Improving flood inundation monitoring and modelling using remotely sensed data

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Introduction

Globally, flooding causes half of all deaths due to natural hazards, and one-third of all economic losses. In Europe alone, there were 100 major floods between 1998 and 2011, causing more than 700 deaths, the displacement of over 500,000 people and 25 billion euro of insured losses. In the UK, the devastating floods of summer 2007 cost a total of £3.2 billion, and caused the country's worst peacetime emergency since WW2. The impact of climate change means that the probability of events of a similar scale happening in the future is increasing.

In recent times, the technology of Earth Observation has begun to be adopted to improve flood visualisation and reduce flood modelling uncertainties. High resolution satellite Synthetic Aperture Radar (SAR) sensors are now commonly used in natural disasters such as flooding because they allow images to be taken from space over a wide area, can see through clouds, and can acquire images at night-time as well as during the day. These sensors have resolutions as high as 1m, so that they are able to image flooded streets in urban areas. In the absence of significant surface water turbulence due to wind, rain or currents, flood-water generally appears dark in a SAR image because the water acts like a mirror. As the SAR images the ground at an angle away from the nadir, the incident radar signal is reflected away into space rather than back to the sensor.

As an example, fig. 1(a) shows a 3m-resolution TerraSAR-X image of the 1-in-150-year flood that took place on the lower Severn and Avon rivers around Tewkesbury, UK, in July 2007. Fig. 1(b) shows the great detail visible in the Tewkesbury urban area. Substantial flooding of both urban and rural areas occurred during this event.

This article describes a prototype system for extracting flood extents from SAR imagery and using them to improve flood forecasting using data assimilation (fig. 2). We first consider some of the uses of flood extents, including damage assessment and mitigation, operational flood relief management and improved flood forecasting.

