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An approach for flood monitoring by the combined use of Landsat 8 optical imagery and COSMO-SkyMed radar imagery

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ABSTRACT

Remote sensing techniques offer potential for effective flood detection with the advantages of low-cost, large-scale, and real-time surface observations. The easily accessible data sources of optical remote sensing imagery provide abundant spectral information for accurate surface water body extraction, and synthetic aperture radar (SAR) systems represent a powerful tool for flood monitoring because of their all-weather capability. This paper introduces a new approach for flood monitoring by the combined use of both Landsat 8 optical imagery and COSMO-SkyMed radar imagery. Specifically, the proposed method applies support vector machine and the active contour without edges model for water extent determination in the periods before and during the flood, respectively. A map difference method is used for the flood inundation analysis. The proposed approach is particularly suitable for large-scale flood monitoring, and it was tested on a serious flood that occurred in northeastern China in August 2013, which caused immense loss of human lives and properties. High overall accuracies of 97.46% for the optical imagery and 93.70% for the radar imagery are achieved by the use of the techniques presented in this study. The results show that about 12% of the whole study area was inundated, corresponding to 5466 km^2 of land surface.

1. Introduction

As one of the most common and devastating natural disasters, floods endanger human lives and cause severe economic damage, disaster-induced diseases, and extensive homelessness throughout the world. In recent years, floods have threatened many regions of the world more frequently (Kundzewicz, 2008; Berz, 2001; Milly et al., 2002), and according to the Centre for Research of the Epidemiology of Disasters (CRED), flooding has affected nearly one billion people in the decade of 2001–2010 globally, and resulted in estimated damages of about 142 billion US dollars (Martinis, 2010). In order to assess the scale of flood disaster and limit the consequences (loss of life and property) when a flood has occurred, which in turn provides the basis for gathering experiences for the future disasters, accurate water extent information before and during the flood need to be acquired in a rapid manner. In the past decades, with the launching of numerous satellite sensors, such as the Advanced Very High Resolution Radiometer (AVHRR), the Landsat series sensors (MSS, TM, ETM+, OLI), the Moderate Resolution Imaging Spectroradiometer (MODIS) and synthetic aperture radar (SAR) systems, techniques utilizing satellite remote sensing data to monitor and map flood events have proven to be useful in numerous crises (Li et al., 2015; Malinowski et al., 2016; Lee et al., 2016). Compared with the punctual surface data which depends to the application and needs such as rainfall records and measurements obtained from water-level meters, satellite data provides continuous land cover information and a basis for preparation of digital elevation models which might help in flood risk assessment, flood monitoring, and damage assessment (Sanyal and Lu, 2004; Bates, 2004).

Generally speaking, the satellite remote sensing data used for flood detection is either acquired using active or passive sensors. All the optical satellite imagery is obtained by passive sensors, such as the Landsat series, the AVHRR, the Satellite Pour l'Observation de la Terre (SPOT), etc. Thanks to its various advantages, optical

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satellite imagery has been widely used for flood detection and inundation mapping (Niedermeier et al., 2005; Blasco et al., 1992; Smith, 1997; Van der Sande et al., 2003; Khan et al., 2011). Unlike optical systems, SAR sensors can penetrate thick clouds to collect ground information under all weather conditions, which is ideal for flood monitoring (Haruyama and Shida, 2008). With the recent launch of new active sensors such as COSMO-SkyMed (CSK) (Covello et al., 2010), TerraSAR-X, and Envisat Advanced Synthetic Aperture Radar (ASAR) (Gstaiger et al., 2012a,b), active satellite data with high spatial and temporal resolutions has become available and has been widely used for flood monitoring. Accurate knowledge of water bodies of the periods before and during the flood is crucial for flood extent mapping based on remote sensing images. In this context, the commonly used water body extraction techniques based on optical satellite imagery can be categorized into three basic types: (1) single-band thresholding (Gstaiger et al., 2012a,b); (2) spectral water indices (Xu, 2006; Feyisa et al., 2014; Xie et al., 2014); and (3) thematic classification methods (Lira, 2006; Ko et al., 2015). Single-band thresholding and spectral water indices are the commonly used water extraction methods because of the ease of use and the fact that they are computationally less time-consuming. Thematic classification methods use a deep learning algorithm to make full use of the spectral information of the remote sensing images, and they possess the capability of highly accurate water extraction, especially for highly complex land-surface regions (Chen et al., 2015; Mueller et al., 2016). Furthermore, combinations of various methods have also been proposed to improve the water extraction accuracy. Examples are the methods proposed by Jiang et al. (2012), Sheng et al. (2008), Sun et al. (2012) and Verpoorter et al. (2012). As a result of the widespread and in-depth study of water extraction using optical satellite imagery, the current methods can meet the demands of most water body mapping applications in the case of high-quality remote sensing imagery and weather conditions that are free of clouds.

