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Utilization of remote sensing in post-disaster recovery for environmental damage assessment

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ABSTRACT

Background: Remote sensing techniques have become one of the important methods in post-disaster recovery for assessing environmental damage. They offer the ability to quickly and accurately identify and map damage at a wide scale, which is particularly useful in dynamic and often unpredictable post-disaster situations. **Methods:** This research aims to explore the use of various remote sensing technologies, such as satellite imagery, radar and drones, in assessing environmental damage after natural disasters. In this study, brainstorming focused on how remote sensing technologies can be optimally applied in post-disaster recovery, with an emphasis on environmental damage assessment. **Findings:** The results showed that remote sensing technology enables the identification of structural and environmental damage more efficiently than traditional methods. Satellite imagery provides an overview of the extent of the affected area, while radar and LiDAR technologies can be used to measure physical damage in greater detail. Drones, with their high resolution and flexibility, serve as an additional tool for detailed surveys in areas that are difficult to access. However, the application of this technology is not free from challenges, such as access to high-resolution data that is often expensive, the need for field validation to ensure accuracy, and infrastructure limitations in some disaster-prone developing countries. **Conclusion:** This research recommends increasing access to remote sensing data at affordable costs or for free for developing countries, integration of multi-source technologies to improve assessment accuracy. In addition, policy development based on remote sensing data for disaster risk mitigation. Thus, remote sensing is very useful for long-term disaster mitigation and adaptation planning and for post-disaster assessment. **Novelty/Originality of this article:** This article integrative exploration of multi-source remote sensing technologies—satellite imagery, radar, LiDAR, and drones—for comprehensive environmental damage assessment in post-disaster recovery, with a specific emphasis on challenges and policy implications in developing countries.

KEYWORDS: drones; environmental damage assessment; post-disaster recovery; radar; remote sensing; satellite imagery.

1. Introduction

Natural disasters, including earthquakes, floods, tsunamis, and forest fires, often leave behind significant environmental damage, requiring rapid and appropriate response. Post-disaster recovery, especially with regard to extensive environmental, infrastructure, and ecological damage, often faces challenges such as access to affected sites, time constraints, and the need for accurate and timely data (Wu et al., 2019).

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In this context, remote sensing technology, also known as remote sensing, has developed rapidly and is now an important solution to many problems. To assist many parties in monitoring, assessing and managing disaster impacts more efficiently and effectively. Remote sensing enables damage detection on a wide scale and facilitates temporal analysis to identify environmental changes over time. In addition, the use of satellite and UAV (Unmanned Aerial Vehicle) data provides highly detailed spatial information that enables more in-depth and comprehensive damage assessment (Tralli et al., 2005). With this technology, various parties can access visual and spatial data regarding disaster-affected areas, allowing them to make decisions about recovery efforts that can be implemented quickly.

Indonesia has the highest rate of natural disasters, according to data from the National Disaster Management Agency (BNPB). It suffers huge economic and environmental losses every year. The use of this technology includes devices such as satellites, radars, and drones. Remote sensing technology, with its real-time mapping capabilities, has great potential to accelerate the environmental recovery process and assist in long-term mitigation planning. However, to date, optimizing the use of this technology has been hampered by limited human resources, infrastructure, and policies that support the widespread implementation of remote sensing in post-disaster recovery (Navalgund & Roy, 2007). The use of this technology includes various devices such as satellites, radar, and drones, which are used to monitor the physical conditions of the Earth's surface and its surrounding environment in real-time with a very wide coverage.

In post-disaster emergency situations, remote sensing has the advantage of being able to provide large spatial data in a short period of time. The purpose of this research is to study how remote sensing functions in post-disaster recovery, especially in assessing environmental damage. The main types of technologies used in remote sensing, the implementation of these technologies in the field, the problems often encountered, and the advantages of using these technologies in the recovery process will be discussed. Specifically, this research will examine the extent to which remote sensing technology can improve efficiency in identifying environmental damage, accelerate the recovery process, and provide policy recommendations that support the optimization of this technology in disaster management in Indonesia.

