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Remote Sensing for Monitoring Natural Disastersand Earthquakes

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Abstract

Natural disasters such as earthquakes, floods, landslides, hurricanes, and wildfires pose serious threats to human lives, infrastructure, and the environment. Effective monitoring is essential for disaster preparedness, risk reduction, and recovery planning. Remote sensing has emerged as a vital tool in this context due to its ability to provide timely, wide-scale, and multi-sensor observations. Satellite-based techniques, particularly Synthetic Aperture Radar (SAR), enable detection of seismic ground deformation, rapid damage mapping, and flood extent delineation under all-weather conditions. Aerial platforms, including UAVs, complement satellite data by supplying ultra-high-resolution imagery for detailed post-disaster assessment, while ground-based systems such as LiDAR and photogrammetry deliver precise local measurements. The integration of these approaches enhances disaster monitoring capabilities and mitigates limitations inherent to individual platforms. Applications extend beyond earthquake monitoring to include flood forecasting, wildfire mapping, landslide susceptibility analysis, and hurricane track prediction. Emerging technologies such as machine learning and artificial intelligence further improve the interpretation of remote sensing datasets, supporting early warning systems and real-time decision-making. This paper highlights the importance of combining satellite, aerial, and ground-based remote sensing techniques to strengthen disaster management strategies and foster global resilience against natural hazards.

Keywords: Remote Sensing, Natural Disasters, Earthquake Monitoring, Flood Mapping, Synthetic Aperture Radar (SAR), Disaster Management

1. Introduction

Natural disasters, including earthquakes, floods, wildfires, landslides, and hurricanes, have significant social, economic, and environmental impacts. Monitoring such events and their consequences is crucial for assessing hazardous areas, informing recovery priorities, mitigating future risk, and enhancing preparedness. Remote sensing provides a rapid and effective tool for detecting, analysing, and monitoring these occurrences by combining data from multiple sensor types. Earthquakes constitute one of the most destructive natural hazards worldwide, making the integration of remote sensing methods particularly vital for their study and for rapidly mapping affected zones when seismic stations are absent or poorly distributed.

Remote sensing technologies encompass satellite, aerial, and ground-based platforms. Satellite sensors operate in optical, infrared, or radar wavelengths, offering varying information on surface parameters, meteorological conditions, land cover, and topography. They exhibit high flexibility in temporal and spatial coverage yet often provide data at resolutions insufficient for detailed post-event analyses. Aerial platforms—manned aircraft, unmanned aerial vehicles (UAVs), kites, and balloons—deliver ultra-high-resolution images necessary for precise damage assessment but are sensitive to weather and daylight conditions and possess limited acquisition range. Ground-based systems, such as terrestrial laser scanners and fixed cameras, can acquire ultra-high-resolution data at regular intervals, facilitating direct deformation measurements through photogrammetry. Integrating different sensor platforms partly mitigates the constraints inherent to each system.

Earthquakes generate low-frequency waves that propagate through the Earth's interior, reaching the surface and inducing ground shaking. This process leads to structural damage and, indirectly, to secondary hazards including tsunamis, landslides, and liquefaction. Advanced seismic tomography inversions refine knowledge of earthquake sources and enable forecasts at local and national scales. A central challenge in earthquake monitoring is the distribution and reliability of seismic stations; limited networks impede comprehensive coverage, particularly in remote regions. In such contexts, satellite imagery offers a broader perspective on global changes linked to seismic events, independent of land infrastructure and human presence (Rege Cambrin & Garza, 2024).

2. Overview of Remote Sensing Technologies

Remote sensing technologies offer innovative support for investigating natural disasters (Novellino et al., 2018). These technologies include satellite, aerial, and ground-based sensors, with artificial intelligence playing an increasingly prominent role in enhancing monitoring capabilities. Satellite remote sensing is particularly suited for assessing vast areas frequently affected by seismic events. It provides precise georeferenced information essential for both monitoring and mitigation efforts. This capability is vital for mapping the spatial distribution of seismic damage following earthquakes (Zhang et al., 2014). Satellite Synthetic Aperture Radar (SAR) aids in detecting ground deformation induced by seismic activity, facilitating immediate risk assessment and post-event investigations.

Aerial remote sensing enables rapid assessment of specific 'hot spots' identified by satellite observations. It proves valuable for monitoring large areas once critical zones have been pinpointed. Ground-based remote sensing utilizes strategically positioned poles and continuous monitoring to capture detailed information. Systematic image acquisition supports both immediate data collection after an event and subsequent monitoring of long-term phenomena. Ground-based systems also accommodate autonomous devices for ongoing observation.