Compared to optical systems, SAR systems provide some advantages in acquiring accurate information on rainy days, especially during floods. For instance, as radar returns are usually low over smooth, open water surfaces, flooded areas can be easily distinguished from other types of land cover, if they are not disturbed by strong wind, which leads to increased surface roughness (waves) (Matgen et al., 2007). As radar images contain only one band, all the approaches are focused on the backscattering properties in this band. In the literature, the main SAR-based flood extent mapping methods are simple visual interpretation (Oberstadler et al., 1997), supervised classification (De Roo et al., 1999; Townsend, 2002; Pulvirenti et al., 2013), histogram thresholding (Topographic, 2006; Pierdicca et al., 2008; Chini et al., 2013; Schumann et al., 2007), and interferometric SAR coherence (Bazi et al., 2005). In particular, active contour models based on image statistics have been widely used in flood extent delineation (Bates et al., 1997; Horritt, 1999). Currently, a wealth of algorithms is available for flash flood mapping during a crisis (Gstaiger et al., 2012a,b; Mason et al., 2010, 2012; O'Grady et al., 2011; Martinis et al., 2009; Giustarini et al., 2016; Pulvirenti et al., 2011). For example, Pulvirenti et al. (2011) introduced a method that couples segmentation techniques and a SAR backscatter model. Matgen et al. (2011) introduced a SAR-based flood mapping technique that combines thresholding and region growing, benefitting from the respective strengths of the specific processes, while avoiding their individual shortcomings.

Numerous researchers have evaluated flood conditions using a single radar dataset, simply depicting the uni-temporal flood water extent and discussing the flood water impact on other land-cover classes, such as urban regions or infrastructure (Mason et al., 2010; Giustarini et al., 2013). However, to monitor floods more accurately, more advanced studies should focus on the efficient use of multi-temporal and multi-source data. In general, three combinations of satellite imagery can be used for flood inundation detection, respectively applied to the periods of before and during flood: (1) optical imagery/optical imagery; (2) optical imagery/SAR imagery; and (3) SAR imagery/SAR imagery. The easily accessible optical imagery provides abundant spectral information that enables highly accurate water extraction in weather conditions free of clouds. SAR imagery, despite the limited data sources and the cost, is particularly useful for flood map generation thanks to its all-weather and day-night operation capability (Pulvirenti et al., 2011; Dellepiane and Angiati, 2012; Matgen et al., 2011). Clearly, the second combination of imagery would seem to be the best choice for flood inundation detection. A number of methods for flood progression analysis relying on multi-temporal and multi-source data have previously been proposed (Schumann et al., 2007; Pulvirenti et al., 2011; Mason et al., 2010; Kuenzer et al., 2013; Schumann et al., 2011); however, these methods only work in specific situations, and the potential of flood monitoring by the use of a combination of two kinds of imagery still needs further exploration.

The objective of this study is flood monitoring in real-time by combining multi-source remote sensing data. Specifically, we use medium-resolution CSK images to describe a large-scale water area with a high accuracy during the flood, and to further identify flooded area through comparing the water map derived from the Landsat 8 images before the flood. The rest of this paper is structured as follows. In Section 2, we describe the study datasets and give some background to SAR imagery. In Section 3, the water extraction methods based on Landsat OLI imagery and CSK imagery are described in detail. In Section 4, the results derived by the different methods are evaluated and an in-depth discussion is carried out in Section 5. In Section 6, we draw our conclusions for this study.

2. Study area and datasets

Northeastern China contains a large number of rivers, which have been historically prone to massive floods. The principal river of northeastern China, the Heilongjiang River, flowing through China, Russia, and Mongolia, is the world's tenth largest river, with a basin area of 1,843,000 km^2. It contains 200 tributaries, including the Songhua River and the Ussuri River (see Fig. 1). On August 12, 2013, heavy rain hit the area upstream of the Nen River, which led to the greatest flood in northeastern China since 1998. Up until August 30, the Chinese government reported that a direct economic loss of 78 million Yuan had been caused by this flood.

To monitor the damage caused by the flood, two kinds of remote sensing data sources were used in this study: optical imagery and SAR imagery. For the purpose of water extraction before the rainstorm, five Landsat 8 OLI images of product level L1T were acquired from the USGS database at: http://glovis.usgs.gov/. Due to the reduced information and increased image noise in the cirrus band, seven spectral bands with the cirrus band removed were used for the experiments.

The CSK system is a constellation of four satellites funded by the Italian Space Agency (ASI) and the Italian Defense Ministry that is aimed at supplying SAR data for a wide range of applications. The system hosts an X-band SAR sensor with right- and left-looking imaging capabilities, an incidence angle range of 20–60°, and a revisit time of 12 h in the worst case. The antenna has been designed to implement four different operation modes (i.e., Spotlight, Stripmap Himage, Stripmap PingPong, and ScanSAR), in order