radar imagery. Bright target thresholding has been used in the past to map flooded vegetation (Townsend, 2002; Kasischke et al 2003; Chapman et al., 2015); however, this approach was never operationalized by EGS because it leads to significant commission error caused by the presence of other corner reflectors such as buildings and rock outcrops. Post-classification editing in a GIS environment can be performed to help reduce commission error, but this relies on ancillary data and layers that may be out of date or contain errors. A robust flooded vegetation extraction methodology is preferred for emergency flood mapping that is independent of ancillary data requirements for product quality and processing speed and efficiency.

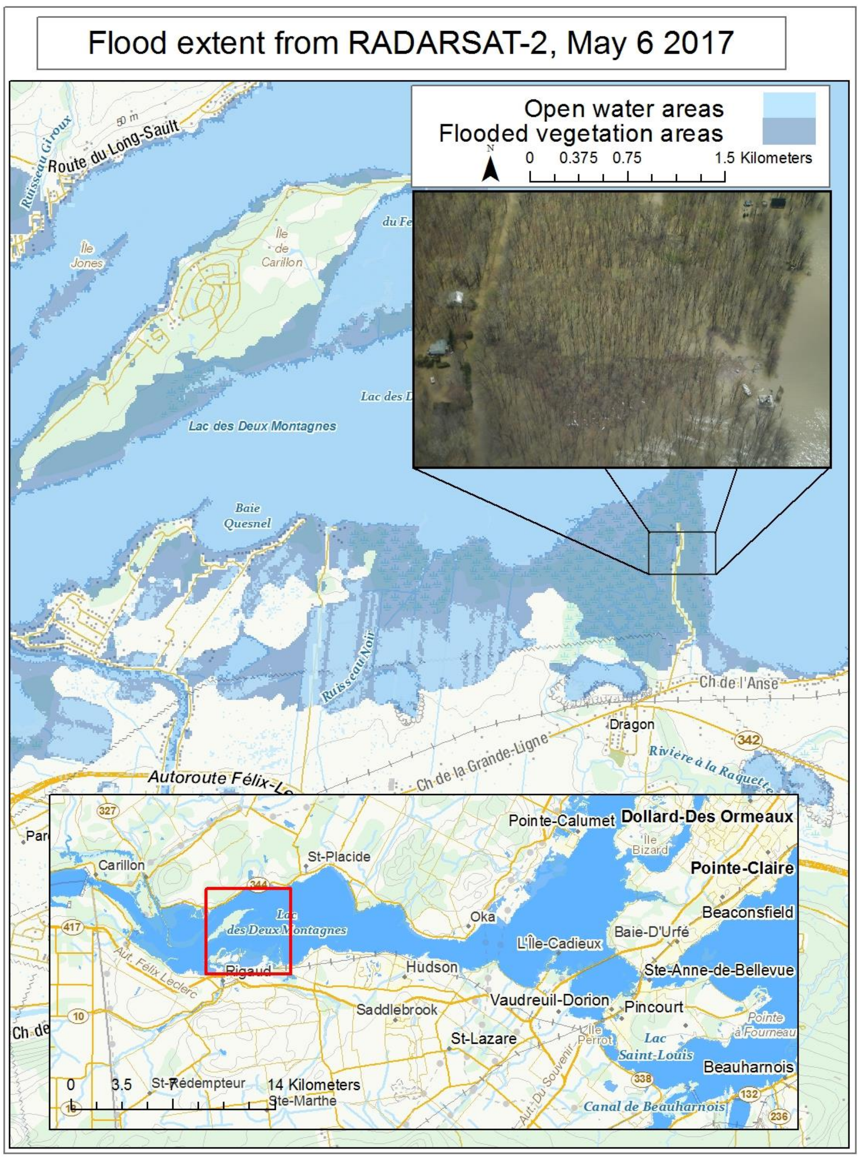

Figure 2. Open water and flooded vegetation mapped from RADARSAT-2 near Rigaud, Quebec, confirmed by oblique airphotos

2. NEW OPERATIONAL METHODS

The new methodology makes use of multiple radar polarizations when available to perform multi-channel supervised machine learning classification to first map open water, and then bright threshold region growing seeded in open water to map flooded vegetation (Figure 3).

