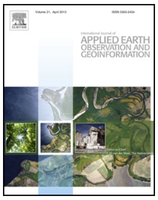
International Journal of Applied Earth Observation and Geoinformation 46 (2016) 63–83

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

journal homepage: www.elsevier.com/locate/jag



Earth observation data based rapid flood-extent modelling for tsunami-devastated coastal areas

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ARTICLE INFO

Article history:
Received 10 March 2015
Received in revised form 19 October 2015
Accepted 4 November 2015
Available online 7 December 2015

Keywords:
Flood mapping
Coastal areas
Cost function
Rapid mapping
Tsunami
RapidEye
Disaster
Coast
Floods
Multispectral
Data Fusion

ABSTRACT

Earth observation (EO)-based mapping and analysis of natural hazards plays a critical role in various aspects of post-disaster aid management. Spatial very high-resolution Earth observation data provide important information for managing post-tsunami activities on devastated land and monitoring re-cultivation and reconstruction. The automatic and fast use of high-resolution EO data for rapid mapping is, however, complicated by high spectral variability in densely populated urban areas and unpredictable textural and spectral land-surface changes. The present paper presents the results of the SENDAI project, which developed an automatic post-tsunami flood-extent modelling concept using RapidEye multispectral satellite data and ASTER Global Digital Elevation Model Version 2 (GDEM V2) data of the eastern coast of Japan (captured after the Tohoku earthquake). In this paper, the authors developed both a bathtub-modelling approach and a cost-distance approach, and integrated the roughness parameters of different land-use types to increase the accuracy of flood-extent modelling. Overall, the accuracy of the developed models reached 87–92%, depending on the analysed test site. The flood-modelling approach was explained and results were compared with published approaches. We came to the conclusion that the cost-factor-based approach reaches accuracy comparable to published results from hydrological modelling. However the proposed cost-factor approach is based on a much simpler dataset, which is available globally.

1. Introduction

The Sendai Bay area in northeast Japan was devastated by a tsunami that followed the $M_w = 9.0$ undersea Tohoku earthquake at 5:46 UTC (UTC + 9: 14:46 JST) on Friday, 11 March 2011. This earthquake is also known as the Great East Japan Earthquake. It was located approximately 70 km East of the Oshika Peninsula of Tohoku (epicenter position). Tohoku was the most powerful megathrust (subduction zone type) earthquake ever measured in Japan (Ammon et al., 2011). The Tohoku earthquake created a 5–8 m up-thrust that triggered a 6–12 m high tsunami, with maximum modelled coastal tsunami heights of up to 36 m (measured in Miyako, Iwate prefecture; Japanese National Policy Agency Japan 2011; Fig. 1). Wave height and run-up height depend greatly on the shape of the coastline and the vertical shore profile (PARI, 2011). The tsunami first reached the coast at 15:12 JST and caused a nuclear Level 7 accident at three reactors in the Fukushima I nuclear power plant within the next 48 h. The Level 7 accident directly contaminated the upper soil, and prompted evacuation in a 20–30 km radius around Fukushima Daiichi I. The disaster directly killed 15,853 people (3282 missing, 60,234 injured) and also heavily impacted the Japanese national economy, power supply, national transportation system and tourism industry; in total it caused 220 billion dollars of damage along the coastline (http://www.npa.go.jp/archive/keibi/biki/higaijokoyo_e.pdf).

The pacific coast of Japan has faced a number of destructive tsunamis throughout history. In 1896 and 1933 the Sanriku events had magnitudes of $M_w = 8.0$ (Tanioka and Satake, 1996) and $M_w = 8.3$ (Kanamori, 1971), respectively. The 2004 disaster in the Indian Ocean caused researchers to reconsider their understanding of past megathrust events; researchers have since suggested that $M_w = 9$ events can be expected within major subduction zones (Lovholdt et al., 2012; Stein and Okal, 2007).

Rapid tsunami disaster assessments are usually based on coarse data and are created manually by labour-intensive digitizing of satellite data. This work is usually performed by national agencies and partners of International Charter Space and Major Disasters. International studies and projects were initiated to inform coastal inhabitants as early as possible about possible tsunami waves. The German-Indonesian system GITEWS has reduced the warning time offset considerably. These systems, however, cannot work effectively if regional infrastructure and communication systems are

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http://dx.doi.org/10.1016/j.jag.2015.11.005