2.1. Satellite-Based Remote Sensing

Satellite-based remote sensing is a critical component in monitoring natural disasters, providing data at various wavelengths such as optical, near-infrared, and thermal infrared. This technology is particularly suited for rapid assessments following earthquakes and tsunamis, which can cause severe damage and loss of life (Novellino et al., 2018). Earthquake monitoring relies heavily on spaceborne synthetic aperture radar (SAR) instruments, which are fundamental in response and reconstruction phases. Major earthquake centers, including global organizations, have developed remote sensing procedures to facilitate rapid analysis through interoperable platforms (Rege Cambrin & Garza, 2024). Aside from Earth observation satellites, manned and unmanned aircraft are valuable bases for sensor deployment, offering direct access and customizable payloads.

2.2. Aerial Remote Sensing

Aerial remote sensing follows a similar approach to satellite remote sensing, as images or data of the Earth's surface are acquired from, typically, a low-flying aircraft. Because aircraft can often be mobilised more quickly than a satellite on orbit, and the resolution of images is significantly higher, it is widespread in disaster studies.

Optical sensors operate within the light spectrum visible by the human eye (390 to 700 nm). Cameras capturing these images use slightly different ecologies depending on the aim of the study but typically cover at least a portion of the red, green and blue components of the visible spectrum to produce so-called "true colour" imagery, though grey scale, infrared and false colour images have been employed. This approach is mostly used to study surface-level damage to infrastructure or land cover types. The main limitation is that the line of sight of a camera will be blocked by clouds, making it increasingly ineffective during a flood event or bushfire, for example, when cloud cover from the damaged areas is widespread (Novellino et al., 2018).

2.3. Ground-Based Remote Sensing

Remote sensing technologies, including satellite, aerial, and ground-based platforms, are indispensable for monitoring natural hazards. They provide observations of a broad range of phenomena ranging in scale from regional through continental. In remote areas where direct observations may be unavailable, ground-based remote sensing can validate and support satellite- and airborne-derived estimates (Novellino et al., 2018).

Ground-based remote sensing platforms comprise a variety of surface-ray sensors—such as C, X, or Ku band radars (Gseradiometer, PulseGPS), lidar, hyperspectral and multispectral cameras, spectrometers, and terahertz and sound sensors—which are deployed according to observed phenomena. The ability to resolve fine spatial features mitigates beam-dilution issues common in airborne and satellite observations, also reducing requirements for proximity to the natural hazard source. Examples of ground-based platforms include portable photogrammetric imagery collected across a study site, terrestrial laser scanning, camera networks feeding into photogrammetric solutions that produce orthophotos and digital elevation models (DEMs), and laser distance sensors coupled with a field-of-view camera to monitor riverbank erosion or perform active mapping of the debris. However, these platforms may be deployed at only one station per hazard type, and their limited field of view presents challenges for monitoring large regions (Rege Cambrin & Garza, 2024).

3. Types of Natural Disasters

Natural disasters cause so much damage that the United Nations Office for Disaster Risk Reduction (UNDRR) INITIATIVE was launched after the 1990 International Decade for Natural Disaster Reduction. Earthquakes, floods, wildfires, landslides, and hurricanes all cause damage every year. Abnormal displacement of tectonic plates at fault lines and volcanic eruptions induce earthquakes. Downpours, snowmelt, and other events lead to floods. Vegetation dried due to drought fuels wildfires. Topographic characteristics, vegetation, and other factors impact landslide susceptibility. Warm air enables hurricane formation. It is difficult for remote-sensing sensors to identify dangerous portions of geological records that precede these disasters. However, remote sensing can rapidly detect destruction and ground deformation after an earthquake (Novellino et al., 2018). Hydrological models based on rainfall and morphology prove useful for flood prediction. Wildfire behavior depends on fuel, weather, and other dynamic variables. Landslide susceptibility can be mapped by using topography and land use. Finally, hurricane monitoring benefits from the forecasting of cyclone tracks and wind fields (Rege Cambrin & Garza, 2024).

