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Sub-pixel flood inundation mapping from multispectral remotely sensed images based on discrete particle swarm optimization

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A B S T R A C T

The study of flood inundation is significant to human life and social economy. Remote sensing technology has provided an effective way to study the spatial and temporal characteristics of inundation. Remotely sensed images with high temporal resolutions are widely used in mapping inundation. However, mixed pixels do exist due to their relatively low spatial resolutions. One of the most popular approaches to resolve this issue is sub-pixel mapping. In this paper, a novel discrete particle swarm optimization (DPSO) based sub-pixel flood inundation mapping (DPSO-SFIM) method is proposed to achieve an improved accuracy in mapping inundation at a sub-pixel scale. The evaluation criterion for sub-pixel inundation mapping is formulated. The DPSO-SFIM algorithm is developed, including particle discrete encoding, fitness function designing and swarm search strategy. The accuracy of DPSO-SFIM in mapping inundation at a sub-pixel scale was evaluated using Landsat ETM + images from study areas in Australia and China. The results show that DPSO-SFIM consistently outperformed the four traditional SFIM methods in these study areas. A sensitivity analysis of DPSO-SFIM was also carried out to evaluate its performances. It is hoped that the results of this study will enhance the application of medium-low spatial resolution images in inundation detection and mapping, and thereby support the ecological and environmental studies of river basins.

1. Introduction

Flood is one of the most frequently occurring natural disasters, causing great damage, human suffering and economic losses. Changes in global climate and land use have increased the severity and frequency of floods all around the world (Akinci and Erdogan, 2014). Therefore, the study of flood inundation has important significance to human life and social economy (Chen et al., 2014a; Chen et al., 2011; Son et al., 2013; Tralli et al., 2005). Inundation has spatio-temporal distributions. Remote sensing technology has provided an effective way to study these inundation characteristics using multi-spatial, multi-temporal and multispectral remotely sensed images (Chen et al., 2014b; Huang et al., 2012; Huang et al., 2013; Huang et al., 2014b; Huang et al., 2014c; Ticehurst et al., 2013). Many remote sensing sensors have been applied to flood inundation detection and mapping (Bryant and Rainey, 2002; Chen et al., 2013; Gan et al., 2012; Huang et al., 2014d; Mason et al., 2014; Thomas et al., 2011), such as the Advanced Very High Resolution Radiometer (AVHRR), Landsat Multispectral Scanner System (MSS), Landsat Thematic Mapper/Enhanced Thematic Mapper Plus (TM/ETM+), the Moderate Resolution Imaging Spectroradiometer (MODIS), Synthetic Aperture Radar (SAR), and Light Detection and Ranging (LIDAR). However, remote sensing sensors generally do not have high temporal and spatial resolutions at the same time. There is usually a trade-off between their temporal and spatial resolutions (Giraldo Osorio and Garcia Galiano, 2012; Huang et al., 2014a). This has limited their ability in inundation mapping. For example, relatively high temporal resolution sensors, such as AVHRR and MODIS, can scan the earth's surface more than once a day, but usually have relatively coarse spatial resolutions. Mixed pixels do exist when mapping inundation using these

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images. One of the most popular approaches to resolve this issue is sub-pixel mapping.

Sub-pixel mapping is a method used to obtain the sub-pixel spatial distribution within mixed pixels, which is based on spatial dependence and fraction images (Aplin and Atkinson, 2001; Atkinson, 1997; Atkinson, 2005). Spatial dependence is the likelihood that observations close together are more alike than those that are further apart. The input to sub-pixel mapping is a fraction image, which is commonly derived from soft classification of remotely sensed imagery. Different from hard classification, which assigns one class to each mixed pixel, soft classification derives a fraction value for each mixed pixel in the fraction image. The fraction value only represents the proportion of the class without specifying the location of the class within each mixed pixel. Sub-pixel mapping can be considered as the post processing of soft classification to obtain more information at a sub-pixel scale. It has become one of the hotspots in remote sensing research and applications. There are various existing sub-pixel mapping methods (Ren and Ge, 2011), such as linear optimization model (Verhoeye and De Wulf, 2002), pixel swapping algorithm (Atkinson, 2005; Huang et al., 2014a; Thornton et al., 2007), spatial attraction models (Mertens et al., 2006; Shen et al., 2009), genetic algorithm (Mertens et al., 2003), artificial neural networks (Li et al., 2014; Mertens et al., 2004b; Quang et al., 2011;Tatem et al., 2001; Zhang et al., 2008), Markov random field (Ardila et al., 2011; Kanemura et al., 2009), and artificial immune systems (Zhong and Zhang, 2013). However, sub-pixel mapping is still a difficult task which is under continual development process due to the complexity and uncertainty of remotely sensed images (Datla et al., 2010; Melin et al., 2012; Wu et al., 2009). Attempts to map sub-pixel inundation from remotely sensed images are relatively rare in literatures. Sub-pixel inundation mapping is a combined optimization issue in essence. New methods based on artificial intelligence may provide potential solutions.