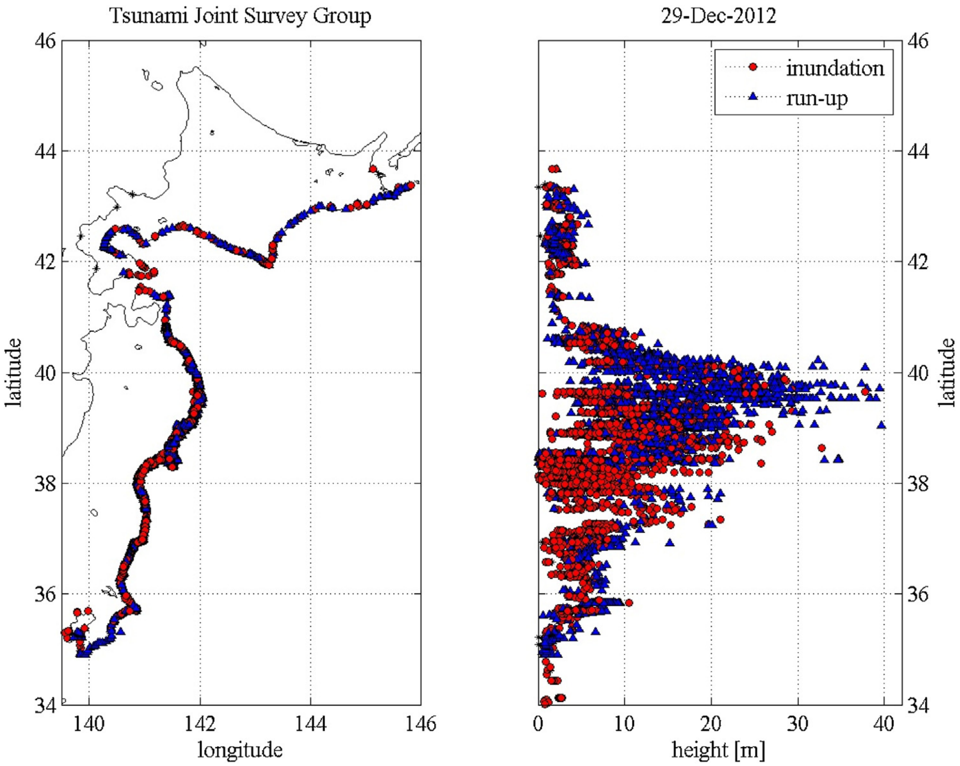

Fig. 1. Flood and run-up height of the Tohoku tsunami (CEC 2011).

not properly developed (Steinmetz et al., 2010). Detection of these vulnerabilities is the aim of some of the tsunami-related research efforts, and will be briefly described later in this section. The management of tsunami crises is supported by International Charter Space and Major Disasters. The immediate availability (within hours) of remote-sensing data has been increased through this initiative, and various EO datasets are now available through the charter and derived products provided by international services (e.g. ZKI (Zentrum für Satellitengestützte Kriseninformation), SERTIT (Service Régional de Traitement d'Image et de Télédétction) or UNOSAT (United Nations Institute for Training and Research Operational Satellite Applications Programme) Mahmood 2012; Zhang and Kerle, 2008).

However, the automatic analysis of these datasets for specific applications (amount and spatial extent of flooded land surface and damaged infrastructure) is still under development. The present paper will therefore provide additional findings related to the automatic analysis of tsunami-flooded area extent. These findings were derived using spatial high-resolution EO data from a constellation sensor setup with high temporal resolution.

The review of the available literature in the field of tsunami disaster management can be split into:

1. Early warning system development.
2. Coastal vulnerability analysis and GIS (Geographical Information System) analysis for evacuation planning.
3. Inundation forecast modelling using inundation models and trans-ocean propagation modelling.
4. Post-disasterland-surface mapping, partly using inundation models, but mainly based on spatial high-resolution EO data and manual delineation of flooded areas.

Various concepts have been published for tsunami early-warning systems. Details can be found in, for example, Beltrami (2011), Eckert et al. (2012), Joseph (2011) and Stosius et al. (2011); however, as this is not the focus of the present paper, details will not be presented here.

Coastal vulnerability has been studied with respect to urban patterns of risk and urban population density (e.g. Taubenböck et al., 2008, 2011; Taubenböck and Strunz, 2013; Papathoma et al., 2003; Leitmann, 2007; Post et al., 2007). Other studies have modelled vulnerability using the building-type information of number of floors, as well as building classifications based on roof-type and building height. These studies have then fused this information within a GIS (e.g. Eckert et al., 2012). Taubenböck et al. (2008) showed that risk and vulnerability in the tsunami context can be assessed using the structural characteristics of urban morphology derived from Ikonos EO data. The analysis done by Taubenböck et al. (2008) identified the potential application of urban structural mapping for the identification of safe areas and the calculation of the potential number of affected people in regions with reduced availability of statistics regarding population density. Vulnerability studies have also highlighted the impacts of post-tsunami policy on coastal regions in terms of serious socio-economic consequences (e.g. building restrictions, relocations of poor fishing communities). These impacts have been documented and analysed by Ingram et al. (2006), and have been identified as the *Post-disaster recovery dilemma*.

Inundation forecast modelling is documented in the literature using hydrodynamic models that account for flow, sedimentation processes. Additionally sea floor deformation information is needed. Zhang and Kerle (2008) provide an overview of the existing non-linear shallow-water-algorithms that are also used for the tsunami flood extent modelling. The quality of hydrodynamic modelling for the tsunami flood situation (Hokkaido-Nansei-Oki Tsunami) was analysed by Titov and Synolakis (1998); the results where compared with ground truth measurements. Titov et al. (2005) analysed the global impact of the Sumatra tsunami from 2004 in combination with station measurements, satellite data and terrestrial measurements. Within a rapid mapping scenario after