COMPARISON OF THREE TECHNIQUES FOR DETECTION OF FLOODED AREAS ON ENVISAT AND RADARSAT-2 SATELLITE IMAGES

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ABSTRACT:

In September 2010 the International Charter Space and Major Disasters was activated to record extensive floods in Slovenia. A time series of medium resolution radar images (ENVISAT, RADARSAT-2) was obtained and three techniques of flood area detection were employed: pixel-based water delineation, object-based classification and machine learning procedure. The paper examines and compares advantages and restrictions of these methods. It also validates water under-detection and over-detection on radar images, and examines specifics for their occurrence. Discussion is focusing on some proposals to overcome specific drawbacks, and addressing the usefulness of mapping products for local disaster relief. The study confirms that rapid estimation of flooded areas could be achieved from medium resolution radar images. However, the accuracy is not adequate neither for timely, in-situ rescue operations nor for damage assessment, where correct location and exact delineation of the event are of utmost importance. Improving the accuracy of detection presents a future challenge for remote sensing to be truly helpful in disaster relief.

1. INTRODUCTION

1.1 Motivation

Intensive rains between September 17th and 19th 2010 caused severe floods in many parts of Slovenia. With 170-180 mm precipitation in 48 hours, it is an event with the highest amount of the precipitation in such a short time in the last 60 years (ARSO, 2010). Amongst the most affected areas was also the capital Ljubljana and especially its southern surrounding – the Ljubljana Moor – which was completely under the water. Last such big waters in this area were recorded around 90 years ago.

The International Charter Space and Major Disasters and also the SAFER were activated to monitor the floods devastation. A two-week time-series of medium resolution radar images (12.5 m) of the satellite systems ENVISAT and Radarsat-2 was obtained, which enabled the study of flood dynamics. Radar images enabled satisfactory near-real-time comprehension of flood dynamics in wider area on different dates, however not in urban areas. There were also some problems with water detection in areas of high-grown plants (trees, crops).

The general insight into the vast extent of floods was possible to recognize by means of pixel-based water delineation technique, first maps were produced few hours after the transfer of satellite data from Charter office. Since the results of this rapid mapping are based on radar images with resolution 12.5 m, the obtained flood pattern can reach an accuracy of details for maps at scale 1: 25.000 or less, however not for larger scale. A more careful review of the results showed that obtained flood pattern (considering its ability for spatial detail comprehension at given resolution) was lacking several water occurrences, resulting in a non-continuous and underestimated flood pattern. Although some areas were known to be completely under the water on specified days, repeatedly interrupted and fragmented pattern of water detection persisted in the results. This situation motivated us to validate the obtained results with regards to water missing occurrences based on field inspection and to approach the floods mapping with different mapping techniques.

1.2 Assessment of Different Flood Detection Techniques Applied in Rapid Mapping and Rescue Operations

The key issue of rapid mapping is to offer to the end user accurate situation maps in a shortest possible time. The processing chain consists of data treatment steps that should facilitate event mapping in an autonomous, fast and reliable way. Radar images are typically best data for flood detection. The pixels belonging to flooded areas have lowest values as the return signal from smooth water surface is weak (Henderson and Lewis, 1998). Thus in many cases water determination on radar images can be well defined through the image thresholding procedure, which makes this approach suitable for automated processing. Simply setting a threshold frequently causes some overestimations in water patches determination, as shadows and part of speckle noise (both very typical on radar images) are also attributed as lowest intensity values. Pixel-based water delineation based on simple thresholding may therefore require substantial cleansing and refinement of the mapping results.

Flood detection on remotely sensed data can be performed through various approaches, derived from delineation techniques, object or pixel based classifications, pre and post event comparisons, and similar. Within this paper comparison of three techniques applied for flood detection on radar images are presented: pixel-based water delineation, object-based classification and machine learning procedure. Methodological background of the three techniques and results obtained are shown in brief. Advantages and restrictions of these methods are examined and compared to obtain an insight what makes

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particular technique promising to facilitate rapid mapping of disastrous flood events. Focus on three types of issues (accuracy, efficiency, usability) in comparison of benefits and drawbacks of employed techniques for local disaster relief is then summarised.

