Chapter

Remote Sensing Approaches and Related Techniques to Map and Study Landslides

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Abstract

Landslide is one of the costliest and fatal geological hazards, threatening and influencing the socioeconomic conditions in many countries globally. Remote sensing approaches are widely used in landslide studies. Landslide threats can also be investigated through slope stability model, susceptibility mapping, hazard assessment, risk analysis, and other methods. Although it is possible to conduct landslide studies using in-situ observation, it is time-consuming, expensive, and sometimes challenging to collect data at inaccessible terrains. Remote sensing data can be used in landslide monitoring, mapping, hazard prediction and assessment, and other investigations. The primary goal of this chapter is to review the existing remote sensing approaches and techniques used to study landslides and explore the possibilities of potential remote sensing tools that can effectively be used in landslide studies in the future. This chapter also provides critical and comprehensive reviews of landslide studies focus¬ing on the role played by remote sensing data and approaches in landslide hazard assessment. Further, the reviews discuss the application of remotely sensed products for landslide detection, mapping, prediction, and evaluation around the world. This systematic review may contribute to better understanding the extensive use of remotely sensed data and spatial analysis techniques to conduct landslide studies at a range of scales.

Keywords: remote sensing, landslide detection, landslide mapping, landslide inventory, natural hazards, susceptibility, assessment

1. Introduction

Landslides are natural hazards that have a significant impact globally [1, 2]. In comparison to other natural hazards, landslides are one of the costliest and fatal geological hazards, threatening and influencing the socioeconomic conditions of many countries throughout the world [3–5]. A landslide can be triggered by various natural phenomena (e.g., earthquakes, heavy rainfall, tsunami, and flood) and human disturbances (e.g., deforestation, infrastructure developments by cutting slopes, and presence of historical underground cavities) [6–8]. A landslide occurs when the soil layers of the slope get detached either from saturation due to extreme rainfall events or from external forces (e.g., earthquakes) and move downhill causing loss of life, properties, environments, and economic damage. For example, in the U.S. alone, landslides cause approximately $3.5 billion in damage and kill between 25 to 50 people each year [9]. Also, in 2014 alone, Nepal had a landslide where livestock loss was many times larger than human loss and infrastructural damage was more expensive in comparison to the economy of the country [10]. Slope failures also cause major sedimentation into streams and lakes, which further represents a major cause of flooding [5, 11].

Landslides are common primarily in the mountainous regions if a slope is unstable or becomes unstable due to external driving forces [10, 12]. Landslide hazard can be classified into high, moderate, and low based on the volume, duration, possible effect in terms of distance, area, and speed at which the slope fails. Since landslides can adversely affect human lives and property, it is essential to monitor, detect, map, and conduct hazard analysis in order to reduce the impact of their hazard and save human lives, property, and environment around the globe. Landslide susceptibility maps can be developed for landslide-prone regions by combining all of the potential predisposing factors, which cause a landslide.

Landslide susceptibility depends on the local terrain, land use, and climatic conditions, which require spatial information [13]. A landslide susceptibility zone includes information of past landslide inventory with an evaluation of future landslide-prone areas, but it does not include assessment of the frequency of landslide occurrence [14]. Also, the temporal probability of a landslide is not included in susceptibility models [15]. High-quality landslide inventory maps can be developed using in situ measurements and field surveying [16, 17]. However, in situ measurements and field surveying are time consuming, expensive, and difficult for local to global scales. On the other hand, landslide susceptibility and inventory maps, as well as landslide hazard analysis, can be possible using remote sensing techniques and data, such as aerial surveys, unmanned aerial vehicles (UAV), light detection and ranging (LiDAR), and satellite imagery [16, 18].

Although remote sensing is continuously used for landslide detection/mapping and monitoring, it is generally considered to have a medium effectiveness/reliability for landslide studies because satellite data are available relatively at coarse resolutions [3]. On the other hand, hazard assessment requires high resolution data to define the spatial distribution of landslides and their state of activity both on a local scale and from studies from regional/global scales [10]. In addition, remotely sensed data are cost-effective because most of the global satellite products are freely available and can cover rugged/complex terrains, which is otherwise not possible to assess with in situ measurements [19]. Even in the late 1990s, stereoscopic air-photo interpretation was the most used remote sensing tool applied to the mapping and monitoring of landslides [20]. Many studies have been carried out on landslide hazard evaluation using geographic information systems (GIS) and geoinformation-related techniques [4]. Recently, GIS and remote sensing tools have become powerful tools for integrating spatial data to conduct landslide studies [10, 21].