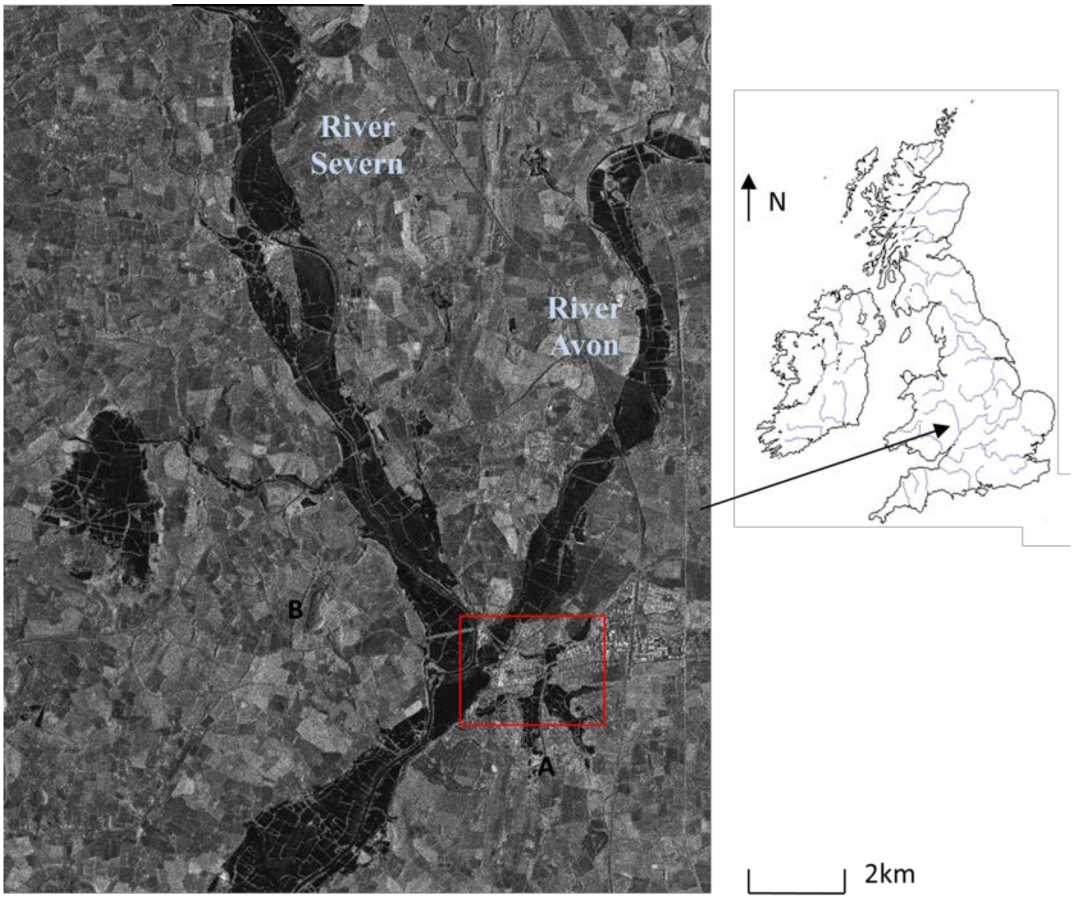

Fig. 1. (a) TerraSAR-X image of the lower Severn/Avon July 2007 flood (dark areas are water) (© DLR 2007). The rectangle includes the urban area of Tewkesbury. (b) Full resolution detail in the urban area (after [1]).

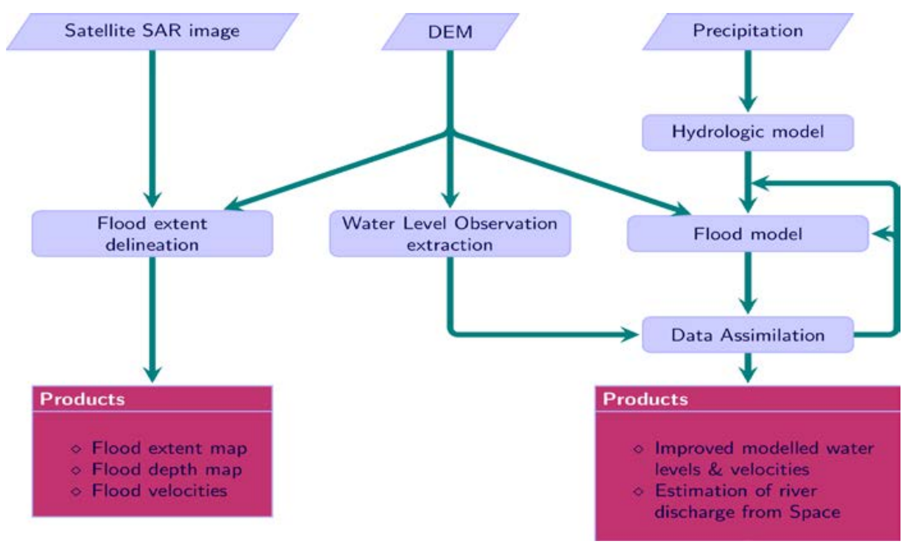

Fig. 2. System flow diagram and flood extent products.

Uses of flood extents derived from SAR images.

1) Damage assessment and mitigation.

The flood extent may be used in damage assessment studies in a post-flood mode to determine those properties that have been flooded, by combining the flood extent with digital map data. This information (together with that below) is useful to re-insurers, for example to weed out false flooding claims.

Additionally, a map of flood depths may be estimated by combining the flood extent with the Digital Terrain Model (DTM) of the floodplain. In general, the deeper a property has been flooded, the more must be spent to make it habitable again.

The flood extent can also help to derive a map of flood velocities at the image acquisition time. The risk to life due to flooding is greater where water velocities are higher. The flood extent can be used to calibrate a computer model of flood inundation, by adjusting model parameters (e.g. channel friction) so that the predicted extent matches that observed. The calibrated model can then be used to predict the velocity map over the floodplain.