3.1. Earthquakes

Earthquakes result from the sudden release of stress accumulated along tectonic plate boundaries. This release generates seismic waves that induce ground shaking and surface fissures. As the main engines of deformation, earthquakes play a major role in continental dynamics. Monitoring these phenomena through remote sensing has become critically important. Synthetic Aperture Radar (SAR) satellites and ground-based seismometer networks enable the observation of earthquake occurrences several days in advance, while detailed maps of ruptures and co-seismic surface deformations can be generated within hours of an earthquake event (Novellino et al., 2018). Seismic intensity also serves as a fundamental parameter for assessing natural hazard damage and estimating local losses. The Wenchuan earthquake of 2008 provides an illustrative example of seismic intensity distribution; this event was initiated by the rupture of the Yingxiu-Beichuan fault along the Longmen Mountain Fault, resulting in the loss of approximately 69,000 lives and 375,000 injuries, as well as the destruction of over 15 million houses (Zhang et al., 2014). Earthquake monitoring is primarily based on seismometers that record seismic waves to detect events, evaluate their strength, and identify their sources. However, achieving global, comprehensive coverage with such instrumentation remains challenging. Satellite instruments offer a broader, more inclusive perspective, facilitating the identification of affected areas—particularly in remote regions—without the need for direct human assessment or extensive seismometer deployment (Rege Cambrin & Garza, 2024).

3.2. Floods

Floods companion earthquakes as one of the deadliest and most frequently occurring natural hazards worldwide, exhibiting diverse causes such as snowmelt, tropical storms, monsoons, and dam failures (Lacava et al., 2018). Earth observation offers a permanent and synoptic view of flooding events for efficiently mapping inundated areas and quantifying soil moisture, while also enhancing understanding and modeling of the underlying hydrologic processes (D. Bolten & Ahamed, 2017).

Flood mapping has garnered significant attention from the scientific community, relying primarily on two approaches involving optical and microwave data. Optical imagery can be used to extract water information by exploiting the significant contrast in reflectance between land and water bodies, analyzing spectral indices, and computing spectral mixture. The presence of clouds can severely contaminate optical data, mainly during the initial phases of the flood event or in humid tropical regions. An alternative approach involves using active microwave sensors operating in a side-looking geometry. Radar sensors provide significant advantages: they are not limited by daylight and penetrate clouds, making them the preferred choice for flood monitoring in tropical and temperate regions.

The flood-prone area can be identified by recognizing relevant urban/industrial classes when analyzing extensive targets. An integrated approach utilizing multi-temporal multi-sensor datasets based on a Major Class Change Detection technique applies saturated dependence graph classification to TerraSAR-X and TanDEM-X data for delineating flooded/landslide and non-flooded/landslide areas. This capability is instrumental in forecasting flood events through systematic classification and monitoring of the terrain under flood conditions. The relative change approach used for evaluating flood extent more effectively captures scenarios with limited inundated areas, reducing the likelihood of misclassification and enabling restorations of semi-submerged objects such as buildings and trees in the MSI analysis.

3.3. Wildfires

Monitoring vegetation stress and recovery following wildfire events constitutes an area of increasing interest in remote sensing research (Fordham, 2002). Wildfires pose serious threats to the atmosphere, biosphere, and climatology, with applications ranging from fire behaviour study to post-fire vegetation assessment (Domenikiotis et al., 2003). Numerous wildfire-dedicated methodologies have been developed. Current satellite remote sensing fire products provide spatial and temporal information in near-real-time and in estimated radiometric terms. These enable rapid study of the initial phase and development of wildfires, as well as the persistence of vegetation loss.

3.4. Landslides

The power of remote sensing techniques for mapping, monitoring, and scene reconstruction, coupled with the availability of large archives, superior spatial and temporal resolution, and the potentials of introducing these data within hazard models, will play a key role in the implementation of early warning systems and advanced hazard and risk management strategies (Novellino et al., 2018).

Landslide phenomena represent one of the major causes of human casualties in the mountainous regions across the continents, with recurrent damage to infrastructures; roads, railways, dams, and water bodies are often involved and subjected to landslide effects. Therefore, risk assessment and early warning are urgent needs for modern societies, and optical and radar satellite data have to be explored to provide an operational tool able to tackle the nowadays demanding requirements (Casagli et al., 2016).

Repeated radar acquisitions permit the observation of the time-variations of the landslide velocity, contributing to better understanding of the sliding mechanisms and to locating the most hazardous area (under the assumption of continuity in the movements). The typical displacement is of a few centimetres per year, and the lower detection threshold of the technique depends on wavelength and system coherence.