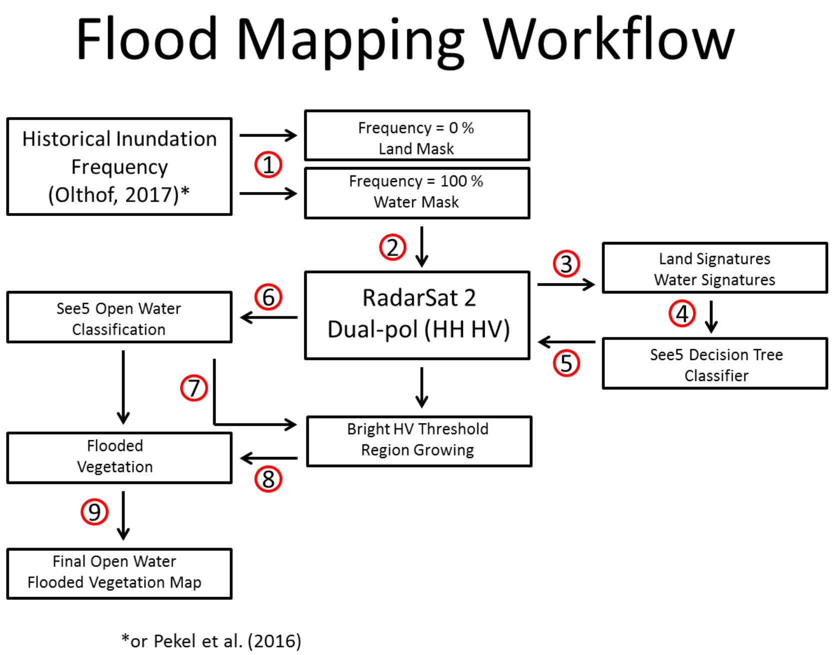

Figure 3. New methodology put into operations for the 2017 flood activation

Information contained in multiple radar polarizations can help to reduce errors in open water extraction; however making use of this information requires an approach other than image thresholding. Supervised multispectral classification has long been used in terrestrial remote sensing applications, but has been under-utilized for surface water extraction from radar. One challenge is that supervised classification approaches require spectral signatures for each class to train a classifier; in the case of water extraction, signatures representing land and water. Use of standard spectra to classify land and water will not achieve an optimal classification result for several reasons. First, the spectral variability of water in radar due to wind and ice leads to confusion between water and land. Second, spectral signatures of land also vary due to the presence of several land cover types that change in time because of vegetation phenology, moisture and atmosphere. An additional complicating factor is that in order to perform a traditional classification approach such as minimum distance or maximum likelihood, separate signatures must be sampled for all land cover types present in the scene. To deal with these limitations, an automated open surface water extraction methodology that is an extension of one already developed in Olthof (2017) was implemented. The approach makes use of recently available inundation frequency products from historical Landsat data (Pekel et al., 2016; Olthof, 2017) to sample scene-specific signatures simultaneously representing multiple land and water classes. Land signatures are extracted where inundation has never occurred based on historical data, while water signatures are extracted where water is permanent. See5 machine learning is then used to automatically classify the image into water vs land using sampled, scene-specific signatures (Quinlan 1993).

Once open water is mapped, flooded vegetation is mapped next by iteratively region growing from open water into adjacent bright intensity areas characteristic of double bounce using a bright threshold value criterion. Region growing has the advantage over the application of a global threshold value of assigning only adjacent pixels to the flooded vegetation class, thereby reducing the amount of commission error caused by double bounce elsewhere in the scene. The problem still persists in areas where corner reflectors other than flooded vegetation are adjacent to water; for example, some of the residential and urban neighborhoods in the vicinity of Montreal were mistakenly included as flooded vegetation due to double bounce off of buildings. These errors were corrected using the urban class from Landsat land cover (Latifovic et al., 2017). Once the first region growing using a bright threshold value is complete, a second region growing is performed using a conservative dark threshold value from open water and flooded vegetation to help infill dark areas contained within bright flooded vegetation and better connect nearby areas of open water. Both instances of region growing stop when either no more adjacent pixels meet the threshold criterion or after a set number of iterations. Open water and flooded vegetation were subsequently improved through image infilling of small land areas entirely surrounded by water, filtering and sieving to reduce both errors of omission and commission.