The flood extent may also be combined with historical flood maps for flood defence design studies.

2) Flood relief management.

If the SAR image is obtained in near real-time, a further use of the flood extent is as a tool for operational flood relief management. This allows the emergency services to view the geo-registered flood extent at high resolution over a large area overlaid on a base map a few hours after overpass. This is difficult to achieve by other means. Among the many recommendations of the UK Government's Pitt Report (which set out to consider what lessons could be learned from the UK 2007 floods) was the need to have real-time or near real-time flood visualisation tools available to enable emergency responders to react to and manage fast-moving events, and to target their limited resources at the highest-priority areas. It was felt that a simple GIS that could be effectively updated with timings, level and extent of flooding during a flood event would be a useful system to keep the emergency services informed.

Current high resolution satellite SARs include TerraSAR-X, RADARSAT-2 and the COSMO-SkyMed constellation. The latter is particularly important for flood detection because it is a constellation of four satellites that can provide images of a flood at 12-hour intervals. This is useful for imaging flooding in British rivers, which tend to be rather small compared to their counterparts in the rest of the world, so that British floods often last for only a few days. Apart from RADARSAT-2, these satellites do not yet provide near real-time geo-registered imagery that can be overlaid directly onto a digital map.

However, the European Space Agency (ESA) will shortly launch the Sentinel-1 two-satellite high resolution SAR constellation which will give almost daily coverage of floods at European latitudes. The first satellite of the pair is due for launch in early 2014, with the second following

18 months later. The system will allow processed multi-look geo-registered SAR images to be available to the user only one hour after download to the ground station. In addition, ESA have developed the Fully Automated Acqua Processing Service (FAAPS) to process SAR images in near real-time to create geo-registered rural flood extent maps and deliver them to the user via the Internet. While currently only tested on medium resolution SAR imagery, it is envisaged that, when launched, the Sentinel-1 satellites will provide the input images to the system.

3) Improved flood forecasting using data assimilation.

The computer models used for flood forecasting solve the mathematical equations governing the flow of water over the local terrain and predict the water levels as a function of time during the flood. They require an estimate of input flow rates in the river for the forecast. The velocity of the flow over the flooded area is determined by the friction between the water and the surface being inundated (e.g. a road or a grassy field). Flood inundation is difficult to model due to the complexity of the mathematical equations describing the flow, and to uncertainties in the input flow rates and bottom friction parameters. We can partly compensate for these uncertainties by updating the model state with observed information as this becomes available, to help keep the model on track. The process of updating the model state with observations is known as data assimilation (fig. 3). As well as correcting the model state, assimilation can also improve the estimates of the input flow rates and bottom friction parameters. If near real-time SAR images are available, these can provide observations for assimilation into a flood forecasting model.

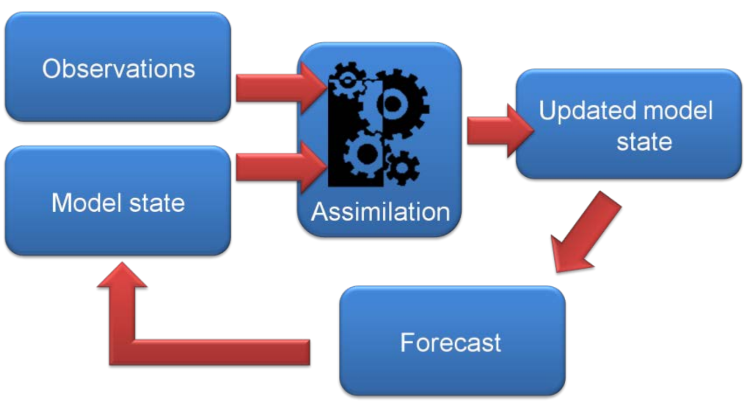

Fig. 3. The process of assimilation.