3.5. Hurricanes

Hurricanes are swiftly rotating storm systems accompanied by strong winds, thunderstorms, and heavy rains. The disturbances affect water quality parameters such as total nitrogen, total phosphorus, dissolved oxygen, dissolved organic carbon, and salinity. After a hurricane, recovery depends on damage assessment speed, the areas affected, and relief efforts. Onsite assessments may take weeks, highlighting the need for quicker methods like remote sensing and GIS to prioritize relief, conduct environmental restoration, and mitigate ecosystem disturbances. Remote sensing provides near real-time data for water quality and vegetation cover assessment in coastal watersheds and estuaries. This can be accomplished by developing models from remotely sensed and ground truth data, using tasseled cap transformation to assess vegetation condition, and incorporating data fusion to evaluate hurricane impact on watersheds (Mostafiz, 2017).

4. Remote Sensing Applications in Earthquake Monitoring

Earthquake monitoring is essential to promptly identify affected areas, determine event severity, estimate damages, and plan recovery. However, the scarcity of seismic stations in remote regions constrains global earthquake information. Hence, satellite remote sensing offers a wide-ranging perspective to track changes worldwide. (Rege

Cambrin & Garza, 2024)

The role of remote sensing in earthquake assessment spans pre-event detection, damage evaluation, and ground deformation analysis (Zhang et al., 2014). Earthquake causes include faults, earthquakes, and volcanic eruptions, which can result in secondary floods. Advanced techniques support these applications. Post-event damage analyses often employ intensity maps generated from remotely sensed data (Novellino et al., 2018) ; these are correlated with seismic intensity and ground-shaking measurements. Additionally, deformation analyses assist in quantifying and delineating affected areas to prioritize aid, highlighting the critical role of remote sensing in comprehensive earthquake monitoring.

4.1. Pre-Earthquake Detection

Numerous methods for earthquake prediction have been proposed, although with limited success (Xiong et al., 2021). Nevertheless, various precursors have been reported, including changes in groundwater levels and chemistry, and electromagnetic anomalies. The study of changes in electromagnetic phenomena at different frequencies before and after earthquakes has gained increased interest in the last decades. Satellite remote sensing is a viable technology for measuring diverse parameters related to potential earthquake precursors, as it provides synoptic coverage of areas hard to reach for measurement devices. Minimum coefficients related to earthquake magnitude can be applied as crop predictions before earthquakes. Several studies have demonstrated a strong relationship between Crop Water Content (CWC) and earthquakes in different regions of the world with diverse climates. The CWC index derived from satellite data has proven to be the most sensitive parameter for forecasting earthquakes in several studies. Machine learning methods have been used to detect changes in satellite data caused by earthquakes and predict events in the following days. Experiments are based on data from the 2010 Haiti earthquake and preceding activity of the 2011 Japan tsunami and the 2017 Hurricane Harvey, which are commonly used in remote sensing examinations of natural disasters (Rege Cambrin & Garza, 2024). Earthquake monitoring is still of fundamental importance and satellite data, if properly exploited, can yield good results toward increasing resilience worldwide.

4.2. Post-Earthquake Damage Assessment

Rapid and accurate assessment of damage scenarios resulting from earthquakes is essential for emergency management. Remote sensing technologies provide critical complementary tools for emergency managers who must prioritize and allocate resources efficiently. The potential for repeated satellite or aerial acquisitions ensures the availability of extensive datasets over damaged areas, facilitating three-dimensional observations and global coverage of large-scale damage. Remote sensing data, when procured soon after the event and combined with ancillary information, can lead to effective characterization of disaster damages and contribute to understanding underlying causes.

Current methodologies for automated damage mapping predominantly rely on optical imagery, which faces limitations such as dependence on daylight and adverse weather conditions, along with difficulties in decoupling damage-related changes from surface modifications induced by other effects. Interferometric Synthetic Aperture Radar (InSAR) coherence has emerged as a promising alternative for large-scale damage detection following catastrophic earthquakes. The analysis of multi-temporal acquisitions enhances the ability to separate anomalous post-event signals from seasonal or long-term consistency variations and transient phenomena, such as land–atmosphere or land–vegetation interactions. Incorporating advanced machine learning models, particularly Recurrent Neural Networks (RNNs) capable of capturing complex temporal patterns, further improves damage mapping accuracy.

Damage assessment methods for built-up regions often exploit the detailed information derivable from unmanned aerial systems (UAS). Beyond the visual scrutiny of high-resolution imagery, Structure-from-Motion (SfM) techniques enable the reconstruction of three-dimensional point clouds from freely available flight data. An evaluation algorithm based on the local geometric properties of these point clouds has demonstrated the capability to identify damage at a structural level, providing a rapid, economical, and secure approach for preliminary emergency response and severity appraisal (Ebrahim Mohammadi & L. Wood, 2018).