Separate section in the paper is committed to the validation of the quality of mapped products. Water determination is addressed from semantic and spatial completeness and accuracy. The potential of radar imagery based products in various surface or landscape settings and at different ranges of observation (natural, agricultural, urban environment) is addressed as well.

The paper concludes by presenting key elements for supporting disaster management with remote sensing. Understanding the advantages and limits of floods identification on radar images and the assessment of water determination practices are important for damage assessment studies, flood prevention modelling and local relief policy development. The study, outlined in the following sections, aims at contributing to increased understanding of the water detection on medium resolution radar images and to improving the value of flood mapping products for local disaster relief needs.

2. RADAR IMAGES AND DATA PROCESSING

Within International Charter Space and Major Disasters around thirty satellite images were obtained, acquired on different dates (new and archive data), covering different areas in Slovenia. Four after-event radar images (ENVISAT and RADARSAT-2) were obtained for the area of the capital Ljubljana and its surroundings (Table 1). ENVISAT image was acquired few hours after the heaviest rain has stopped (on 19.9.2010 evening). The three RADARSAT-2 images are from the days after the disastrous event. These images allowed us to map the situation and the dynamics of the floods on the Ljubljana Moor.

Satellite and Sensor (Space agency)	Date of Capture	Spatial Resolution (m)
ENVISAT ASAR APM (ESA)	19.9.2010	12.5
RADARSAT-2 EH HH (CSA)	23.9.2010	12.5
RADARSAT-2 PIP HH (CSA)	26.9.2010	12.5
RADARSAT-2 PIP HH (CSA)	2.10.2010	12.5

Table 1. A list of radar images received through the activation of the International Charter Space and Major Disasters. Table includes images covering the area of capital Ljubljana and its surroundings.

2.1 Radar Data Treatment

Known parameters of the geometry of radar satellite imaging enabled the orthorectification of images. The latter was done in Erdas modul OrthoRadar with the use of the digital elevation model of resolution 12.5 m. It eliminated the differences in incidence angle and minimized deviations in terrain position. The speckle noise was reduced by radiometric enhancements. Mean filter in a range 3×3 pixel was applied. For every image the threshold for water detection was manually set and supervised filtering of shadows and remaining speckle noise was applied. Distinction between water and shadows were done taking into account shadow mask and surface slope information.

The described procedure of radar image processing is half-automatic and applicable to all received radar images. Results are available within few hours after receiving satellite data. Described image processing provided the maps of flooded areas on the Ljubljana Moor for acquisition dates. Maps were afterwards sent to the end user, the Administration for Civil Protection and Disaster Relief.

2.2 Flood Detection and Interpretation

Radar images are typically most valued data for flood detection. The pixels on flooded areas have lower values because the return signal from smooth water surface is weak (Henderson, 1998). But there are many disturbances in real situations: speckle noise, shadows, and presence of objects amplifying the return signal. Shadows present a disturbance in mountainous surfaces. Shady areas have low values and can be wrongly detected as flooded. False water detection can be dismissed considering slope and sensor viewing angle.

The observed area consists of urban and agricultural land where other problems occurred. Objects above the water surface (houses, traffic lights, trees, corn) and water waves cause part of radar signal is reflected back to the satellite receiver. Therefore, the intensity of the reflected signal is higher and the area is not recognised as flooded. Reflectance can be induced by every object with the size of a few centimetres or larger. Furthermore, artificial objects in the urban area can make complete reflection to one direction. The listed situations may cause also that objects within neighbourhood area reflect increased intensity, and are thus not represented as flooded on the images.

Figure 1: High plants (especially corn) make the detection of floods in these areas impossible. The white line indicates the height of the water (over 1.5 m).

Figure 2: The mosaic of tree-groups and narrow corn-fields in the Ljubljana Moor presents a specific problem for flood detection on medium resolution radar imagery (field width is similar to pixel size).

On the Ljubljana Moor area we met several specific problems. There are a lot of fields covered with high crops (in September especially corn, Figure 1). These areas are detected as non-flooded. A similar problem is posed by trees and shrubs. This sounds reasonable considering that radar signal cannot penetrate through dense crops or leaves to reach the water on the ground.