One common observation that may be assimilated is the water level at various points along the modelled reach. Water levels can be estimated along the boundaries of a flood extent by intersecting them with the floodplain DTM. Assimilation involves combining the predicted water levels with the observed levels in a statistically optimal sense in order to produce revised predicted water levels. An advantage of measuring Water Level Observations (WLOs) from

SAR flood extents is that the method will work in un-gauged catchments. Half of the world's rivers contain no river gauges, and the number of gauges that exist is actually falling.

Many floodplains in the developed world have now been imaged with high resolution LiDAR or airborne InSAR, giving accurate DTMs that can provide accurate WLOs. This is not the case in developing countries. However, the accuracy of WLOs produced for remote rivers should be enhanced in the near future by the TanDEM-X mission. The world DTM currently used for hydrology in parts of the world without accurate DTMs is the Shuttle Radar Topography Mission (SRTM) DTM, which over most of the world is only accurate in height to about 6m in floodplains, with 90m spatial resolution. From 2014, a TanDEM-X world DTM will be available, giving about 1m height accuracy in floodplains and 12m spatial resolution, which should give more accurate WLOs.

In the future, NASA's Surface Water and Ocean Topography (SWOT) Mission will be able using radar interferometry to measure remote surface water levels accurately, but this is not scheduled for launch until 2020. There is thus likely to be a period during which water levels from SAR flood extents will form a unique source of data for assimilation into flood models.

Flood extent delineation algorithm

We have developed a near real-time algorithm for detecting flooding in both urban and rural areas of a high resolution SAR scene [1]. The algorithm assumes that high resolution LiDAR data are available for at least the urban areas in the scene.

The first step in the processing is the generation of the flood extent in the rural areas of the SAR image, employing an algorithm that uses image segmentation to group the very large numbers of pixels in the scene into homogeneous regions. A critical step is the automatic determination of a threshold on the region mean SAR backscatter, such that regions having mean backscatter below the threshold are classified as flooded, and others as un-flooded. Extensive use is made of Trimble's eCognition Developer software at this stage.

The initial rural flood classification may be improved by refining it in a number of ways. For example, emergent vegetation adjacent to the flood such as hedgerows may produce a high rather than low SAR backscatter even though they are flooded. This is due to an effect known as double scattering, whereby radar rays transmitted from the sensor to the water are reflected first to the hedgerow then back to the sensor (or vice versa). Regions of high backscatter that are long, thin, fairly straight and adjacent to flooding are thus reclassified as flooded. The backscatter threshold may also be raised to include in the flood category regions of flooding adjacent to the flood class that have slightly higher mean backscatter than the original threshold (e.g. due to wind ruffling the water surface in more exposed parts of the floodplain).

The vast majority of a flooded area may be rural rather than urban (as in fig. 1), but it is very important to detect the urban flooding because of the increased risks and costs associated with it. The second part of the algorithm detects urban flooding.

A difficulty of urban flood detection using SAR is that, because the SAR views the ground at an angle away from nadir, substantial areas of urban ground surface may not be visible to the SAR due to radar shadowing and layover caused by buildings or taller vegetation. Consider the case of a road running parallel to the satellite direction of travel, with buildings on either side of it. The road immediately behind the buildings nearer to the satellite will be in radar shadow as it is hidden from the radar by the intervening buildings. The shadowed area will appear dark in the SAR image, and may be misclassified as water even if it is dry. In contrast, an area of flooded ground in front of the wall of a building on the opposite side of the road farther from the satellite may be allocated to the same image range bin as the wall, causing a phenomenon known as radar layover which generally results in a strong return, and a possible misclassification of flooded road as un-flooded. This inability of SAR to see the whole of the road surface makes SAR less effective at detecting flooding on this type of road. On the other hand, if the road is