This research is supported by several previous studies that examined remote sensing as an important technology in environmental monitoring and disaster management. Remote sensing is very effective in detecting land changes, ecosystem monitoring, and damage analysis due to natural disasters. According to Chien & Tanpipat (2012), satellite data can provide a clear picture of land cover changes due to earthquakes, making it easier to identify significantly affected areas.

However, it becomes a major issue to obtain data that can be accessed in real-time, especially in remote areas or developing countries that lack the adequate infrastructure to process large volumes of data. Through this literature review, it can be concluded that although remote sensing technology has great potential in post-disaster recovery, further research is still needed on the best ways to address technical and policy constraints, especially in areas with limited infrastructure. Furthermore, the quality of data produced by remote sensing sensors can be affected by weather conditions, such as thick clouds or rain, which can hinder the ability of the equipment to accurately monitor the affected areas. Another challenge is the need to conduct field validation of the obtained data. Although satellite or drone imagery can provide a broad visual overview, field observations are still necessary to ensure that the analysis conducted aligns with the actual conditions in the affected area.

2. Methods

The utilization of remote sensing technology in post-disaster recovery has a role to play in environmental damage assessment. It allows for the rapid and accurate collection of data from affected areas, assisting in the development of more efficient and productive mitigation strategies. This research uses brainstorming as one of the qualitative methods to identify important aspects of utilizing this technology. Brainstorming is an exploratory method that aims to generate ideas creatively and without restrictions. This technique is often used in academic research to explore possible approaches and innovations in a field. In this research, brainstorming focused on how remote sensing technology can be optimally applied in post-disaster recovery, with an emphasis on environmental damage assessment (Osborn, 1953). Brainstorming steps were carried out as follows:

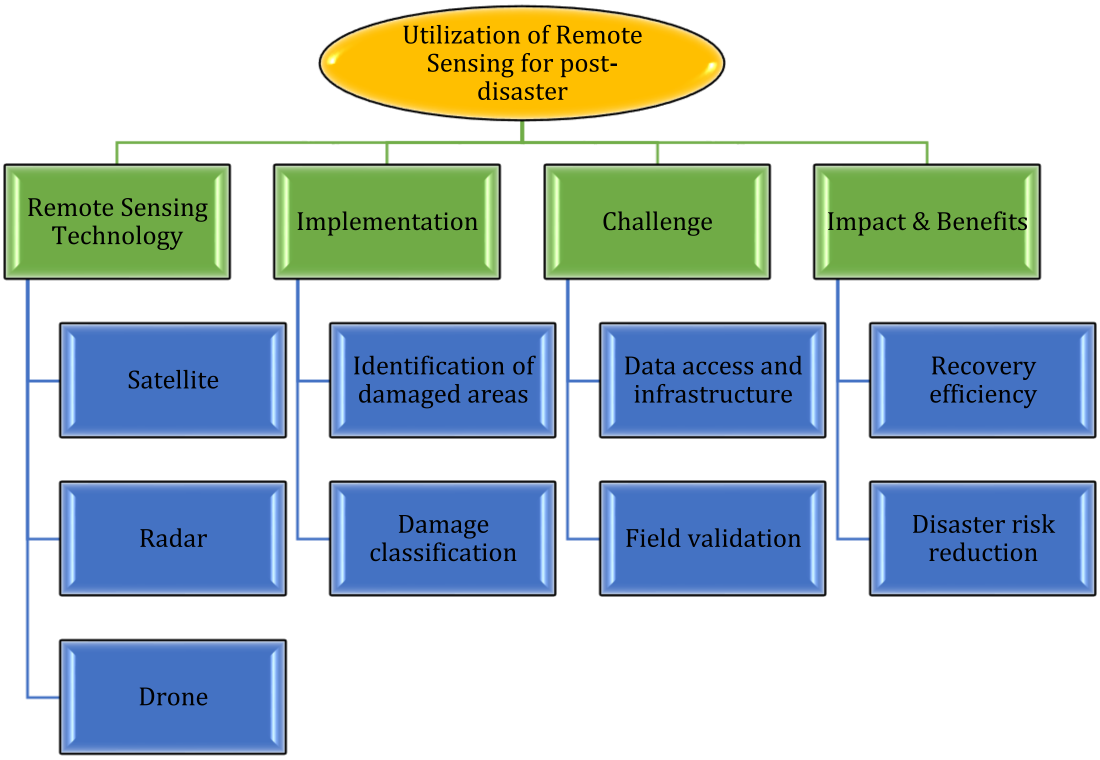

Fig. 1. Brainstorming steps

Based on the Figure 1 above is a brainstorming diagram that describes the utilization of remote sensing technology in post-disaster recovery, with four main components, namely: sensing technology, implementation, challenges, and impacts and benefits. The following is a detailed explanation. Remote sensing technology used in post-disaster recovery includes three main technologies, namely satellites, radar, and drones. Satellites are utilized to obtain images of large areas and monitor disaster damage at a macro level. Radar is capable of penetrating clouds and fog to provide detailed information about the earth's surface, particularly in unfavorable weather conditions. Drones are employed to capture data in hard-to-reach areas and provide high-resolution imagery at a local scale.

In the implementation of remote sensing technology, there are two main stages. The first stage is the identification of damage areas, where the technology is used to quickly and accurately detect regions affected by disasters. The second stage is damage classification, in which identified areas are assessed based on the severity and type of environmental damage, such as damage to infrastructure, vegetation, or residential zones.

However, several challenges are often encountered in applying this technology. One of the primary challenges is related to data access and infrastructure, as not all affected areas possess adequate infrastructure to access remote sensing data, and the availability of such data is sometimes limited or expensive. Another significant challenge is the need for field validation, where remote sensing data must be corroborated through on-site surveys to ensure the accuracy of image interpretation.

Despite these challenges, the use of remote sensing technology in post-disaster recovery offers several important benefits. It enhances recovery efficiency by enabling

faster response due to the availability of timely and accurate damage data. Additionally, it contributes to disaster risk reduction by providing valuable information that aids in recovery planning and the mitigation of future disaster risks.
The Brainstorming Figure above can help summarize how remote sensing technology can contribute to various aspects of post-disaster recovery, from early identification to long-term impacts in reducing disaster risk.

3. Results and Discussion

Based on the brainstorming diagram presented earlier, the results of this research focus on how remote sensing can be utilized in the context of post-disaster recovery for environmental damage assessment. The research involved various remote sensing technologies such as satellites, radars and drones, and evaluated their implementation, challenges, and impacts and benefits. Below are the details of the research results:

3.1 Remote sensing technology in post-disaster recovery

Today, remote sensing technology is essential for all stages of natural disaster management, including disaster reduction, emergency response, and post-disaster recovery (Kulawardhana, 2012). Remote sensing is particularly helpful for post-disaster recovery as it can provide accurate and rapid information on the condition of the affected environment. In emergencies such as earthquakes, tsunamis or floods, time is of the essence. These technologies allow access to large-scale spatial data with multiple resolutions without having to travel to the site. The research found that three key technologies such as satellites, radar and drones. Play an important role in helping to assess disaster damage quickly and effectively.

3.1.1 Satellites

A satellite is generally an object that orbits around a planet or other celestial body. Satellite technology has become an important part of remote sensing and disaster recovery. Satellites that have optical, infrared, radar, and multispectral sensors can collect data with great precision from various parts of the Earth, such as the atmosphere, land, oceans, and polar regions (Asrar, 2019). Satellites have multispectral, infrared, and microwave sensors that can observe the Earth's surface conditions at various times and weather conditions, including at night or when thick clouds cover certain areas (Bluestein et al., 2022). This capability is crucial for disaster mitigation. When natural disasters occur, satellites can quantify the damage in a short period of time (Parker et al., 2021). For example, radar satellite imagery can provide information on surface changes due to landslides (Mondini et al., 2021).