In addition to the problem of the presence of corner reflectors other than flooded vegetation producing commission error, a second limitation of the methodology is related to the local topography of the riverbanks. Where riverbanks are steep and roughly parallel with the SAR orbit, flooded vegetation commission error will also occur. These errors are caused by the proximity of the riverbanks to the main channels satisfying the region growing criterion with steep local incidence angles that increase backscatter values to the point where confusion with flooded vegetation occurs. Hence, steep riverbanks oriented perpendicular to the radar look direction will appear bright and will be incorrectly classified as flooded vegetation. Using ancillary datasets such as slope and aspect based on look direction help solve this problem by preventing region growing on slopes above a certain grade.

Because the methodology relies on signatures extracted from each scene to classify open water, and only specification of a bright and dark threshold value is needed to map flooded vegetation, the approach is sensor-independent. As new charter data was received during the activation, scripts were modified to accept the number of polarizations available so that they now work on single polarization (e.g. TerraSAR-X), dual-polarization (e.g. Sentinel-1) and quad-polarization (e.g. RADARSAT-2) (Figure 4). Where multiple polarizations are available, specification of the polarization to use for flooded vegetation region growing must be specified. Generally, the polarization with the best contrast between flooded vegetation and surrounding water and land is selected. Like polarizations seemed to provide the best contrast, for example HH in RADARSAT-2. Scripts have been modified to accept and test any number of polarizations available in RADARSAT Constellation Mission (RCM) data and are currently being tested on simulated RCM data. Because the method has been shown to perform well across a range of sensors and data types from optical to radar, implementation risks in transferring the methodology to RCM data are low; however, research into optimal polarizations, thresholds and other parameters still needs to be conducted to achieve the best results.