4.3. Ground Deformation Analysis

Ground deformation analysis assumes a critical role in earthquake studies, as the displacement of the Earth's crust may signal the inner processes preceding an earthquake or be a direct consequence of seismic events. Satellite radar interferometry (InSAR) techniques thus have the potential to improve risk assessment and damage estimation in earthquake scenarios (Alatza et al., 2020). Platforms that provide data with high recall and high geographical coverage, such as Sentinel-1, enable monitoring of the displacement of ground points over extensive areas and in response to both natural and anthropogenic hazards (Rege Cambrin & Garza, 2024). Empirical studies indicate that surface deformation can be accurately measured by alignment of SAR pairs based on geometric constraints and the unwrapped phase difference. A straightforward method for surface deformation estimation on earthquakes involves processing the SAR raw data to determine the delay of the echo in the acquired scenes. Pre-seismic ground displacement is characterized by acceleration of deformation towards the rupture zone in the days and hours preceding an earthquake; consequently, signal propagation and the increment of the delay parameter provide useful information. The Geohazards Exploitation Platform (GEP) developed by the European Space Agency (ESA) for Earth Observation provides three examples of seismic events with extensive InSAR time-series data and geophysical information to facilitate analysis and comprehension.

5. Remote Sensing Applications in Flood Monitoring

Remote sensing provides images that outline the spatial extent of flooding and can be used to assess damages and plan recovery scenarios (Domenikiotis et al., 2003). Satellites capturing visible and infrared imagery can define the boundaries of lakes and reservoirs, and during significant floods, identify channels and inundated areas. Post-flood, the retreat of floodwaters can be monitored from the drying of the floods, mapping the areas vulnerable to future flooding. The extent of damage can also be mapped, although the presence of clouds or smoke over flooded and damaged areas may limit observations.

Regional flood extents can be obtained from satellites equipped with Synthetic Aperture Radar (SAR) instruments. Operating in a microwave frequency band, SAR can acquire data under all weather conditions, day or night, making it particularly useful for flood regions frequently covered by clouds. Although spatial resolution may be coarse for large imaged areas, techniques have been developed to extract flooded zones and their recession stages.

In addition to providing crucial input for hydrological modeling and flood forecasting, remote sensing data contribute to mapping basin characteristics such as stream networks, watershed boundaries, and slope, which are essential for understanding flood dynamics. These datasets, when combined with hydrological models, can simulate flood events and inform mitigation strategies. Mapping the spatial extent of floods is key to assessing vulnerability by defining the areas affected by heavy rains. The use of remote sensing for monitoring flooding and flood-related characteristics is well documented and widely employed.

5.1. Flood Extent Mapping

Flood extent mapping constitutes a primary remote sensing technique for determining the spatial distribution of floodwaters, serving a vital role in disaster planning, response, and recovery. Optical, thermal, and microwave remote sensing instruments are employed to quantify flood extent, which then informs hydrodynamic models for forecasting flood propagation. Satellite passive microwave data have been demonstrated as predictors for land surface flooding, as exemplified in the Zambezi river basin (Wieland & Martinis, 2019).

The application of satellite remote sensing for flood detection and mapping has seen marked development in recent years, evolving towards automated processing chains that focus on rapid mapping and near-real-time delivery, crucial for supporting disaster management operations and emergency responses (Tiwari et al., 2020). Synthetic aperture radar (SAR) systems have become particularly prominent for flood monitoring due to their all-weather, day-and-night capabilities that enable acquisition over extensive regions. Satellite SAR data are instrumental across all stages of flood event management—pre-event, during-event, and post-event analyses. Numerous complementary approaches have been investigated in this context, including thresholding, change detection enhanced by image filtering and segmentation, as well as fusion techniques combining SAR intensity and interferometric coherence using Bayesian networks. Machine-learning methodologies, such as K-nearest neighbor classifiers and convolutional neural networks, further support both inundation and flood susceptibility analyses.

Extensive research utilizing multi-temporal satellite data—including SAR acquisitions from Sentinel-1, ALOS-2 PALSAR-2, and TerraSAR-X—has been undertaken to map flood extent following river flooding events in regions like Kerala (India), Japan, Estonia, and the Mekong Basin. Satellite-based flood products have been developed and validated in these settings, enabling provision of near-real-time flood cyclone, demora, and tsunami information to civil protection authorities.