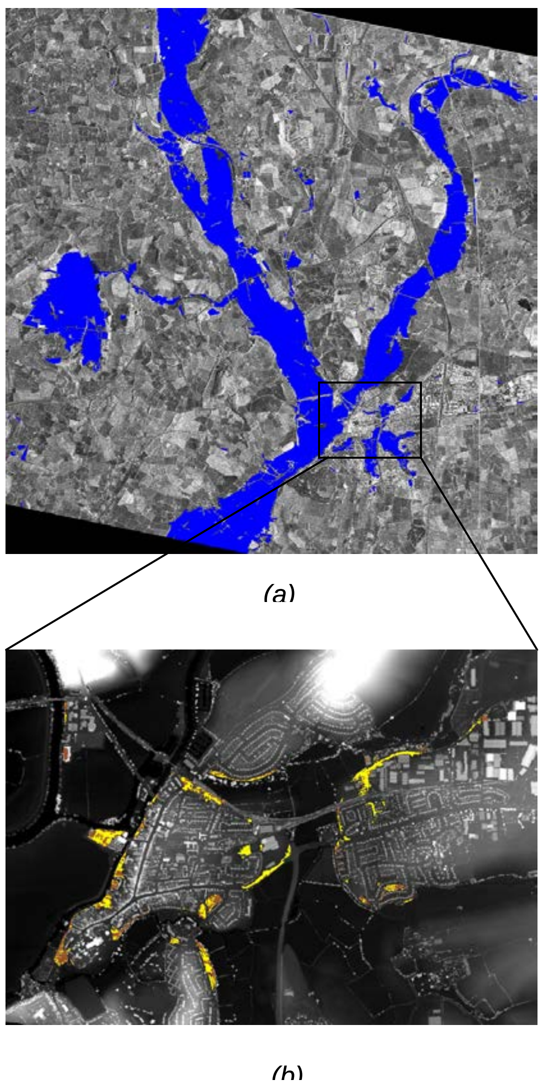

Fig. 4. Possible multi-scale visualization of flood extents in (a) rural (blue = predicted flood), and (b) urban areas (yellow = predicted flood, brown = shadow/layover areas that may be flooded) (after [1]).

perpendicular to the satellite direction of travel, then the satellite will be able to image flooding over the whole width of the road. To address this effect, the algorithm uses a SAR simulator to estimate regions in the SAR image in which water will not be visible due to shadow or layover. The estimation of these regions is purely geometrical and uses the LiDAR height data of the scene surface as well as the radar flight trajectory and incidence angle.

The urban flood detection is guided by the rural flood detection, using the local waterline heights in the rural areas, and assuming that flooding in urban areas should not be at a substantially higher level than in nearby rural areas. Pixels in the urban area having a SAR backscatter less than the threshold and a height similar to or less than that of nearby rural flooding are clustered together into urban flood regions using a simple region-growing process. Regions of shadow and layover are masked out in this process. Fig. 4 shows a possible multi-scale visualization of the flood extents in the rural and urban areas for the flood event of fig. 1.

Assimilation of Water Level Observations

We have also developed software for assimilation of water level observations into a flood inundation model [2, 3].

Every pixel along a flood extent boundary will provide a water level, and we first select a subset of levels for assimilation because adjacent levels will be strongly correlated and add little new information. We select candidate waterline points in rural areas of low slope and vegetation, so that levels can be measured as accurately as possible. The levels and their positions are corrected for the effects of double scattering between the water surface and emergent vegetation at the flood edge. Waterline points are also selected in flooded urban areas away from shadow and layover areas. The resulting points are thinned to reduce spatial correlation, so that we eventually end up with representative water levels reasonably uniformly distributed every 500 m or so down the reach being modelled. Typically such water levels have a height accuracy of 25cm or so.