Additional obstacle for proper water detection is the fact that fields on the Ljubljana Moor are typically long and narrow (Figure 2). The width of the fields is often similar to the spatial resolution of the images (12.5 m). Since fields are alternately planted with corn (high) and other plants (low), this causes problems at the given imaging resolution.

2.3 Mapping of Flooded Areas on the Ljubljana Moor

Analyses of radar images gave us a good insight into the extent of floods and dynamics of water (inflow/outflow) on the Ljubljana Moor. Figure 3 presents how the water was receding from the Ljubljana Moor within the first two weeks after the disastrous event: on east part the recession was rather quick, on west part however very slow. On the other hand flood perception in urban areas (e.g. Vič – south-eastern quarter of Ljubljana) was unsuccessful because of characteristics of radar waves on heterogeneous surfaces. Geometry and arrangement of objects influence the reflection of radar signal. It causes an increase in the intensity of radar reflection also in nearby pixels while totally dismissing flooded areas in urban environment.

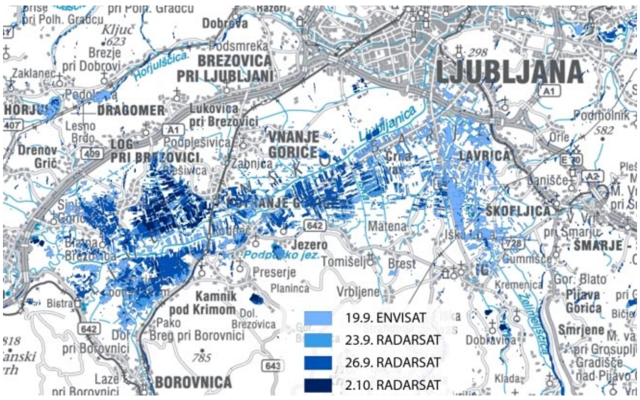

Figure 3. Time series of radar images show spatial and temporal aspects of water receding of the Ljubljana Moor.

3. VALIDATION OF FLOODED AREAS DETECTION AND DETERMINATION

This section outlines the validation of water under-detection and over-detection on used radar images, and examines specifics for their occurrence. The validation data was obtained during two field surveys. The first was performed together with the team of SAFER project as a part of their field survey on 30.9.2010, and the second was made on 5.10.2010 by our own side. An extra source of data for validation was report of the Administration for Civil Protection and Disasters Relief (URSZR, 2010).

Interpretation of radar images is much more difficult than interpretation of optical images. The intensity of reflectance of radar waves depends on the characteristics of the surface like roughness and dielectricity, and on the geometry of observation, especially the viewing angle. Considering some known disadvantages related to water identification from radar images (Puech et al, 2009; Chen et al, 1999; Mason et al, 2010; Pradhan, 2009) and the field survey validation data we draw the following conclusions about under and over-detection of water.

Water under-detection mainly occurs in these situations:

- The resolution of radar images 12.5 m is too low for the area with a non-homogenous surface cover. There a lot of different land cover types are combined on relatively small area. Therefore, reflections of radar waves from different types of land are mixed, so e.g. boundaries of fields are not consistently recognized.
- In urban land flooded areas were not detected at all. The geometry and arrangement of objects (houses, trees, traffic lights and power lines etc.) cause a strong reflection of radar waves. Consequently, the intensity of return signals from urban flooded area can be significantly higher than the one from smooth water surface with no surrounding object disturbances.
- On the intensive agricultural areas there are – in the middle of September – a lot of corn fields, which had not yet been cropped. Many of these areas were flooded but the water was not detected because the radar waves did not penetrate through the crop down to the flooded grounds.
- Shrubs, individual trees or tiny lines of high grass extending slightly above the water surface also present the difficulty for flood detection. The flooded areas around such type of vegetation are usually classified as not flooded because of a quite considerable reflectance from these objects.

On the other hand water over-detection presents less frequent problem, however the main reasons were also examined. Larger patches of shadows in mountainous terrain can be classified as water. Isolated small patches (of few pixels), consequence of radar-typical speckle noise, can be also classified as water.