5.2. Hydrological Modeling

Hydrological models enhance the understanding of the dynamics between surface water and groundwater through mathematical simulations of the hydrological processes within a catchment. The main aim is to predict how a catchment behaves during an event of intense precipitation or an extreme flooding episode.

The Spatial Hydrology Toolbox (or the 'Topo to Raster hydrological modelling toolbox') was developed to support conceptual rainfall–runoff modelling in the R programming environment. The toolbox comprises functions for construction of: (i) watershed modelling infrastructure—stream channels, subcatchments and flow-paths; and (ii) an initial abstraction layer based on land use classifications. It integrates data-driven modelling methodologies to allow regional-scale (<“10–100 000 km2) estimation of streamflow for almost any catchment in Australia, with an inverse model developed to facilitate model calibration (Novellino et al., 2018).

5.3. Damage Assessment

It is very important to estimate the damage after an earthquake to provide necessary aids to the damaged area (Novellino et al., 2018). Monitoring should be quick and extensive because the affected region is usually large and infrastructure may be in a bad condition. Satellite-borne remote sensing is suitable for this purpose, as it can quickly monitor a large area, regardless of accessibility. Wide-area survey of active volcanoes, which are often located in inaccessible areas, is another demanding task that remote sensing is suited for. Damage detection techniques are often developed in the framework of earthquake monitoring.

Coherent Change Detection (CCD) estimates the difference between two synthetic aperture radar (SAR) images acquired before and after an event, in terms of phase coherence at a pixel level (Oxoli et al., 2018). This procedure has been applied to the 2016 Norcia earthquake to detect structural damages in the historic centre and to estimate time series of displacements in the epicentral region. While uncalibrated CCD maps of North Italy may reveal only a few fields with a significant degree of change, higher-quality data sets can enhance the analysis. Optical and multi-spectral sensors are used to reduce uncertainties of CCD or interferometric synthetic aperture radar (InSAR) deformation maps and to characterize damage information. They are advantageous because the interpretation of structural changes in the temporal domain can be difficult for SAR data. Filtering methods, originally developed for optical imagery, may be successfully applied to low-resolution SAR data.

To detect damages correlated with a seismic event, a multi-temporal analysis helps differentiate between co-seismic and seasonal changes. To use satellite imagery, which usually features interference caused by clouds or weather conditions, weather information should be incorporated, or casualty estimates and damage assessments can help the analysis. Photogrammetric approaches are commonly used and supported by novel methods to automatically reconstruct three-dimensional (3-D) building models. The availability of very-high-resolution (VHR) stereo-optical satellite imagery has significantly enhanced the feasibility of generating accurate 3-D topographic data from space.

6. Remote Sensing Applications in Wildfire Monitoring

Monitoring the duration and severity of wildfires is a major strain on existing resources for agencies responsible for response and recovery efforts. Remote sensing addresses this problem by supporting rapid collection of information to assist damage assessment, evaluation, and rehabilitation plans. Emerging applications of satellite and sensor technologies show promise for overcoming current data limitations.

As forest fires progress across a region, the rate of spread, temperature of the fire front, and the total area affected are of considerable value to emergency response and land management agencies. Long-term rehabilitation planning further demands accurate spatial information concerning the extent and distribution of biomass lost during the fire. Existing ground measurement techniques offer information at limited localities but are largely insufficient for rapid monitoring across wide areas. Satellite remote sensing through analysis of visible and near infrared reflectance, multispectral thermal infrared measurements, as well as wideband microwave and radar sensors offers several methods for addressing the needs of both immediate and long-term wildfire assessments. (Domenikiotis et al., 2003)