Satellite photos are essential for recording physical damage. High-resolution images allow for quick identification of structural damage, road damage and terrain changes caused by earthquakes or floods (Elliott et al., 2022; Lung et al., 2013; Voigt et al., 2007). To plan relief distribution and evacuation, satellite data can also be used as it makes it easier to identify safe routes, affected areas and potential physical obstacles (Franck et al., 2011).

In addition, satellites aid post-disaster recovery by providing information in real time, which enables monitoring of changes in the affected area (Sublime & Kalinicheva, 2019). This long-term monitoring is crucial for spotting potential hazards. In these situations, satellites not only provide emergency response data, but also provide early warning tools to people who remain in the hazard area (Choy et al., 2016).

Satellite mapping is particularly useful for disaster management in hard-to-reach areas, such as small islands or mountainous regions (Zhu et al., 2015), while microwaves can be used to observe soil moisture levels, providing important information on landslide risk (Ray et al, 2010). By integrating different types of data obtained from satellites, a comprehensive risk analysis can be conducted so that more effective mitigation measures can be taken before further disasters occur.

With higher image resolution, faster data capture speed, and stronger cloud penetration capabilities, satellite technology is evolving rapidly. Modern satellites equipped with radar sensors (SAR-Synthetic Aperture Radar) enable the assessment of emergency situations without light or weather limitations as they provide an overview of the earth's terrain even under heavy clouds or at night (Villano, 2015).

In the future, with the development of artificial intelligence and machine learning technologies integrated into satellite data analysis, the use of satellites in post-disaster recovery will further advance (Mukonza & Chiang, 2023). When AI is used to analysed images, it can automatically find damage patterns, predict which areas may be affected, and assist in faster and more accurate decision-making (Cheng et al., 2022).

3.1.2 Radar

Radar (radio detection and ranging) is a technology that uses electromagnetic waves to detect objects and measure distance, speed, and changes in the earth's surface. This is done by emitting waves to the object or surface to be observed from the radar antenna, and then reflected back to the receiving antenna (Brennan & Reed, 1973; Shanmugan et al., 1981).

Remote sensing radars are excellent because they can penetrate clouds, fog, rain, and darkness. This makes it ideal for use in bad weather or enclosed areas such as dense forests or dense urban areas (Li , 2020). This makes radar particularly useful in situations where conventional optical or satellite sensors are ineffective, such as during storms or at night. In addition, a technology known as interferometric radar (InSAR) has the ability to detect small changes in the Earth's surface over time (Pepe & Calò, 2017). InSAR can measure ground deformation caused by volcanic activity, ground shifts, or earthquakes (Camacho et al., 2020). The data obtained is important for continuous monitoring of changes in the earth's surface. Radar has proven effective for use in areas with unfavourable weather conditions, such as heavy clouds, or at night. Radar provides high accuracy images of the land surface even under extreme environmental conditions. Research results show that radar is very useful in cases of floods, landslides, where ordinary visual imagery may not be able to capture the necessary details due to bad weather.

Radar technology is very useful in various disaster mitigation applications. In flood disasters, radar applications are used to monitor the extent of standing water, allowing researchers to map the waterlogged area more clearly. Despite cloud cover, the damage identification process can take place without weather hindrance. In the case of flooding, for example, radar allows researchers to map the area submerged in water more clearly despite cloud cover, so that the damage identification process can take place without weather obstacles (Kim et al., 2013). Radar is a perfect tool for monitoring floods, helping local authorities organize evacuations or water diversions to reduce losses caused by flooding

In closed areas such as dense tropical forests, radar can provide information that cannot be obtained using optical remote sensing technology (Blackwell et al., 2020). The development of satellite-based radar will also expand the coverage and frequency of data collection, enabling global and continuous monitoring of the Earth's surface. This will be crucial in addressing the challenges of climate change.