Particle swarm optimization (PSO) is a relatively new artificial intelligence method that was developed through the simulation of simplified social models of bird flocks (Bratton and Kennedy, 2007; Kennedy and Eberhart, 1995, 1997; Shi and Eberhart, 1998). It has a strong ability to search for the optimal solutions for optimization problems because of its intelligent properties, such as adaptation and self-organization. Different from standard PSO, discrete PSO (DPSO) is commonly used to solve combined optimization issues (Kennedy and Eberhart, 1997). PSO has become one of the most well-known methods in artificial intelligence research and has already proven to be useful in solving optimization problems encountered in many fields such as the electricity industry (Azevedo et al., 2007), transportation (Garcia-Nieto et al., 2013), the chemical industry (Lin et al., 2005), and remote sensing (Li 2011, 2013; Li and Li, 2008, 2009; Saeedi and Faez, 2011).

In this study, a new DPSO-based sub-pixel flood inundation mapping (DPSO-SFIM) method is proposed to achieve an improved accuracy in mapping inundation at a sub-pixel scale from multispectral remotely sensed images. The main objectives are (1) to formulate an evaluation criterion for sub-pixel inundation mapping and to transform sub-pixel inundation mapping into a combined optimization issue; (2) to develop the DPSO-SFIM algorithm, including particle discrete encoding, fitness function designing and swarm search strategy; and (3) to evaluate the accuracy of the DPSO-SFIM method in mapping inundation at a sub-pixel scale using Landsat ETM + images from study areas in Australia and China.

2. Methodology

2.1. Concept of sub-pixel inundation mapping

The intention of sub-pixel inundation mapping is to obtain the sub-pixel spatial distribution of inundation within mixed pixels by maximizing their spatial dependence while maintaining the original proportions of inundation within the mixed pixels. Sub-pixel inundation mapping divides each mixed pixel in fraction images into $S * S$ sub-pixels, where S represents a scale factor which refers to the scale ratio between a mixed pixel and its sub-pixels. For example, if S equals to 5, then 25 sub-pixels in each mixed pixel will be created. The basic principle of sub-pixel inundation mapping is shown in Fig. 1 which is a simple example with two classes representing inundation and non-inundation respectively. The fraction image is shown in Fig. 1(a), where the fraction value represents the proportion of inundation in a mixed pixel. Fig. 1(b)–(d) describe three possible distributions of sub-pixels in the mixed pixel in the center. The fraction value in the mixed pixel in the center is 20%, so there are 5 inundation sub-pixels and 20 non-inundation sub-pixels in the mixed pixel. The spatial dependence principle can be used to compare different possible distributions of sub-pixels: the distribution of sub-pixels is more likely if it has higher spatial dependence. Therefore, the most likely distribution of sub-pixels in the three distributions should be Fig. 1(b).

Actually there are far more than three possible distributions of sub-pixels in the above example, so it is usually difficult to find the optimal possible distribution from numerous possible distributions. If '1' represents inundation and '0' represents non-inundation, then sub-pixel inundation mapping is transformed into a combined optimization issue.

According to spatial dependence principles (Atkinson, 1997, 2005), sub-pixel inundation mapping can be formulated as a maximum combined optimization issue. Flood inundation spatial dependence index (FISDI) can be calculated for a mixed pixel considering the spatial correlation between its sub-pixels and the neighboring coarse pixels. For each sub-pixel i in a mixed pixel, $FISDI_i$ is calculated as a distance-weighted function of its $j = 1, 2, \ldots, J$ neighboring inundation fractions:

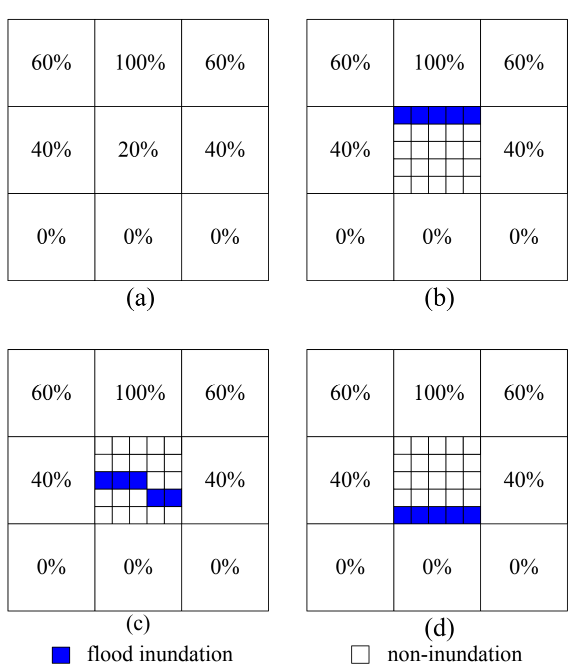

Fig. 1. Example of sub-pixel inundation mapping (scale = 5). (a) Fraction image of inundation. (b) Possible distribution 1. (c) Possible distribution 2. (d) Possible distribution 3.