Remotely sensed data and techniques are widely used in landslide studies, including landslide inventory/detection, monitoring, and mapping, and hazard analysis (e.g., [16, 22, 23]). Timely and high-quality information derived from space-borne observations helps in managing natural and human-made disasters [1]. Accordingly, landslide risk mapping and management can help reduce disaster risk [10]. Similarly, early landslide predictions and warnings are important in curtailing landslide hazards [4, 24]. Landslide vulnerability assessment is used in identifying what elements are at risk and why; such information helps in landslide disaster mitigation measures [10, 21].

The use of remote sensing data for landslide studies, whether air, satellite, or ground-based measurements, is mainly classified into three main categories: (a) detection and identification, (b) monitoring, and (c) spatial analysis and hazard prediction [20]. However, we have reviewed landslide studies using multiple categories as they appear in the literature.

This chapter aims to provide a critical and comprehensive review of recent landslide studies conducted using remotely sensed data and techniques. It includes an overview of landslide inventory/detection, mapping and monitoring, susceptibility, and hazard analysis using remotely sensed data at a range of scales. It helps to understand the potential benefits of conducting landslide studies using satellite data to save human lives, properties, and environments around the globe.

2. Landslide inventory/detection

Landslides, influenced by several preparatory and triggering factors, are naturally hazardous events causing loss of lives and properties and environmental degradation [25]. Landslide-triggering factors such as intense or prolonged rainfall or rapid snowmelt, earthquakes, or volcanic eruptions are enhanced by human-induced triggering factors such as deforestation, mining, and cutting slopes for road development [8, 26, 27]. Landslides include various movements like flowing, sliding, toppling, or falling, and many landslides combine two or more of these movements at the same time or during the lifetime of a landslide [28]. Traditionally, landslide inventory maps can be retrieved from historical sources, archives documents, and newspapers, which are important but not detailed enough, making quantitative risk assessment challenging [29]. Historical landslide events offer a good opportunity to evaluate landslide detection techniques to develop landslide inventory, which can also be used in developing or validating landslide susceptibility and hazard mappings models [30].

An inventory map identifies landslides in a study area to establish the spatial correlation between landslides and environmental factors [31]. A landslide inventory map is required to quantify landslide occurrence effectively. Landslide inventories generally include the size of landslides, its locations, and volume (preferred) [26]. Inventory maps, which provide information on the location of landslide distributions, help implement necessary mitigation measures [25]. The first step in evaluating landslide hazards is a comprehensive landslide inventory map [32].

Although landslide inventory mapping is a crucial requirement for a thorough hazard and risk analysis, the usefulness of these maps for land management and planning is rather limited due to their inhomogeneous spatial distribution and the use of different mapping and classification criteria and methods [33]. However, large-scale landslide inventory maps, developed using remotely sensed data, can overcome these problems and limitations, thus making susceptibility hazard and risk assessment more efficacious [34].

Since it is time consuming and expensive to develop landslide inventories using in situ measurements, remote sensing data, and tools can be an effective way to develop landslide inventory maps. High-resolution satellite image and advanced remote sensing and spatial analysis techniques allow developing more reliable landslide inventory maps [29, 35]. Methods involved in generating landslide inventories include visual interpretation of multi-temporal aerial photographs and remotely sensed images and geomorphological field mapping, expert knowledge on the geological setting in combination [36, 37].

For example, Harp et al. [38] suggested mapping criteria for landslide inventory as follows:

a. GIS tool can be used to develop a spatial map for statistical analysis in relation to other spatial variables; and

b. the entire population of landslides triggered by the external forces or natural and anthropogenic causes must be mapped and plotted so that a complete landslide distribution can be obtained.

However, detailed inventories are rarely available because evidence could have been lost due to various degrees of modification in the past [26]. On the other hand, an inventory map/data can be developed using high-resolution historical remote sensing data, especially if morphological indicators for past landslide activities are present [34].

