Geoinformatic approach for mapping the Thomas fire and post-fire mudflow event in Montecito area (Santa Barbara, USA)

Abstract

Fires, post-fire mudflows, and the resulting coastal changes can have significant financial impact on societies and lead to extensive human casualties. In order to assess the damages, a robust geoinformatic framework is implemented in this paper. In particular, this study aims to examine the remote sensing and GIS methods that can assess the burn severity, post-fire mudflow paths, and the post-mudflow coastal changes. The applied methods evaluate several hazards and risk scenarios that can be useful in the decision-making process about the future development and protection of an area.

As a case study the Thomas fire incident, which took place on the 4th of December 2017, in combination with the flash flood event that led to mudflows in the area of Montecito (California, USA) was selected as the most notable example, but such framework can also be applied to similar cases in other places, and in particular in Greece. The dataset consisted of two satellite images, one before the Thomas fire event (18/11/2017 at 18:46 UTC) and one after the post-fire mudflow (11/02/2018 at 18:45 UTC). To detect the burned areas and the mudflow paths, the Normalized Burn Index (NBI) and the delta Normalized Burn Index (dNBI) are calculated. In order to assess any coastal changes that might have occurred due to the mudflow event, the Normalized Difference Water Index (NDWI) and a global threshold operator, which relies on the NDWI values, is implemented.

The results indicate that the dNBI is an effective tool for estimating mudflow paths, while the image segmentation of NDWI method proved to be unreliable, due to existing climatological and tidal conditions that occurred during the sensing period. A hydrological analysis of the Montecito basin is implemented to evaluate the resulting mudflow paths. Overall, the results seem to be of high accuracy, with the exception of the coastal change. The paper also includes future implementations and changes in the applied methods that could significantly improve the results. The study uses open source software, such as SNAP and QGIS, in combination with free datasets, such as Sentinel-2 images and ASTER DEM, while some visualization is done in ArcGIS 10.2.

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Keywords: Geoinformatics, Montecito, Thomas fire, mudflows, coastal change
Introduction

The phenomenon of fire is a common disaster in forests and vegetation areas, which constitutes a serious threat to the environment, life, and property (Jaiswal et al., 2002; Siegert et al., 2001). Such fires burn vegetation, which on the one hand improves water penetration into the ground, and reduces the stability of slopes (Mooney, 1981). On the other hand, if there is no protection vegetation, the amount of water that can be absorbed by the soil may not exceed the rate of rainfall, and it can cause surface runoff. Cannon et al. (2008) found that most post-fire mudflows are created through the process of progressive entrainment of material eroded from slopes and channels. When a large amount of ash layer and loose sediment appear as rich material sources after mountain fires, the process of progressive entrainment becomes easier. The probability of mudflows is increased by 50% after forest fires (Short et al., 2015). Mudflows often damage infrastructures, they can have a significant financial impact on societies, and they can lead to extensive human casualties (Cheng et al., 2018; Ciurleo et al., 2019). Mapping the consequences of such catastrophes allows civil protection to prioritize the most vulnerable areas, and estimate the burn severity.

This paper implements a simple but robust GIS/RS framework on the Thomas fire and post-fire mudflow incident, in order to map the burned areas around Montecito, to identify the mudflow paths and to detect potential coastal changes. Optical satellite imagery before and after the incident is used in order to detect the severely burned areas, the mudflow paths, and the coastal changes. Also, a GIS-based evaluation method is applied for the mudflow paths.

Study Area

Montecito is a small community in Santa Barbara and it is located at the foot of the Santa Ynez mountains (see Fig. 1). It experiences a cool Mediterranean climate with warmer winters and cooler summers compared to inland regions (Cui et al., 2019).

Thomas fire was ignited on 4/12/2017 and burned 1140km$^2$ in Santa Barbara and Ventura counties before it was completely contained on 12/1/2018. It destroyed 1063 structures, directly resulted in two fatalities, and it was not fully contained until 12/1/2018 (Nauslar et al., 2018). On the morning of 9/1/2018, about one month since the start of Thomas fire, heavy rainfall caused mud and boulders from the Santa Ynez Mountains to flow down creeks and valleys into Montecito (Cui et al., 2019). These post-fire mudflows consisting of mud, boulders, and tree branches were up to 5m in height, moving at estimated speeds of up to 20-30 km/h into the lower areas of Montecito (Hamilton & Serna, 2018). The cascading processes resulted in 21 deaths and two missing persons (Dolan, J., 2018).