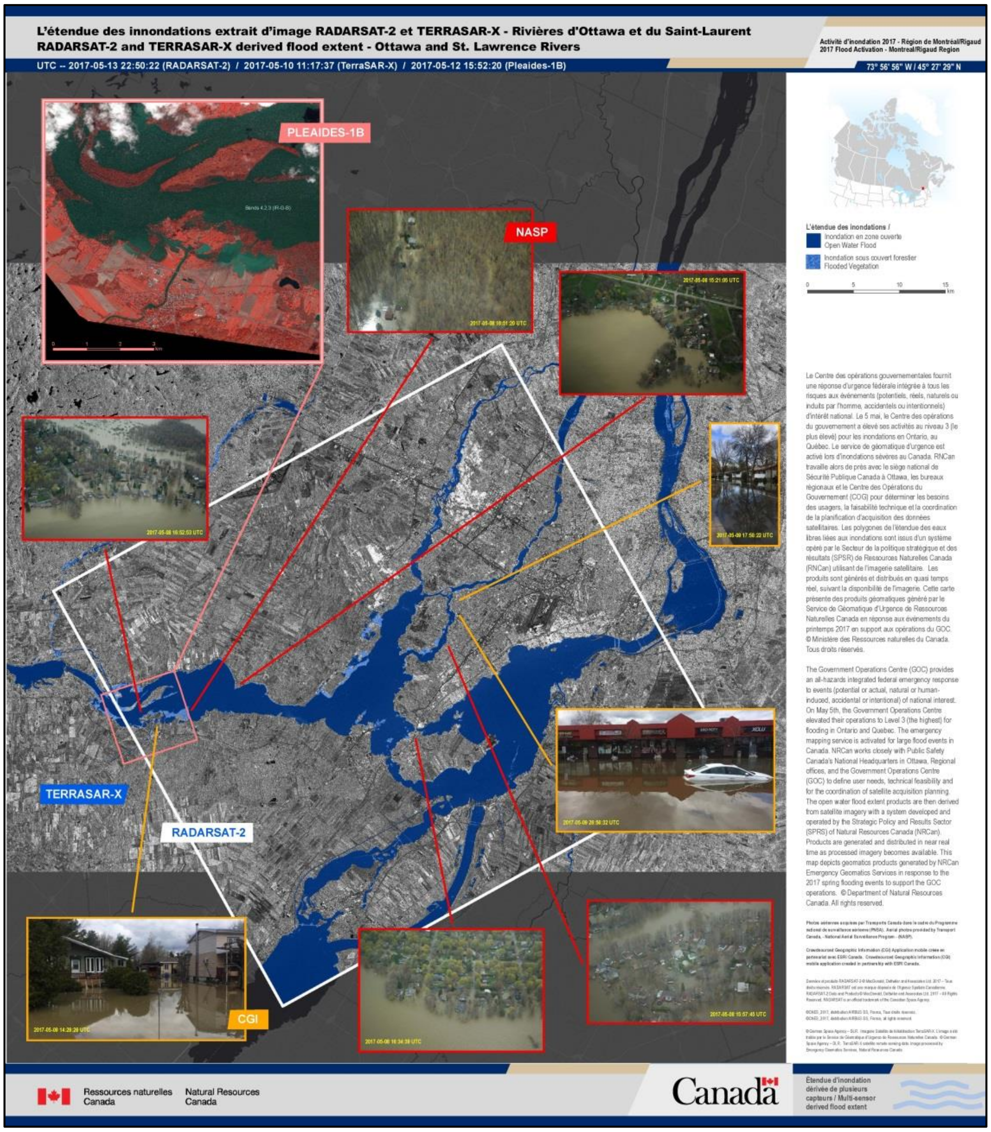

Figure 4. Example of multi-sensor flood mapping using the new operational methodology from RADARSAT-2 (interior white box), and TerraSar-X (outside), showing the consistency in mapping open water and flooded vegetation between sensors

The methodology relies on historical inundation frequency products, which to date have been generated from Landsat (Pekel et al., 2016; Olthof, 2017). Prior to the 2017 activation, flood products were generated for the Red River in Manitoba using historical Landsat inundation products generated by EGS. However, at the start of the 2017 activation, EGS had not yet produced its own historical inundation product for Ottawa to Lac St-Pierre. Fortunately, a global product exists (Pekel et al., 2016) that was used for the activation in this region. Historical inundation is currently being generated by EGS from RADARSAT-1 and 2 over the Saint Johns River basin for comparison to both Olthof's and Pekel's Landsat products. An initial comparison suggests that Pekel's product omits some inundation because it represents a subset of a global product, while Olthof's Landsat product is slightly better tuned to the local region and its conditions (Figure 5). Both Landsat products omit water and especially flooded vegetation compared to radar, due to the fact that radar's ability to penetrate cloud enables capturing peak flood conditions that often occur during rainy and cloudy conditions that contribute to flooding. Public Safety Quebec has stated to EGS recently that maximum water extent is the most critical, if not the only information needed. Although literature suggests that optical data, especially those that include longer wavelength channels into the NIR and SWIR perform slightly better than radar for open water detection (Frasier and Page, 2000; Hong et al., 2015; Bolanos et al., 2016), radar is generally considered to be the preferred sensor for flood mapping due to cloud penetration, thereby capturing the full range of flood extents regardless of weather conditions.