Good knowledge of the causes for the under- and over-detection of water on the radar images and the circumstances in which they occur, allow that the described defects can be partially eliminated by modelling and spatial analysis. Some examples are: masking riparian vegetation, identification of shadows due to terrain parameters and viewing angle, and generalization of the contour lines of flooded areas where land use is mixed (and where consequently the contour lines are fragmented and flood pattern is repeatedly interrupted and non-continuous). For the needs of rapid mapping, we can reduce the effects of over-detection errors quite simply with semi-automatic procedures. Reduction of errors of water under-detection is more complicated. It cannot be easily performed via automated processing procedures, and therefore has a lower potential for the implementation in the process of rapid mapping.

4. COMPARISON OF PIXEL-BASED WATER DELINEATION, OBJECT-BASED CLASSIFICATION AND MACHINE LEARNING PROCEDURE

Flood extent, detected on radar images of satellite systems ENVISAT and RADARSAT-2, is highly dependent on the shape and land cover of the surface. We realise that the use of radar data of medium resolution is sufficient for mapping of floods in the natural environment and at regional scale. The great value of radar data lies in the important fact, that the images can be acquired within any needed time frame (independently of meteorological conditions), thus supporting monitoring of event dynamics in the wider area and in a continuous way.

However the quality of mapped results on a large (local) scale is not satisfactory due to water under-detections. Obtained flood pattern reflects the situation "seen from above", therefore fails to reveal floods where natural or man-made objects extend above water surface. The main deficiency of detected flood pattern is therefore its non-continuous (repeatedly interrupted and fragmented) and underestimated outline. To overcome this problem we tested and compared three approaches and examined their potential in eliminating these specific drawbacks. Input radar data were pre-processed as described in section 2.1.

4.1 Description of the Methods

Pixel-based water delineation is a thresholding technique. The procedure on pre-processed radar data was composed of several steps: manual identification of best threshold value, delineation of associated pixels, refinement with elimination of small patches (MMU < 5 pixels) with sieve and clump algorithm, refinement with elimination of shadows classified as water with modelling and masking out shadows and areas of steeper slopes (above 3˚). Apart from the first step which is a manual one, all other steps were performed automatically. This procedure was developed and implemented in Erdas.

Object-based classification was composed from the following steps: initial segmentation, where attention was paid to obtain distinguishable water bodies boundaries, calculation of segments' attributes (spectral, spatial, textural), and semantic classification based on decision rules (e.g. rule-based). Combining spectral attributes, gentle slope fitness and shadow exclusions, water and moisture class were defined. The procedure required user interventions at every step to fine-tune the parameters, therefore it was not automatic. This procedure was implemented in ENVI Zoom.

Additional data used in both procedures described above was DEM and its derivates (shadow locations, slope information).

Application of machine learning procedure for determination of flooded areas is different from methods described above, since it is using wider set of auxiliary data. Besides radar image and DEM derivatives (slope, heights) also hydrology (distance from water streams) and land use data were used to model flooded areas. Machine learning approach proved to be successful in addressing the problem, where other two methods failed: detection of floods under the corn fields where radar waves do not penetrate through the crop down to the flooded grounds.

The machine learning procedure was carried out through the following steps. Preparation of a meaningful set of training data: 300 training points were generated to represent the 25 × 20 km wide area. Each of these points was described by six attributes: pixel value of radar image (intensity), height, slope, distance from water (permanent rivers and streams), land use, and tag "flooded" with only two allowed values: 0 for non-flooded and 1 for flooded areas. Then WEKA software and its J4.8 algorithm were used to build a decision tree. The most important attributes to determine flooded areas proved to be heights and distances from water. After the decision tree was applied to the entire image and visualised within Erdas Knowledge Engineer tool.

4.2 Comparison of Performance

Maps on figure 4 show flooded areas on the heterogeneous landscape ("mosaic" of fields, forest and settled areas) using three different techniques on the same radar image.