The disaster caused at least $177 million of property damage, at least $7 million in emergency responses, and another $43 million in cleaning costs. The shutdown of US-101 between January 9th and 22nd additionally resulted in tens of millions lost wages to workers in both Santa Barbara and Ventura counties, and led to a significant drop in the short-term tourism in Santa Barbara county (Niehaus, 2018).
Materials and Methods

For the purpose of this paper, Sentinel-2A and 2B images are used in order to detect the severely burned areas of Montecito, visualize the post-fire mudflow paths and monitor the coastal changes due to the mudflow. The dataset is available by the Copernicus open access hub (https://scihub.copernicus.eu). The dataset consists of 2 satellite images, one before the Thomas fire (18/11/2017 at 18:46 UTC) and one after the post-fire mudflow (11/02/2018 at 18:45 UTC). Both images are MSI1C products with ascending orbits. These satellite images are selected due to their low percentage in cloud coverage and their short sensing period after the events.

In order to verify the mudflow paths, a second dataset is acquired from the ASTER GLOBAL DEM (https://asterweb.jpl.nasa.gov/gdem.asp). This spatial information is then processed by a GIS in order to produce the necessary thematic layers (e.g., slope, flow direction, flow accumulation, hydrological basins, drainage networks).

The atmospheric correction is implemented for both images through the Sen2Cor tool by ESA’s SNAP. The satellite images are resampled, for bands B1 through B12, to a spatial resolution of 10 meters, with the nearest neighbor method. This process is necessary due to later on implementation of the spectral indices NBI, and NDWI. Because the raw size of the images is substantial enough to make further computational analysis slow, it is crucial to define the area of interest (AOI). After clipping the dataset to the AOI, the implementation of the spectral indices begun.
In this paper, the Normalized Burn Index (NBI) and its corresponding delta Normalized Burn Index (dNBI) are calculated. The formula is similar to the NDVI, except that it uses near-infrared (NIR) and shortwave-infrared (SWIR) wavelengths with their equivalent bands in Sentinel-2 being B8 and B12 (Lutes et al., 2006; Miller & Thode, 2007).

\[ \text{NBI} = \frac{(\text{NIR} - \text{SWIR})}{(\text{NIR} + \text{SWIR})} = \frac{(B8 - B12)}{(B8 + B12)} \]

Healthy vegetation has very high NIR reflectance and low reflectance in the SWIR portion of the spectrum. Burned areas, on the other hand, have relatively low reflectance in the NIR and high reflectance in the SWIR. High NBI values generally indicate healthy vegetation while a low value indicates bare ground and recently burned areas. To identify recently burned areas and differentiate them from bare soil and other non-vegetated areas, the difference between the pre-fire and post-fire NBI (dNBI) is applied.

\[ \text{dNBI} = \text{NBI}_{\text{pre-fire}} - \text{NBI}_{\text{post-fire}} \]

The meaning of the dNBI values can vary by scene, and for best result interpretation in specific instances, there should always be a field assessment. Because no field assessment is completed in this work, the reference table from Lutes et al. (2006) can be useful as a first approximation for interpreting the dNBI difference. Then the dNBI values are reclassified into seven classes that range from high severity burn to high post-fire regrowth.

To assess the potential post-mudflow coastal changes, an image segmentation technique is applied. The purpose of image segmentation is to separate the image into its constituent homogeneous regions. The border pixels between segmented land and water regions can then be delineated as the coastline. To separate water objects from the land background, a global threshold operator is used, similar to the one in Bioresita & Hayati (2016). The global threshold value was determined by the Normalized Difference Water Index (NDWI). It uses green and NIR wavelengths with their equivalent bands in Sentinel-2 being B3 and B8 (McFeeters, 1996).

\[ \text{NDWI} = \frac{(\text{GREEN} - \text{NIR})}{(\text{GREEN} + \text{NIR})} = \frac{(B3 - B8)}{(B3 + B8)} \]

From the literature review, it is known that NDWI values above 0.3 indicate the existence of water. Hence, the global threshold value was set globally to be above or equal to 0.3. The result is a binary image, in which the pixels with higher or equal NDWI value than 0.3 are coded as 1 (water pixels), while the ones with lower NDWI value than 0.3 are coded as 0 (land pixels). Then, by taking the difference between those two images (the one pre-mudflow and post-mudflow) it is possible to calculate the post-mudflow coastal changes.