The method of data assimilation used is called the Ensemble Kalman Filter (EnKF). This assumes that a sequence of SAR images can be obtained in near real-time over the duration of the flood. At the time of acquisition of each processed image, the flood extent and WLOs are extracted, and the EnKF uses the WLOs to correct the water levels predicted by the flood inundation model at this time. This improves the forecast of the future flood level and extent. The EnKF requires a number of model runs (an ensemble) to be made in order to represent the forecast uncertainty. These are obtained by making small perturbations in the time-varying input water flow rate into the flood inundation model domain about its estimated values, and performing a model run for each perturbed inflow. At each point in time and space, the ensemble produces a mean model water level and a spread about this representing the water level uncertainty. An additional feature of the EnKF is that it uses these uncertainties to correct the errors in the input flow rate.

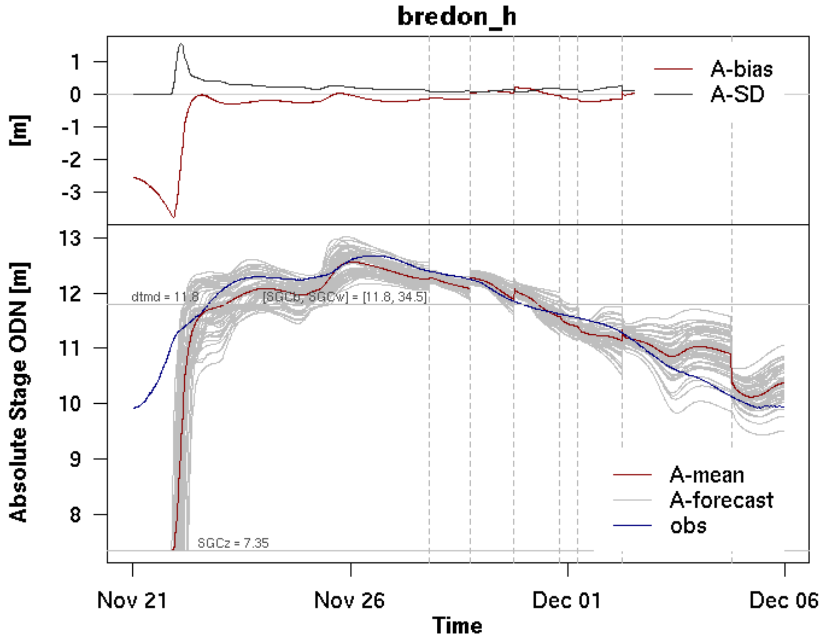

Fig. 5. November 2012 flood event on the Severn-Avon. Water Level time series in the Avon near Tewkesbury (Bredon). In the lower plot, grey lines are the forecast ensemble, adjusted with the sequential SAR observations. The mean forecast (red line) successfully approaches the reference gauge time series (blue line). The upper plot indicates the bias and standard deviation of the forecast.

An example is shown in fig. 5, based on the assimilation of WLOs derived from a 7-image sequence of COSMO-SkyMed images of a flood event on the lower Severn and Avon in November 2012. The graph shows the water levels (stages) of the runs in the forecast ensemble (grey lines) at a location (Bredon) near Tewkesbury in the Avon. The satellite overpass times are indicated by dashed vertical lines. At each assimilation time, the WLOs are used to correct the predicted water levels. The red line is the mean forecast line. The blue line indicates the Water Level time series recorded by a gauge at the location, and is used here as a reference and not for modelling or assimilation. While the first satellite overpass misses the peak of the flood, once the SAR data are available, the processing chain is able to successfully adjust the sequential forecast and keep the flood model on track.

It should be emphasised that the systems described above are prototype software that require extensive further testing on other flooding scenarios before they can be made operational.

Conclusion

Remotely sensed data, in particular those from high resolution satellite SAR sensors, can provide substantial improvements to river flood inundation monitoring and modelling. Flood extents derived from SAR imagery can already be used for damage assessment studies and the design of flood defences. When near real-time geo-registered SAR images become more readily available, there should be a substantial market for flood extents for emergency flood relief management and improved flood forecasting.

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