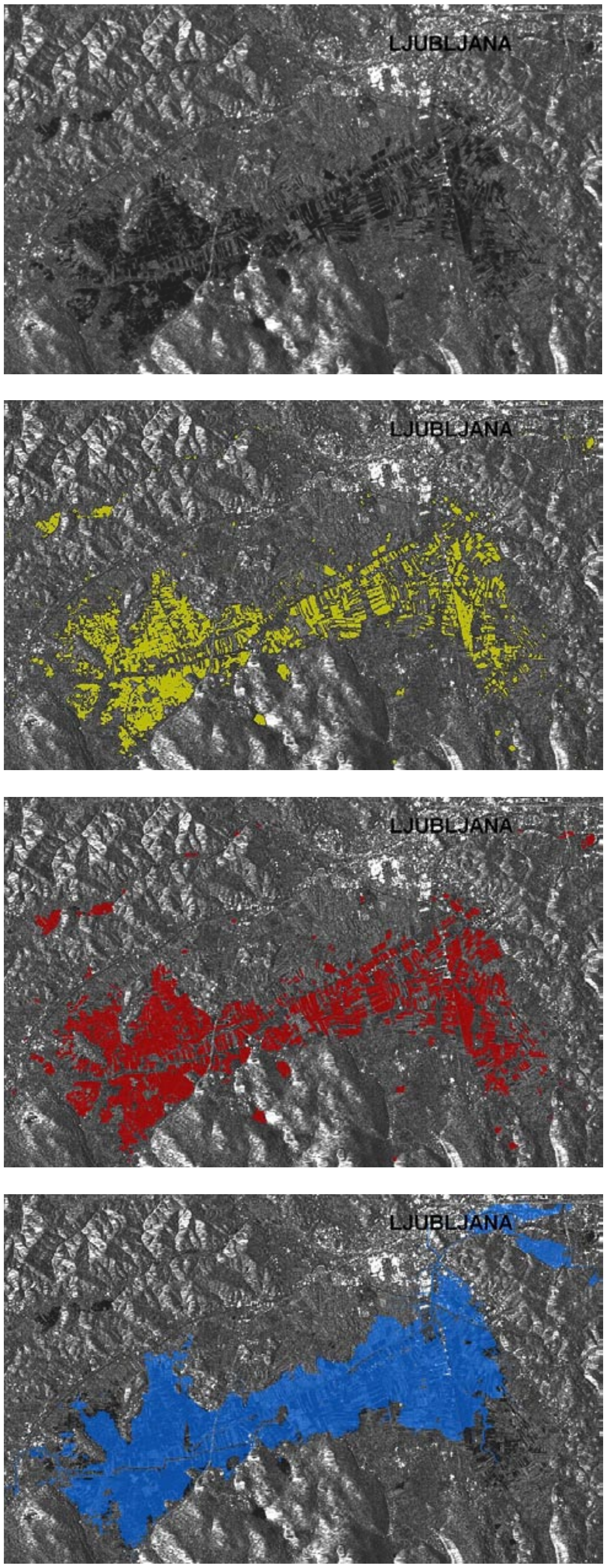

Figure 4: Comparison of input image (19.9.2010 Envisat image) and mapped results using three different techniques: ENVISAT image (top), pixel-based water delineation (upper middle), object-based classification (lower middle) and machine learning procedure (bottom).

Patterns of flooded areas that were produced with the pixel-based thresholding and the object-based classification are discontinuous. On the other hand the machine learning algorithms – where apart from the radar imagery also other data are utilized – enable extraction of more continuous flood pattern. However, there some wrong flood annotations (erroneous classifications) are present.