According to Guzzetti et al. [33] and Malamud et al. [26], landslide inventory maps are categorized into archive inventory (based on records in archives, newspapers, and so on). Similarly, in Guzzetti et al. [33] landslide inventory maps are categorized as geomorphological inventory which can further be classified as follows:

- historical inventory (showing the cumulative effect of landslide over a long period without further temporal differentiation),

- event-based inventory (landslides caused by a single triggering event, such as a strong earthquake),

- seasonal inventory (landslides triggered within one active season) and multi-temporal inventory (continuous monitoring of landslide activity over longer periods independent of particular triggering events), and

- the multi-temporal inventory is the most labor-intensive inventory type and the only one with the potential for spatio-temporal completeness, and it generally requires the use of remote sensing.

A historical inventory is the most popular approach developing landslide inventories using past landslide events. High spatial resolution and long-term remotely sensed data help rapid mapping and monitoring, especially during an emergency [1]. Based on the available in situ information and remotely sensed data, various landslide inventories can be produced and detailed at different scales covering the entire area affected by landslides, including, wherever possible, all sizes of landslides, and mapping landslides as polygons to depict their exact shapes [38].

In addition, landslide inventory maps are prepared for multiple scopes, including:

- documenting the extent of landslide phenomena in areas ranging from small to large watersheds and from regions to states or nations,

- taking a preliminary step toward landslide susceptibility, hazard, and risk assessment,

- investigating distribution, types, and patterns of landslides in relation to morphological and geological characteristics, and distribution of slope failure processes,

- studying the evolution of landscapes dominated by mass-wasting processes,

- investigating the recent and historical relationships between mass movement processes, settlements, and high cultural value areas [39], and
- extracting thresholds of rainfall-induced landslides [40].

Landslide inventory and detection are technically very close and often used interchangeably. An inventory must be carried out through direct visual inspections (or field surveys) and/or in situ measurements (when possible), which, altogether, identify "detection." In other words, there is no good and effective inventory without detection.

A complete and accurate landslide inventory is crucial for landslide predictions; therefore, the accuracy of landslide inventory can be maintained by analyzing high-resolution satellite images [41]. Identification of landslide's boundaries, terrestrial and topography verification, and third-party review are the procedures in interpreting the accuracy of landslide inventory [41].

The systematic information on the type, abundance, and distribution of landslide is still lacking, which helps document essential details on landslide types, patterns, recurrence, and statistics of slope failures. These pieces of information are helpful to identify landslide susceptible zones and determine potential hazards and landslide risk assessment [33]. Multi-temporal inventories are needed, especially in regions of frequently occurring landslide. These regions require high spatio-temporal resolution data and efficient methods for landslide mapping and analysis [42]. An inventory map which contains landslide type, state of activity, depth, volume, date, and place of occurrence, can be used for the calculation of predisposing factors for performance and reliability analysis [30, 37]. In addition to analyze and understand the causes of past landslides, landslide detection is equally useful for monitoring and predicting future hazards [43].

Landslide inventory/detection maps can be developed using the consolidated procedure of photo-interpretation of different sets of stereoscopic aerial photos, that can be integrated with an extensive field control of each recognized landslide. The field control process includes acquiring additional information about the main geomorphic elements and topographic signatures related to mass movement processes and their interpretation in terms of pattern, distribution, state of activity, and evolution of slope processes. In particular, the geomorphological field survey focuses on:

1. the validation of the information acquired by aerial photo-interpretation,
2. recognition of landslide types and state of activity,
3. analysis of deposits involved in slope failures, and
4. evaluation of damages to infrastructures.

Landslides of different sizes and types also offer to detect landslides, which can be used to develop a landslide inventory map [30]. A landslide can be detected or identified using visual interpretation techniques combined with field investigations as a ground control to develop the most reliable form of inventory maps for scientific studies [44–47].

Numerous researchers have conducted studies to develop landslide inventories using remotely sensed data (e.g., [35, 37, 48–50]) (**Table 1**). For example, Moosavi et al. [37] produced a landslide inventory map using GeoEye remotely sensed data and found that thematic mapping using high spatial resolution satellite imagery necessitates a new methodology. Also, Sun et al. [35] used Geofen-1 remotely sensed data to develop a landslide inventory map in a complex region with numerous gullies, which was otherwise challenging and impractical via field investigations.