3.1.3 Drones

In fields such as mapping, aerial surveying, and remote sensing, drones have increased in use in recent years (Colomina & Molina, 2014). Drones, also referred to as UAVs, are unmanned aircraft that can fly automatically or be remotely controlled (Xing & Johnson, 2023). Drones can collect data from the air quickly and effectively, especially in locations that are difficult to access or could endanger humans.

One of the advantages of using drones is the ability to collect high-resolution data and are usually equipped with advanced cameras and sensors such as LiDAR sensors, infrared cameras, or high-resolution cameras (Harvey et al., 2016; Svanström et al., 2022). This is particularly useful for mapping, environmental monitoring, and surveying (Zhu et al., 2022). This is necessary for environmental monitoring applications such as identifying land cover change, coastal erosion, or soil movement in landslide-prone areas. High-resolution drones allow urban planners and scientists to make better decisions based on data (Hu & Minner, 2023).

The use of drones in this study showed very positive results in detailed and localized damage mapping. Drones can fly low over hard-to-reach areas, such as mountainous terrain or areas affected by landslides, and provide high-resolution imagery that can be used to assess damage to buildings, bridges or other critical infrastructure (Jordan, 2019; Whitehurst et al., 2022; Ybañez et al., 2021). Drones are particularly useful in areas with limited physical access due to disasters. For example, after an earthquake, drones can be used to check the stability of building structures and identify areas that require emergency assistance. With a relatively small size and various types of sensors and cameras, drones can be remotely controlled (Hassanalian & Abdelkefi, 2017).

In hazardous locations such as areas recently affected by natural disasters, drones can provide very useful visual access without having to send personnel to high-risk areas. Drones can be used to monitor infrastructure such as collapsed buildings or areas flooded due to heavy rain. So that it can provide information to the emergency response team to plan rescue or evacuation actions. Drones can also be set to fly at varying altitudes, allowing them to provide data from different angles and perspectives. In terms of cost efficiency, the use of drones is much cheaper compared to the use of planes or satellites for aerial surveys. Drone operations require less labor and lower fuel costs. Drones can also be flown repeatedly without significant additional costs, making them a cost-effective solution for long-term mapping or surveying projects.

3.2 Implementation of remote sensing for environmental damage assessment

One of the most effective technologies for monitoring and assessing environmental damage is remote sensing. This is especially true for areas that are large and difficult to access. In its implementation, it involves the use of radars, satellites, drones, and advanced data processing technologies such as artificial intelligence (AI) and machine learning to provide accurate information about the condition of an area after a natural disaster or human actions that cause damage. The results of this study show that the application of remote sensing technology in post-disaster recovery. The following is an explanation of how remote sensing is used to identify, classify and assess environmental damage.

3.2.1 *Identification of damage areas*

Satellite, radar and drone technologies are collectively used to identify affected areas. Research has found that by combining these technologies, identification of disaster-affected areas is faster and more accurate. The use of satellite imagery for wide area coverage, followed by drones for ground verification, provides a complete picture of the damage (Atmaca et al., 2023). Remote sensing, which uses satellite and drone imagery, can provide a detailed perspective of the damaged area. This technique enables effective and speedy damage detection, particularly in areas where rescue crews cannot immediately reach. Techniques such as Synthetic Aperture Radar (SAR) can make continuous observations even if clouds or smoke cover the area. By using the phase difference between two images taken at different times, radar interferometry can detect changes in the Earth's surface (Massonnet & Feigl, 1998).

For visual damage mapping, optical satellites are essential. High-resolution satellites such as Landsat and Sentinel-2 are used to identify infrastructure damage, vegetation changes, and building damage (Chaves et al., 2020). Drones with low-flying capabilities and greater flexibility can take high-resolution photos of small areas that are often needed for detailed analysis.