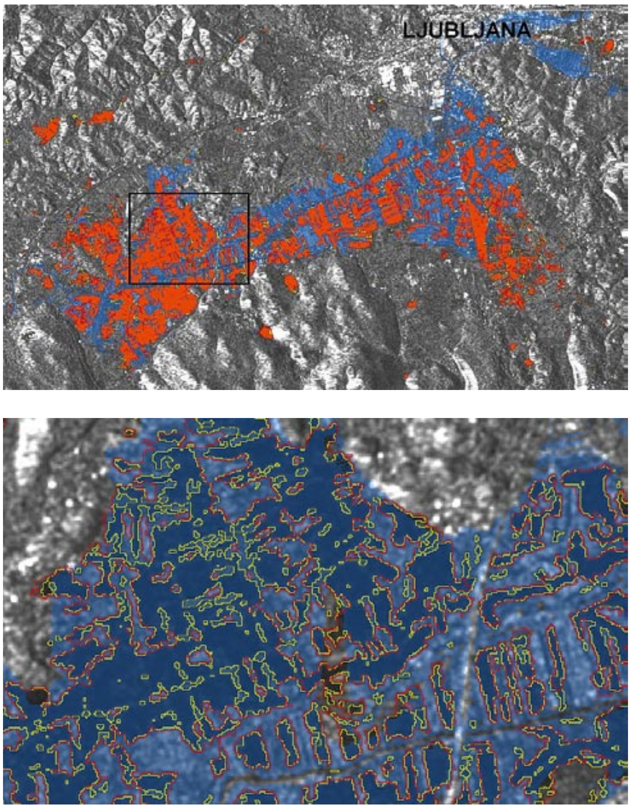

Figure 5: Comparison of flood detection performance for the 19.9.2010 ENVISAT image based mappings using the three techniques over the Ljubljana Moor (top), and in detailed view (bottom). ENVISAT image acquired on the same date serves as background.

4.3 Potential for Eliminating the Drawbacks of Water Detection on Radar Imagery

The key advantage of pixel-based delineation is its high level of automation and autonomy and thus suitability for rapid mapping. The drawbacks are three. Of all the three techniques this method delivers the highest level of noise (small patches detection) in flooded areas pattern. Since the calculation is pixel-based, the results obtained are in raster form and need to be transformed to vectors (and generalised) afterwards. The obtained flood pattern represent underestimated flood situation on the ground, characterised with a high level of its discontinuity. On the other hand this approach support a variety of possibilities for mid- or post processing routines for overestimated (erroneous) flood pattern refinements due to known radar imagery properties.

Object based classification technique gives most straightforward results considering how to obtain the object of interest – flooded areas. The drawback of the technique is that it is merely user driven, thus is less appropriate when a mass of images is to be processed. Important merit of object based technique is its nature in semantic modelling. The object of interest can be conceptually very well defined based on many possibilities of combining attribute properties, thus leading to a low degree of erroneous classifications. The procedure produces raster and vector output simultaneously, and may require minor post-classification refinements. The limit of this method, similar to pixel-based delineation, is underestimation of actual situation on the ground due to satellite detection ability and perspective.

The machine learning procedure is the only technique that overcomes the problem of flood pattern discontinuity, but also introduces some evident misclassifications. Honestly speaking this is understandable, since the decision tree algorithm assigned more importance to the attributes elevation, slope and distance from water, while information obtained from radar data was assigned the least importance. This may be explained by the attributed terrain characteristics of the studied area: very flat, marshy terrain, being almost a lake also in normal conditions. Results obtained from this technique are primarily in raster form, where two classes are presented: flooded and non-flooded pixel candidates. The main drawback of machine learning is substantial data preparation for data mining approach, and that places this procedure on the most time-demanding position. With current status of technology this procedure is not yet appropriate for disaster rapid mapping purposes.

In general we can summarise that each of presented techniques has positive and negative properties for observation of affected areas within near-real-time requests (Table 2). The pixel-based thresholding and the object-based classification give similar mapping results, the former with slightly higher rate of under-detection and fragmentation, and both suffering the discontinuity problem. Machine learning approach best overcomes the fragmentation issue, but may introduce some erroneous results due to low ranking of radar data information in the classification model.

Concerning the completeness and accuracy of flood determination ability from radar data the object-based approach performs best, and pixel-based approach being at the second position. While both give similar results, the preferred one can be chosen upon user preferences and overall disaster mapping situation. The main issue that we cannot overcome is that satellites record what can be seen from the bird's-eye perspective. For this reason it is important to stress that high resolution data and combinations with other data (field data, local referential maps) are imperative for disaster monitoring, mapping and modelling. In particular high resolution optical satellite images and digital elevation model with its derivates (heights, slope, and shadows) can improve the detection of floods with remote sensing data in heterogeneous landscapes.