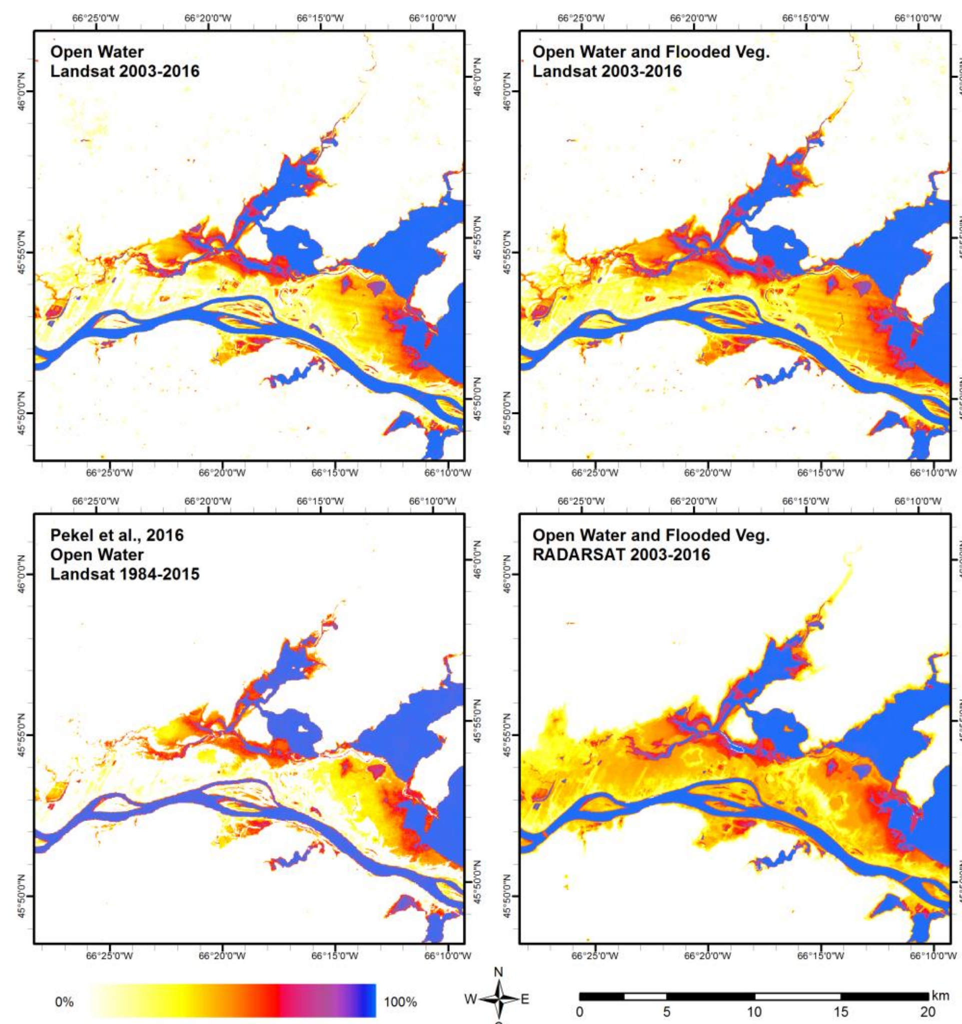

Figure 5. A comparison of inundation frequency products depicting open water, and open water + flooded vegetation inundation from Landsat and RadarSat

3. CHALLENGES AND WAY FORWARD

Although from both an operational and science perspective the 2017 activation was considered an overall success, there were problems along the way. Public Safety Quebec provided feedback on EGS products early on in the activation, suggesting that flooded vegetation was not being accurately portrayed in our maps. Refinement of threshold values for flooded vegetation was tested and subsequent products were improved as a result.

There were some technical issues related to some of the Charter data and the application of the new flood extraction methodology. Radar data such as TerraSAR-X is single polarization, which causes See5 to resort to single image thresholding for open water extraction. Under ideal conditions, this approach works well; however, known problems with thresholding such as windy conditions or turbulent water sometimes made it difficult to separate open water from land. Another technical challenge was caused by data volume, specifically the file size of some of the images provided through the Charter. For example, KOMPSAT5 data were 16-bit at 1.11 m spatial resolution, producing individual image files that were several Gigabytes in size. Not only did file size affect the time needed to download images, but the current implementation of the new flood extraction methodology in R Statistics has memory limits that cannot handle such large files in a single process. Typically, a single RADARSAT-2 image will take 20 minutes to generate a flood product, while even after sub setting some of the largest images took more than one hour. Different cloud computing options are currently being considered to handle large file sizes and speed processing for future activations.

High resolution optical data file size was also large in many cases, making it difficult and time-consuming to process. Scenes of high resolution optical data typically covered less than one hundred square kilometers, limiting their usefulness for mapping. However, in conjunction with oblique airphotos acquired by Transport Canada under the National Aerial Surveillance Program (NASP), they proved extremely useful to help position and validate residential, vegetated and open water flooding; all visible and easily interpreted in the optical imagery from the Charter.
A major shortcoming of the approach applied to radar data was its inability to accurately map open water in urban environments. The presence of buildings acting as corner reflectors made dark water target detection difficult to impossible, while confidence that any detected dark targets were water was low. Further, urban areas located on the water were often mapped as flooded vegetation due to their high intensity return. Post-classification improvements were made with ancillary data to remove flooded vegetation in urban settings; however, this also removed any real water that was detected. It is strongly suspected that with current radar technology and polarizations, reliably detecting flooding in urban environments may be impossible. New sensor technology available in RCM including more polarizations may improve chances of mapping floods in urban areas.