A multisensor technique has various advantages in environmental damage assessment, including improved analysis accuracy and dependability. The results provided by merging data from several sensors, such as radar, visual, and thermal, are more representative of actual field circumstances. This technique tackles several sensor flaws, resulting in more accurate data in tough settings. In addition, this strategy improves data resolution. To validate data in a local area, satellites' extensive coverage can be supplemented with high-resolution photos from drones. Furthermore, this technology enables the mapping and monitoring of directly affected areas, allowing for faster and more accurate environmental decision-making. The Normalized Difference Vegetation Index (NDVI) technique, which is often used to measure vegetation damage, can also be used by remote sensing (Martinez & Labib, 2022). Low NDVI values indicate that the vegetation in an area has been damaged by flooding, drought or forest fires (Vicente-Serrano et al., 2015). For example, in post-tsunami Japan, this technology allowed researchers to quickly identify the worst-affected areas and target aid to those areas.

3.2.2 Classification of damage

Once the initial identification is complete, the next step is to determine the type of damage incurred. This classification process is essential for calculating the level of damage experienced by different components of the environment, such as vegetation, buildings, infrastructure and agricultural land. Satellites and drones can take multispectral imagery to distinguish different types of damage. The non-infrared and shortwave infrared (SWIR) bands, for example, are excellent at detecting vegetation damage and forest fires (Li et al., 2022). Research has found that satellites and drones are helpful in determining these damage categories, so that recovery actions can be prioritized based on severity.

Examples of applications include categorizing forest damage using satellite imagery to distinguish burnt areas from intact areas. This can be done using vegetation indices such as NDVI (Segah et al., 2010). Another application involves using drones or high-resolution satellites to classify farmland damage by identifying areas affected by flooding, drought, or pest infestation. Infrared spectral bands can also be utilized to determine crop conditions (Yang et al., 2011). Classification of infrastructure damage can be carried out using SAR or satellite radar, which is capable of detecting damage to infrastructure such as roads, bridges, and buildings after an earthquake or other disaster (Brunner et al., 2010).

Combining data from different sensors and platforms is a key feature of remote sensing, which allows for a more complete and thorough analysis of the damage. Its main advantage is when one sensor has limitations, such as optical satellites that cannot function properly under clouds, but radar still works well in any weather condition (Hussain et al., 2022). A multisensor technique has various advantages in environmental damage assessment, including improved analysis accuracy and dependability. The results provided by merging data from several sensors, such as radar, visual, and thermal, are more representative of actual field circumstances. This technique tackles several sensor flaws, resulting in more accurate data in tough settings. In addition, this strategy improves data resolution. To validate data in a local area, satellites' extensive coverage can be supplemented with high-resolution photos from drones. Furthermore, this technology enables the mapping and monitoring of directly affected areas, allowing for faster and more accurate environmental decision-making.

3.3 Challenges in the utilization of remote sensing

Although remote sensing offers many benefits in monitoring and managing various aspects of the environment, such as climate change monitoring and disaster mitigation, its implementation also faces many challenges. Implementation faces many problems, including limited data access, infrastructure issues, field validation, and current technological limitations. In this section, we will discuss the main issues faced when using remote sensing.

3.3.1 Data access and infrastructure

This research found that access to remote sensing data is often limited by cost and infrastructure availability (Li & Roy, 2017; Tahu et al., 1998). Not all countries or regions have easy access to high-quality satellite imagery data or advanced drone technology (Voigt et al., 2016). This becomes a challenge, especially in developing countries affected by natural disasters. Additionally, the frequency of data collection constraints also affects the availability of real-time data.

The infrastructure required to process and store remote sensing data is also an additional issue. Remote sensing data generated by multispectral and hyperspectral sensors or high-resolution satellites can be very large (Žížala et al., 2019). To process this data, a strong and efficient computing infrastructure is required, such as a supercomputer or cloud computing. Countries with less advanced technological infrastructure do not always have infrastructure like this (Li et al., 2023). Moreover, there is a major issue with data storage. Remote sensing data often requires large storage capacity and storage solutions that can be accessed quickly without compromising data security and integrity (Tang et al., 2021).