5. ADDRESSING THE USEFULNESS OF MAPPING PRODUCTS FOR LOCAL DISASTER RELIEF

This section addresses the usefulness of mapping products for local disaster relief and focuses on some proposals to overcome specific gap between the end user actual needs (local disaster relief) and available products from data providers (emergency response initiatives).

The study showed the usefulness of time series of satellite images. They help to analyze the waters dynamics. They help to define which areas were flooded first, which were flooded last and where the water stayed longest. This information can help to improve flood protection and support flood prevention in critical areas in the future. Maps of flooded areas at different dates can also be applied as control parameters in flood simulations.

In this disaster event the usefulness and the necessity of the International Charter Space and Major Disasters was shown once more. Natural disasters are happening unpredictably all over the world and help should be given immediately. The satellite imagery acquired by the Charter cooperating space agencies enable local communities to react in more effective ways. However, when maps of affected areas of floods in Slovenia were produced and disseminated to local end users (local disaster relief), the accuracy was not adequate neither for their timely, in-situ rescue operations nor for damage assessment, where correct location and exact delineation of the event are of utmost importance.

With medium resolution data we can effectively monitor situations on regional scale, and those areas that are remote or hardly accessible. Yet for local scale disaster relief interventions there is a strong need for products based on high resolution data.

In the following table we compare benefits and drawbacks of employed techniques for local disaster relief activities and needs. We focus on three types of issues: accuracy, efficiency and usability. The table is based on our experiences obtained from data processing and end-user feedback on mapping results.

	Pixel-based water delineation	**Object-based classification**	**Machine learning procedure**
ACCURACY *Degree of overcoming water under-detection (false negative)*	Low	Medium	High
ACCURACY *Degree of overcoming water over-detection (false positive)*	Medium	High	Medium
EFFICIENCY *Rapid mapping capabilities: degree of automation*	Medium	Low	Low
EFFICIENCY *Rapid mapping capabilities: speed of computation*	High	Medium	Low
USABILITY *For Near–Real-Time system implementation*	High	Medium	Medium
USABILITY *For disaster mitigation and preparedness*	Medium	High	Medium

Table 2: Comparison of benefits and drawbacks of the three employed techniques in view of near-real-time request for local disaster relief and management.

As the table implies, for a general flood event determination on medium resolution radar imagery there is no preferable method. The selection of the most suitable method depends on the event specifics, the characteristics of the flooded terrain and demands of the end user.

6. CONCLUSIONS

In September 2010 the International Charter Space and Major Disasters was activated to record extensive floods in Slovenia. The paper presents the results of determination of flooded areas produced from obtained medium resolution radar images. First, the analyses of radar observations from four dates were shown to exemplify the potential of continuous monitoring of the extent of floods and dynamics of water (inflow/outflow) on the Ljubljana Moor. This information is crucial for flood prevention measures in future. Second, three different techniques (pixel-based water delineation, object-based classification and machine learning procedure) were examined in their performance to overcome specific limitations in floods determination from the same radar images. The former two techniques suffered the discontinuity problem, while the later overcomes it, but introduces some erroneous results due to low ranking of radar data information in the decision model. None of three techniques could present overall better performance, so the selection of the proper technique is the matter of specific case. The pixel-based tresholding is the fastest and most automatic, the object-based classification gives conceptually best defined objects, and the machine learning procedure successfully utilizes also other (non-satellite) data, respectively. The techniques were also compared for their benefits for local disaster relief activities and needs.

Paper also discusses the deficiencies of radar images for detection of water area in heterogeneous landscapes. After validation it was possible to expose several water under-detections and over-detections, and to evidence specifics for their occurrence. Although the reasons for deficiencies were established, we were able to eliminate them only to limited extent integrating additional data and applying contextual modelling in post rapid mapping activities.

The study confirmed that rapid estimation of flooded areas from medium resolution radar images can be achieved. The accuracy is sufficient for regional scale. On the other hand, the accuracy is not adequate neither for rescue operations immediately after the disaster event, nor for damage assessment afterwards. Improving the accuracy of detection presents a future challenge for remote sensing to be truly helpful in disaster relief.

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