As Crowdsourced Geographic Information (CGI) data submitted during the event became available towards the end of the activation, tests began on using it in combination with newly available LIDAR DEM data to map urban flooding. Use of LIDAR data for flood mapping requires a water depth measurement, which can be estimated at a location from CGI data assuming the observer is taking pictures at or near the flood perimeter and can be confirmed by looking at the pictures themselves. Once an elevation along the flood perimeter has been established from CGI, the full local flood extent can be mapped by filling any adjacent pixels that are below the elevation at the flood perimeter with water (Figure 6). The extent to which infilling can be done varies with the degree of local variation in the geoide. For example, if a single elevation threshold were applied to a LIDAR DEM from Ottawa to Montreal, flooding would be under predicted in Ottawa and simultaneously over predicted in Montreal due to the slope of the geoide from Ottawa to Montreal that causes water to flow in that direction. Due to variation in the geoide over large spatial extents, integration of CGI and DEM data should be used to estimate local flooding only. Therefore, local residential / urban flooding may be estimated from inland to the nearest adjacent permanent water body using this method, but not between flooding in separate neighborhoods disconnected by land.

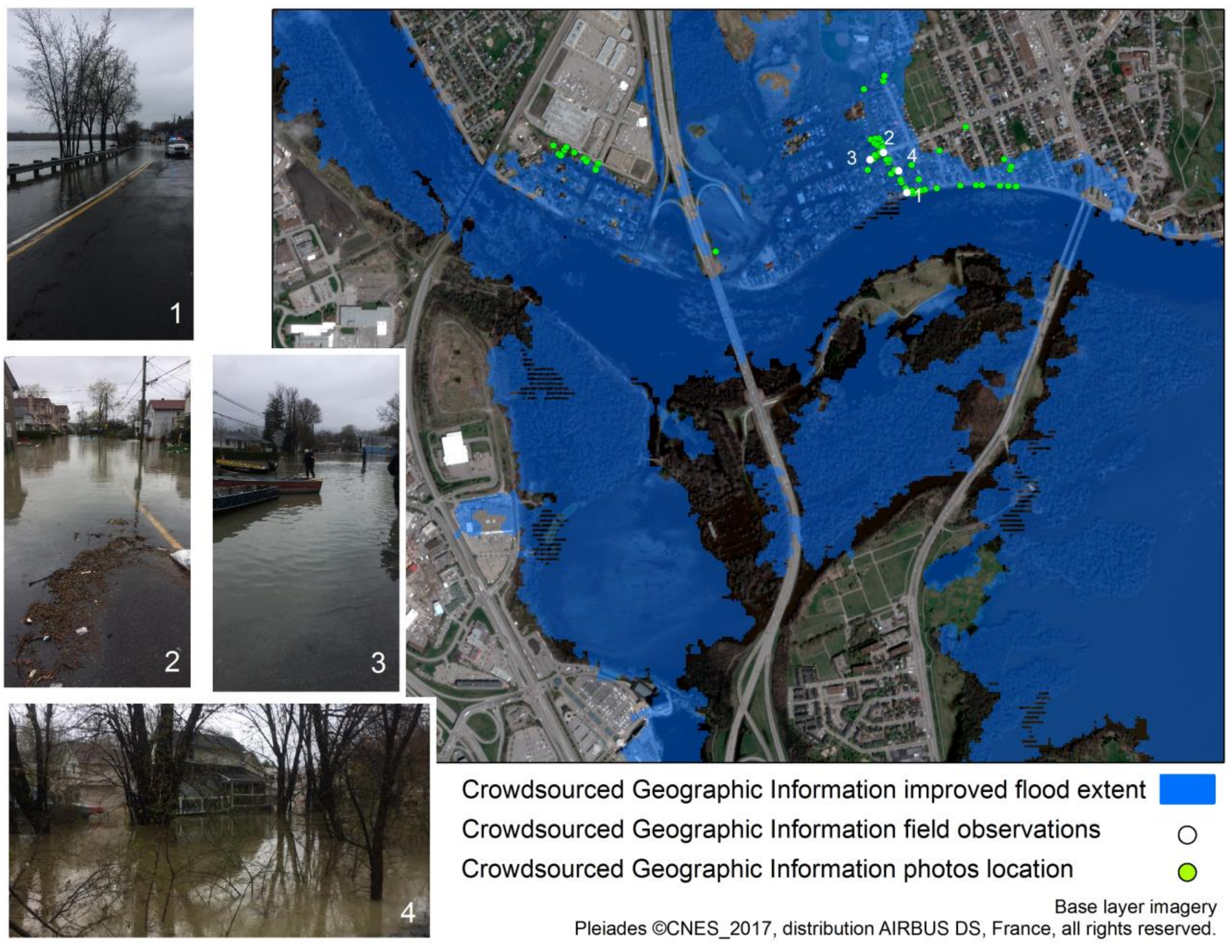

Figure 6. Use of Crowdsourced Geographic Information (CGI) data and a new LIDAR DEM to map urban flooding in Gatineau, Quebec

Preparation for the RADARSAT Constellation Mission will be leveraged to improve flooded vegetation mapping. Brisco et al. (in prep.) are comparing several intensity, polarimetric decompositions, as well as interferometric coherence measures to improve separability between flooded vegetation and other land cover types in the Peace Athabasca Delta (PAD). Initial results suggest that although intensity has the ability to separate flooded vegetation from other land cover types, polarimetry may be better at discriminating double-bounce targets such as flooded vegetation. Therefore, research should continue to determine the best measures to separate classes of interest for flooding, and incorporate them into the current workflow methodology to improve flood mapping results. Thus, region growing for flooded vegetation will not be performed on single polarization intensity, but rather on a polarimetric decomposition measure that is found to be optimal for this discrimination.

The fact that global historical dynamic surface water maps exist raises the question on whether EGS / CCRS should generate its own dynamic surface water maps as an input for operational flood mapping. Errors in input historical inundation frequency maps may not significantly affect the quality of flood maps since machine learning used to classify open water is known to be robust to errors in training data. Therefore, even if global maps omit some water due to the use of optical data from Landsat, errors in training data extracted using these maps should be relatively small compared to the overall training sample size. The activation season was also considered extremely successful using a global historical map product as input, further supporting the use of Pekel's map. However, the more