3.3.2 Field validation

Results from remote sensing imagery often require field validation to ensure data accuracy (Wu et al., 2019). involves the use of remote sensing to monitor field conditions directly (Baccini et al., 2007). Remote sensing results also require adjustments for factors such as weather, cloud cover, or sensor technical errors (Foga et al., 2017; Li et al., 2019). This becomes a challenge, especially in areas that are still in critical condition due to the disaster, where field validation teams may have difficulty accessing the affected locations (Bayarsaikhan et al., 2022). This research suggests enhancing the integration between remote sensing and field-based monitoring systems to address this challenge.

Access to the impacted areas, particularly in emergency scenarios, is another common challenge that emerges during field validation. Coordination between field crews and data processors can be difficult, particularly if the communication infrastructure is broken or inadequate. Natural disasters strike in remote areas or pose a significant risk to field personnel. For example, when a significant forest fire happens, there is limited access to the area, making it difficult for the field validation team to visit affected areas. Drones may be useful in instances like this, however they cannot always be used due to weather and limited airspace.

3.3.3 Technological limitations

In poor weather conditions, remote sensing technology is very limited. Because the images produced differ from optical images and often require special analysis, radar images have limitations in interpretation (Bryan, 1975). because the images produced differ from optical images and often require analysis conducted with specialized skills. Additionally, satellite imagery often cannot provide detailed information on a smaller scale. For example, while satellites can track large changes in the Earth's surface conditions or vegetation, they cannot track small changes such as building or road damage caused by earthquakes, which can only be seen on a local scale.

One of the other issues with remote sensing related to the impact of climate change is the limitations in analyzing complex data (Coro et al., 2020). To study the impact of climate change on vegetation growth or ecosystems, remote sensing data must be combined with data from various sources, such as weather, land use, and animal populations (Caparros-

Santiago et al., 2021). Complex mathematical models are often used in this analysis, as well as the processing of very large data sets, which require advanced computing resources.

Additionally, the limitation of temporal resolution in remote sensing images for monitoring climate change. Climate change occurs over a very long period, so images taken at certain time intervals may not be sufficient to capture slow but significant changes in the environment. In the context of addressing these challenges, data from various sources, including field observations and climate models, need to be integrated to provide a more comprehensive understanding (Hall et al., 2019).

Additionally, it can use cloud computing-based technology that can help address data deviation issues and large-scale data processing (Hashem et al., 2015). Since cloud storage doesn't require a significant infrastructure, data access from many locations is made easier. Additionally, utilizing drones to gather field data in real-time can help lessen reliance on satellite photography. Obtaining information rapidly is crucial, particularly in emergency situations. The development of AI and machine learning to analyze complicated data can improve the efficiency and accuracy of data processing, especially for long-term analysis and climate change monitoring. Investment in radar technology and hyperspectral sensors can help overcome technological restrictions.

3.4 The impact and benefits of remote sensing in post-disaster recovery

In post-disaster recovery, remote sensing is very helpful in identifying, planning, and implementing the necessary actions. Through risk mapping and mitigation strategies, remote sensing data can be used to reduce future disaster risks.

Remote sensing technology accelerates the process because it allows for real-time or near-real-time observation of field conditions, without having to wait for reports from the field team. In a post-disaster situation, this speed is very important because a quick response can save lives and reduce the long-term impact on society and the environment. Its ability to reach inaccessible areas is one of the major advantages of remote sensing. In disasters such as volcanic eruptions, landslides, or flash floods, some areas may be very dangerous or may not be accessible to rescue teams or field assessors. Disaster response teams can assess the level of damage without entering hazardous areas by using satellite images or drones. This research also identifies various positive impacts and benefits of applying remote sensing technology in post-disaster recovery.