6.1. Fire Behavior Monitoring

The monitoring and assessment of fire behavior is of major importance in the mitigation of its disastrous effects on environment, economies, and human life (Domenikiotis et al., 2003). Monitoring the temporal and spatial variation of fire, identification of areas affected by fire, assessment of fire management practices and the rehabilitation progress of the burnt areas are very useful for decision makers in formulating plans, policies and prioritization of the fire fighting and evacuation practices. The availability of thermal bands in almost all of the currently operational satellite systems together with enhancements in radiometric calibration and geo-location accuracy enabled better fire detection and behavior monitoring. Satellite instruments have significant advantages over airborne and ground monitoring in the wide area coverage, repetitive observation capability at better temporal resolution and detection of otherwise inaccessible remote areas (Fordham, 2002). Most of the currently employed fire monitoring applications utilize NOAA Polar Orbiting Satellites with the AVHRR instrument that combines visible (0.58–0.68 ˜m), near-IR (0.725–1.10 ˜m) and thermal-IR channels (3.55–3.93 ˜m, 10.3–11.3 ˜m, 11.5–12.5 ˜m) to detect active fires and map burn scars. NOAA stations transmit AVHRR data every 102–114 min from the moment the satellite crosses the horizon until the satellite passes below it. The combination of vis/near-IR and thermal-IR data enables detection of the fires under partially cloudy conditions during day and night (D. Killough, 2003). Although the Visible Infrared Spin-Scan Radiometer (VISSR) on the Geostationary Operational Environmental Satellite (GOES) platform is mainly used for cloud and aerosol research, it also features a 5-channel radiometer at 0.55–0.75, 3.80-4.00, 6.50–7.00, 10.20–11.20 and 11.50–12.50 ˜m in geosynchronous orbit, providing continuous 24-h coverage which has found some application in the detection of biomass burning from orbit. The 1999 launched Earth Observing System (EOS) TERRA and Aqua platforms combine a multi-spectral radiometer, the Moderate Resolution Imaging Spectroradiometer (MODIS), with a wide range of other instruments and offers two (TERRA) and four (Aqua) fire detections per day. They provide quantitative information on location, fire emitted energy, a flame-to-smouldering ratio, the vegetation cover for the burnt and surrounding areas and accumulated thermal energy release. TIR-developed algorithms coupled with ancillary information of topography, fuel type and moisture, atmospheric and meteorological data in a fuzzy-logic framework provide a detailed model for spatial and temporal wildfire behaviour.

6.2. Post-Fire Recovery Assessment

Post-fire recovery assessment is an essential element in understanding fire-induced ecological disturbance and promoting the implementation of efficient management policies (Domenikiotis et al., 2003). NOAA/AVHRR satellite data have been used to delineate the aerial extent of the burned area by means of image analysis and to observe spatial signs of vegetation loss. Before, during, and after a flood event, various satellite data lead to valuable information for managing the entire event. EDIFICE (Flood Emergency and Disaster Information system) is proposed as a tool for the analysis of airborne sensor data during natural disasters. The second phase of the EDIFICE work focuses on flood hazards, disaster reduction, and floodplain management. Satellite data provide a rapid depiction of the flood extent and damage as well as the mapping of the recession of the flood waters. This information is valuable to authorities as well as to insurance companies for damage evaluation and recovery assessment purposes.

7. Remote Sensing Applications in Landslide Monitoring

Depending on the geometrical and geological structure of the terrain, landslides may occur instantly or after a latent period and in some cases can be preceded by a series of foreshocks. The ability to map past landslides and to detect and monitor their reactivation is therefore paramount to mitigation and planning strategies (Casagli et al., 2016).

Remote sensing methods are of value for landslide mapping and monitoring because the data cover large areas and can be acquired repeatedly over time, thus helping to tackle the issue of on-site accessibility. Two distinct approaches were adopted in the EU-funded FP7-SPACE project SAFER for landslide inventory mapping and continual landslide monitoring.

The first was through the use of Interferometric Synthetic Aperture Radar (InSAR) data that provide the spatial distribution of the displacements of the ground surface, detecting and measuring the movement or deformation along the sensor line-of-sight. The second was through the use of high-resolution optical satellite imagery coupled with object-based image analysis (OBIA) techniques that allow the detection and mapping of potential landslide source areas and outline the affected zones. These two methods were evaluated through several case studies in the European Alps to test their efficiency in different landslide-affected, geological environments and conventional methodologies based on optical satellite image analysis, thermal- and multi-spectral data and digital topographic information.

7.1. Landslide Susceptibility Mapping

Satellite-based landslide susceptibility assessment is crucial for post-seismic hazard evaluation. Previous landslide susceptibility models centered on static variables have limitations due to the complex interplay of multiple causative factors in seismically active regions (Golovko et al., 2017). Remote sensing techniques facilitate diverse landslide investigations, encompassing inventory mapping, susceptibility analysis, hazard assessment, movement monitoring, volume calculation, and tectonic studies (Casagli et al., 2016). Landslides rank among the most devastating natural hazards globally, triggering significant degradation and loss of life. Mapping landslides is challenging, yet essential for hazard mitigation and risk reduction; initiating a comprehensive landslide mapping and monitoring program is fundamental (Novellino et al., 2018).