extreme the flood event, the more errors will be introduced when relying on a product that omits water in favour of land. EGS is currently evaluating the level of improvement that can be achieved with better historical inundation information. For this reason, work is continuing to generate Canadian products tuned to our geography and seasonality over select floodplains in Canada. In addition to other sensors, the historical RadarSat archive will be exploited for this purpose as is ongoing along the Saint John River, NB. Finally, the entire approach contains feedbacks in which current flood products are used to update and improve historical inundation products, which will then in turn be used to produce flood products next season. As scenes are added to the time-series of water maps, both historical and near-real time water maps should continue to improve.

Editing of flood maps is still required to remove either false detections or those that are not of interest for public safety. However, we believe that false detections are relatively rare, and those detections that are not of interest for public safety may be relevant to other potential users. Enhancing flood products with ancillary information to target these users may be an avenue worth pursuing to make flood maps useful to a wider audience. For example, flooding is consistently detected in agricultural fields, and standing water is confirmed as a common occurrence when driving through the countryside during the flood season. These detections are ephemeral and are currently being removed from flood maps, but they may be relevant to agricultural production as tilling and seeding are delayed by standing water in fields. Agriculture Canada and crop insurance companies may be interested from a crop inventory perspective to know if crops will be planted late, how much and where. Intersection between flood maps and land cover may be sufficient to characterize different types of flooding in terms of longevity and impacts to different stakeholders.

4. CONCLUSIONS

This Open File presents new EGS operational methods to extract open water and flooded vegetation that were developed on historical data from multiple satellite sensors, and proved to be reliable and robust on a range of sensor data received through the International Disasters Charter during activation. Feedback received from Public Safety Quebec was extremely positive, stating that new products were significantly improved over previous products generated by EGS during the 2011 Richelieu River activation, particularly for flooded vegetation that was mapped operationally for the first time. Technical challenges related to data volume and file size that affect file transfer and processing time still need to be addressed and improved. Work on multi-sensor historical inundation frequency for floodplain characterization should continue rather than relying on global inundation products from optical data to better tailor products to the Canadian context and assess the level of optimization that is still possible. This work should be integrated with ongoing work to incorporate the best RCM parameters at extracting flooded vegetation. Finally, we envision enhancing our flood products through ancillary data integration to make them more relevant to a wider set of users and stakeholders.

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