Satellites	Spatial resolutions (m)	Launch date	Applications	References for examples
Geofen-1	2	2013	Inventory	[35]
GeoEye-1	1.65	2008	Inventory	[37]
IRS-1C Resources at 2-LISS III RapidEye	188 24 5	1995 2011 2008	Inventory	[48]
TERRA/ASTER	15, 30	1999	Inventory	[49, 50]
SPOT-5	2.5 Pan 10 Mult	2002	Detection Mapping	[39, 51]
Quickbird-2	0.6	2001	Detection	[52, 53]
LiDAR	0.5	NA	Detection	[33, 45, 54]
IKONOS	0.82 Pan, 3.2 Mult	1999	Mapping	[55]
Landsat-8	15, 30	2013	Mapping	[56, 57]
SRTM	30, 90	2000	Susceptibility Detection	[16, 57]
Cartosat-2	1.0	2017	Susceptibility	[25]
Cartosat-1	2.5	2005	Susceptibility	[30]
AMSR-E	25,000	2002	Susceptibility	[16]
TRMM	25,000	1997	Susceptibility	[58]
GPM-Integrated	Approx. 11,000	NA	Susceptibility	[59, 60]
WorldView-1/ Quickbird-2/ GeoEye-1	1.85/2.4/1.65	2009/2001/2008	Susceptibility Inventories	[61]
Landsat MSS Landsat TM	80 30	1984	Interpretation	[4, 62]
Landsat	30	1992	Planning	[63]
Landsat 7	15, 30	1999	Characterizing Identification	[64, 65]
ALOS ALOS/PALSAR	10	2007	Mapping Deformation	[1, 52]
Landsat TM/SPOT-5	15, 30/2.5, 10	1999/2002	Hazard	[66]
IRS/Landsat-7	6, 23.6, 188/30	1997/1999	Hazard	[67]
Radarsat-1 ERS-2	8 10	1995 1995	Characterizing Monitoring	[68]
ERS SAR	10	1995	Monitoring	[69]
ERS-1/2	10	1991/1995	Monitoring	[70]
COSMO-SkyMed-1, 3	1, 5, 15, 30, 100	2007/2008	Detection	[71]
TerraSAR-X	1	2007	Monitoring	[72]

This list is an effort to compile popularly used satellite data to study landslides; it is not meant to be a comprehensive list as there are many more studies that used other satellite products.

Table 1.
A series of remotely sensed data used for landslide study.

3. Landslide susceptibility mapping

Landslide prediction is vital to prevent possible damages and save human lives. Landslide susceptibility map is important in predicting landslides because it helps to identify potential landslide areas and any area susceptible to landslides [30, 73, 74]. The local topography and hydrological conditions play a significant role in landslide susceptibility [39]. Although a proper landslide inventory may provide both spatial and temporal information on previous landslides over an area, landslide susceptibility map gives information about potential future landslides over an area [60]. However, detailed information on the historical records of previous landslides, rainfall, or earthquake is vital in determining triggering thresholds [74].

Landslide susceptibility can be quantified from stable to highly susceptible. Many researchers categorize slopes into four landslide susceptibility classes; highly susceptible, moderately susceptible, slightly susceptible, and stable (e.g., [12, 16, 58, 75–78]). Some researchers used slightly different susceptible classes to develop landslide susceptibility maps such as unstable, quasi-stable, moderately stable, and stable (e.g., [12]). Some studies also used susceptibility indices: very high, high, moderate, low, and very low (e.g., [59–61, 79]).

For disaster prevention, a landslide susceptibility map can be used in land-use planning and decision making [39]. A detailed susceptibility map for land-use mapping helps local authorities manage these landscapes for urban or industrial planning and development [80]. However, developing an effective landslide susceptibility map is always a challenge because it requires multiple spatial information of soil, geology, vegetation, and hydrology. For example, Stanley and Kirschbaum [60] identified four major issues that are important to be addressed for developing landslide susceptibility maps:

i. lack of detailed inventories,

ii. minimum available input data,

iii. regional differences in the importance of causative factors, and

iv. the dearth of expertise on landscape processes across large regions.

Numerous methods exist in literature developing landslide susceptibility map using in situ measurements, models, remotely sensed data either stand-alone or in combination. For example, landslide inventories and causative factors, along with the statistical approach, are used in developing landslide susceptibility model for predicting potential landslides [39]. In addition, many studies used statistical approaches, physically based models, and deterministic approaches in developing landslide susceptibility maps (e.g., [53, 62, 75, 81]).