7.2. Monitoring of Landslide Movements

Landslides occur frequently during or after natural hazards such as earthquakes and volcanic eruptions. Landslide susceptibility analysis in seismically active areas provides insight into slope conditions, facilitating hazard identification and mitigation. Earth Observation (EO) facilitates the identification of landslide-prone areas, underpinning mitigation and preparedness actions. The EU-funded FP7-SPACE project SAFER delivers Landslide Thematic services encompassing inventory mapping, monitoring, and rapid mapping utilising EO technologies. SAFER capitalises on satellite Interferometric Synthetic Aperture Radar (InSAR) and Object-Based Image Analysis (OBIA) to develop these services. Case study implementations in Italy, Austria, Slovakia, and Taiwan demonstrate the applicability of radar and optical EO data, InSAR, and OBIA for landslide mapping and monitoring throughout the emergency management cycle (mitigation, preparedness, crisis, recovery) (Casagli et al., 2016).

Landslides induce considerable socioeconomic losses annually worldwide. Contributing triggers include heavy precipitation, volcanic eruptions, and earthquakes, with human activities such as deforestation and land utilisation further exacerbating hazard conditions. Effective disaster management is contingent on the availability of high-quality, timely information derived from spaceborne observations, facilitating emergency response efforts. The broader SAFER initiative under FP7 – SPACE extends support for geophysical risks, floods, fires, and humanitarian crises within the framework of the European Earth Observation Programme (Novellino et al., 2018).

8. Future Directions in Remote Sensing

Remote sensing presents a valuable opportunity to enhance the monitoring of global natural disasters and representative phases of earthquakes, such as foreshocks and aftershocks, as well as pre- and post-event occurrences. Earthquake detection relies on seismometers, yet these instruments cannot efficiently cover remote areas. Satellite imagery offers a broader perspective, enabling monitoring of affected regions worldwide without the need for physical sensors. Social media images have demonstrated utility in crisis management but remain dependent on infrastructure availability and the presence of individuals. Satellite monitoring overcomes these limitations by detecting changes globally, supporting emergency response and damage assessment. Recent studies have introduced a dataset comprising Sentinel-1 images tailored to disaster scenarios associated with global earthquakes and subsequent damage assessment tasks. This framework encompasses the discrimination and characterization of seismic events while providing relevant information concerning the state of affected infrastructure (Rege Cambrin & Garza, 2024).

Earth Observation (EO) represents a vital tool for investigating, assessing, and monitoring geohazards across multiple scales and geological contexts. Field verification remains essential to confirm image interpretations. Ongoing advances in sensors, technologies, computational resources, and data-sharing platforms contribute to significant improvements in the collection, processing, and analysis of EO data, facilitating more efficient application. Cloud platforms manage crowd-sourced data; such information can be shared in near real time via web technologies, social media, and mobile devices. These developments enhance the accessibility of environmental information for planners and decision-makers, enabling improved management of geohazards (Novellino et al., 2018).

9. Conclusion

Remote sensing techniques enable comprehensive and timely monitoring of a single natural hazard or cascade events affecting large areas often inaccessible to ground observation (Novellino et al., 2018). Furthermore, the integration of ground observations and numerical models improves the understanding and the accuracy of forecasts of environmental events and their analysis.

Remote sensing has proven to be extremely valuable in monitoring earthquakes and related natural hazards. The combined use of satellite, airborne, and terrestrial sensors is effective in the detection of pre-earthquake phases, the measurement of post-event ground motions and damage, and the mapping of subsequent phenomena such as debris flows and floods. Optical and near-infrared airborne data can be exploited for the efficient derivation of ground control points supporting radar data co-registration and multitemporal Deformation measurements of the Earth's surface based on radar data analysis provide large areal coverage with near real-time information. Data from bistatic SAR sensors facilitate exploration of seismic phenomena with an unprecedented level of accuracy, enabling the investigation of crustal fracturing mechanisms that have been suggested as potential earthquake precursors (Rege Cambrin & Garza, 2024).

Author's Declaration:

I/We, the author(s)/co-author(s), declare that the entire content, views, analysis, and conclusions of this article are solely my/our own. I/We take full responsibility, individually and collectively, for any errors, omissions, ethical misconduct, copyright violations, plagiarism, defamation, misrepresentation, or any legal consequences arising now or in the future. The publisher, editors, and reviewers shall not be held responsible or liable in any way for any legal, ethical, financial, or reputational claims related to this article. All responsibility rests solely with the author(s)/co-author(s), jointly and severally. I/We further affirm that there is no conflict of interest financial, personal, academic, or professional regarding the subject, findings, or publication of this article.

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