3.4.1 Recovery efficiency

Remote sensing technology has proven to accelerate the recovery process by providing accurate damage data in a short time. This research shows that by relying on this technology, post-disaster response time can be reduced, allowing recovery to begin more quickly and efficiently. A case example is the use of remote sensing in post-disaster recovery after the earthquake and tsunami in Palu, Indonesia, in 2018. The government and international organizations utilized satellite images to identify the areas most affected by the disaster. This data assisted rescuers in evacuating victims and delivering humanitarian aid to the hardest-hit regions (Syifa et al., 2019). In the case of Hurricane Katrina in 2005 in the United States, remote sensing played a crucial role in the recovery process. After the storm impacted the coastal area, satellite imagery was used to assess infrastructure damage, including roads, bridges, and buildings, facilitating faster and more effective reconstruction planning. Drone technology was also employed to monitor damaged and inaccessible areas from the air (Li et al., 2016). Similarly, following the earthquake in Nepal in 2015, remote sensing technology was deployed to monitor damage to buildings and infrastructure. Satellites supported aid organizations in prioritizing locations for evacuation and recovery, significantly accelerating the distribution of humanitarian assistance to the affected populations (Ge et al., 2015; Zhao et al., 2017).

3.4.2 Disaster risk reduction

One of the long-term benefits found from this research is the ability of remote sensing technology to reduce disaster risk in the future. With data generated from previous disasters, disaster-prone areas can be mapped more effectively, and mitigation measures can be taken earlier (Tralli et al., 2005). Case example: post-earthquake research in Haiti shows that by using remote sensing data, planners can identify the most earthquake-prone zones and plan for more earthquake-resistant construction in the future (Oktaviani et al., 2017).

The government and other stakeholders can use this data to create better mitigation plans and prepare the community to face disasters. For example, satellite images can be used to observe land cover changes and deforestation, which can increase the risk of floods and landslides. Remote sensing also enables better geological mapping, which is crucial for disaster mitigation planning such as earthquakes and landslides. Geologists can monitor tectonic plate movements or changes in soil structure that can cause earthquakes or landslides using infrared and radar data. Early warnings like this allow the government to take actions to prevent problems, such as relocating people from high-risk areas or reinforcing critical infrastructure.

4. Conclusions

The use of remote sensing technology in post-disaster recovery has proven to significantly contribute to environmental damage assessment and recovery planning. Various technologies such as satellites, radar, and drones enable researchers and policymakers to quickly and accurately identify damage, which is crucial in the dynamic post-disaster conditions. Satellite and radar imagery enable mapping of large areas, while drones provide high-resolution details in hard-to-reach locations. Through this combination of technology, the process of identifying and classifying environmental damage can be carried out more efficiently and with higher accuracy. The improvement of technological infrastructure is crucial to maximizing the potential of remote sensing in post-disaster management.

The research results show that not only does remote sensing technology assist in mapping physical damage, but it also aids in risk assessment and future mitigation planning. Overall, the utilization of remote sensing data to monitor environmental changes over time enables policymakers to understand damage patterns and plan more targeted preventive measures. In the long term, the use of this technology contributes to reducing disaster risk and enhancing the community's ability to cope with natural disasters. Nevertheless, several challenges need to be addressed for remote sensing technology to be used optimally. The main challenges include access to high-quality data, which often requires significant costs, as well as the need for field validation to ensure the accuracy of data obtained from remote sensing. Another challenge is the uneven infrastructure in some developing countries, which limits the widespread access and use of this technology. Therefore, enhancing technical capacity and infrastructure in the affected countries is crucial to maximizing the benefits of remote sensing technology.

Based on the findings of this research, several recommendations can be suggested to enhance the utilization of remote sensing in post-disaster recovery and environmental damage assessment. First, improved access to remote sensing data is essential. Governments and international institutions are encouraged to provide greater access to high-quality remote sensing data at affordable or even free costs, particularly for developing countries that are frequently affected by natural disasters. Second, the integration of multisource technology should be prioritized. To increase the accuracy and efficiency of damage assessments, data from various remote sensing technologies—such as satellites, radar, and drones—should be integrated in a more structured manner. The combination of these technologies can offer a more comprehensive view of the on-ground situation and help prioritize areas in urgent need of assistance. Lastly, the development of remote sensing data-based policies is recommended. Governments and policymakers are urged to utilize this data as a foundation for formulating disaster mitigation strategies and spatial planning. This includes mapping high-risk zones and designing more disaster-resilient infrastructure to strengthen preparedness and resilience against future hazards.

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