Besides the different existing methods for landslide susceptibility analysis and mapping, it is also essential to have advanced tools and detailed spatial information to develop an effective landslide susceptibility map. Digital tools such as GIS and global positioning system (GPS) are mostly used to analyze spatial data and developing landslide susceptibility and hazard maps [29, 81]. Moreover, remotely sensed data and technologies are widely used for effective landslide susceptibility mapping, hazard assessment, and risk assessment, which further helps in awareness, mitigation, and management of potential landslide threats [29].

Many researchers have used remotely sensed data to develop landslide susceptibility maps from local to global scale. For example, Ray and Jacobs [59] and

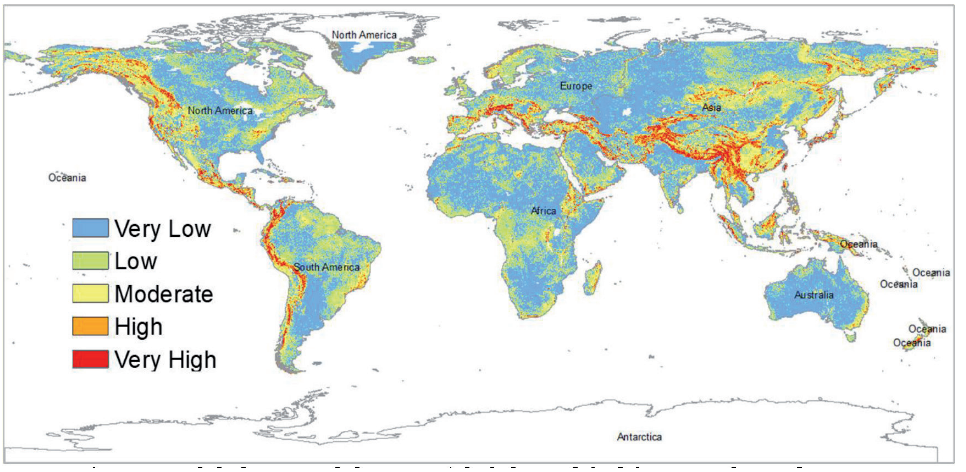

Figure 1.
Global susceptibility map (slightly modified from Stanley and Kirschbaum [60]).

Kirschbaum et al. [60] used remotely sensed precipitation data [TRMM and global precipitation measurement (GPM)] combined with slope, geology, road networks, fault zones, and forest loss to develop landslide susceptibility map at the global scale (**Table 1**, **Figure 1**). Ray et al. [16] used remotely sensed soil moisture (AMSR-E) combined with slope, soil, and vegetation characteristics to develop dynamic landslide susceptibility maps at a regional scale.

4. Landslide hazard analysis

Landslide is a major natural hazard that leads to a significant loss to human lives and properties. Landslide hazard requires systematic and objective assessment of the multi-landslide hazard, which includes different characteristics and casual factors of hazard along with their spatial, temporal, and size probabilities [48, 82]. Effective planning and management reduce social and economic losses caused by landslides [30, 83, 84]. A landslide susceptibility map combined with temporal information can be converted into a landslide hazard map for estimating potential losses due to landslides [30]. Landslide risk can be estimated using landslide hazard maps [85]. A useful hazard map should include local geology, geomorphology, lithology, hydrology, vegetation, and climatic factors. These factors affect landslide events, needed for proper hazard analysis [86].

A vital part of hazard assessment is the quantitative estimate of the pre-failure and failure stages of the susceptibility of the slope [87]. Landslide hazard assessment determines slope failure probability [88]. Over the last 30 years, numerous studies have been conducted on landslide hazard zonation as a result of the demand for slope instability hazard for planning purposes [89]. Despite that susceptible slopes triggers or reactivate slope failures, hazard analysis must consider the speed of landslide movement along the slope [88]. Huabin et al. [90] suggested two important aspects of landslide hazard zonation, which are assessing the susceptibility of the terrain for slope failure, and determining the probability of a specific triggering event occurring.