**Results**

*Fig. 2* shows the reclassified dNBI values. Most of the Santa Ynez mountains are severely affected by the Thomas fire, with more than 40% of the total area being categorized with moderate and high severity burn. Areas that are of high and low post-fire regrowth can be attributed to phenology reasons, due to the three-month interval between the sensing
period. The thin lines of moderate and high severity, which seem to penetrate inside the Montecito, Summerland and Toro Canyon counties, are in fact not burned areas. These are the paths the mudflows advanced and damaged the civilian properties. The mudflows moved within the Santa Ynez channels, through the urban areas, and finally discharged at the Santa Barbara bay.

While it is possible to distinguish the post-fire mudflow paths by the dNBI map, it is necessary to evaluate these results. In Fig. 3, the results from the hydrological analysis of the Montecito basin seem to match the mudflow paths (the arrows point in the direction of the mudflow paths). The only difference can be seen on the left mudflow path that tends to move closer to the second on the left. This mismatch is attributed to the difference in the spatial resolution of the two datasets, one being at 30 meters (DEM) and the other at 10 meters (resampled Sentinel-2).

The results of the post-mudflow coastal change are shown in Fig. 4. Most noticeable changes are detected near the mudflow exit points. While the results highlight some coastal areas that have advanced 60 meters into the ocean, the reality seems to indicate otherwise. There has not been observed such extensive accretion at the Montecito coast, which suggests that the NDWI and the global threshold operator are not reliable techniques, in order to produce quality results. Apart from these issues, due to existing climatological and tidal conditions that occurred during the sensing period, it is nearly impossible to determine with high accuracy any coastal changes with the above-mentioned methods.
Fig. 3: A closer look at the AOI, where the classified flow accumulation tends to match the mudflow paths. Some mismatches are due to difference in spatial resolution.

Fig. 4: Potential coastal changes due to the mudflow event.
Discussion

While this study delivers some notable results, the methodology in combination with the above-mentioned datasets provides some limitations. These limitations stem from the medium spatial resolution of the datasets and from the applied techniques that are used. In order to potentially enhance the findings, some future implementations are mentioned below.

The most noticeable implementation is the replacement of Sentinel-2 imagery with one of higher spatial resolution (while having the SWIR band available). Although this comes with a financial cost, it can accurately detect the high severity areas with their respective post-fire mudflow paths.

As for the post-mudflow coastal changes, one of those additions is the adaptive threshold operator. By replacing the global threshold and applying an adaptive one, the segmentation process becomes more dynamic, thus allowing for better estimation of any coastal accretion. Instead of determining a global value for the whole coastline, a more suitable approach is to split the coastline into smaller segments with each segment having its own threshold value. An edge detection algorithm on the NDWI image or even on the RGB one can yield similar or even better results than the global threshold method.

Lastly, for evaluating the post-fire mudflow paths, a more suitable dataset, such as a high-resolution digital surface model (DSM), would better highlight the potential paths. The produced hydrological network will match better with the urban topography of Montecito, thus providing better alignment with the dNBI post-fire mudflow paths.

Conclusions

The advantage of the combined use of RS and GIS methods is the evaluation of several hazards and risk scenarios that can be used in the decision making about the future development and protection of an area. In this paper, the dNBI methodology is used for detecting not only the burned areas, but also the post-fire mudflow paths, while the NDWI for estimating any coastal change after the post-mudflow event. The main findings are mentioned below.

- The dNBI approach seems to be an effective technique for estimating the fire severity, and detecting the mudflow paths of Montecito county.
- More than 40% of the total Santa Ynez mountains are classified with moderate and high severity burns, which contributes to more than 200,000 km².
- The mudflow paths match well with the resulted paths of the hydrological analysis, which indicates that the dNBI method for detecting the mudflow paths is reliable.
- The image segmentation of NDWI with a global threshold operator proved to be unreliable for this area.

The same framework can also be applied in similar cases of Greece, which the last years suffers greatly from catastrophically wildfires and flash floods. Due to potential climate change, these phenomena will increase in frequency and intensity. This framework can provide an early estimation of such events, without being constraint by factors.
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