Nadim and Kjekstad [91] used a landslide hazard index (Hlandslide) to classify landslide hazard levels from negligible to very high (**Table 2**). The Hlandslide was obtained by multiplying a series of factors such as slope factor (Sr), lithology

Value of $H_{landslide}$	Class	Classification of landslide hazard potential	Approximate annual potential frequency in 1 km^2 grid
<14	1	Negligible	Virtually zero
15–20	2	Very low	Negligible
51–100	3	Low	Very small
101–168	4	Low to moderate	Small
169–256	5	Moderate	0.0025–0.01%
257–360	6	Medium	0.0063–0.025%
360–512	7	Medium to high	0.0125–0.05%
513–720	8	High	0.025–0.1%
>720	9	Very high	0.05–0.2%

Table 2.
Landslide hazard index ($H_{landslide}$), adapted from Nadim and Kjekstad [91].

factor (Sl), soil moisture factor (Sh), precipitation trigger factor (Tp), and seismic trigger factor (Ts); the following equation was used to develop Hlandslide.

$$H_{landslide} = \left(S_r * S_l * S_h\right) * \left(T_s + T_p\right) \tag{1}$$

where S_r = slope factor, S_l = lithology factor, S_h = soil moisture factor, T_s = seismic trigger factor, and T_p = precipitation trigger factor.

Remotely sensed data provide several essential factors used in the equation to develop landslide hazard zones on the range of scales. It is often difficult to obtain the multi-spatio-temporal information on landslide occurrences needed for landslide hazard analysis [48]. Chau et al. [86] suggested that landslide analysis should include landslide-dynamics-based numerical simulations to prevent subjectivity and bias; incorporation with GIS should result in an adequate hazard map to work for better planning.

Susceptible areas can be assessed and predicted, thereby reducing damage caused by landslides through proper preparation and mitigation because landslide prevention is a severe challenge [4]. Generally, landslide hazard analysis is conducted using aerial photographs, and/or remotely sensed images; therefore, it might contain a large degree of uncertainty (**Table 3**) [92]. As listed in **Table 2**, the degree of uncertainty is related to many factors, such as topography, soil, vegetation, and hydrology. On the other hand, the level of uncertainty is strongly related to the degree of susceptibility of a map [92]. Also, the probability of landslide hazard depends on both the intrinsic and extrinsic variables. Intrinsic variables include geological conditions and slope structures, whereas extrinsic variables include rainfall and human activities [90]. Chau et al. [86] explained that a reliable landslide hazard map should include historical landslide events, geomorphological analysis, and mechanical analysis of slides, falls, and flows of earth mass. Since all three aspects of hazard analysis involve handling and interpreting a large amount of data, spatial analysis tools such as GIS is essential for such analysis.

Spatial information from previous landslide events is needed for landslide analysis and evaluating the probability of future landslide occurrence [48]. Therefore, high-resolution spatial information (satellite data) for factors associate in landslide hazards is essential for effective hazard analysis.

Factors	Uncertainty	Factors	Uncertainty
Slope angle	Low	Rainfall distribution	Intermediate
Slope direction	Low	Morphological setting	Low
Slope convexity	Low	Detailed geomorphological situation	Intermediate/high
General lithological zonation	Low	Present mass movement distribution	Intermediate
General lithological composition	High	Present mass movement typology	Intermediate
General tectonic framework	Low	Present mass movement activity	Intermediate/high
Detailed rock structure	High	Past mass movement distribution	High
Soil type distribution	Low/intermediate	Land use	Low
Soil characteristics	Intermediate/high	Past climatological condition	High
Soil thickness	High	Earthquake acceleration	High
Groundwater conditions	High		

Table 3.
Main factors in landslide hazard zonation and their estimated degree of uncertainty, adapted from Mantovani et al. [92].

Recently, GIS tools and remotely sensed data have proven a vital approach for comparing and analyzing landslide, whereby a probabilistic landslide hazard analysis for the affected region is produced [38, 90]. Multiple layers of information are incorporated into the GIS system for a more accurate and reliable landslide hazard and risk analysis [86]. Geotechnical and safety factor-based models are also recommended for an effective landslide hazard analysis [4]. Various scenarios with different volumes or sliding surfaces should be integrated for hazard analysis of potential unknown landslides [2].

Golovko et al. [48] used multiple satellite data (e.g., Landsat, Spot, Aster, IRS-1C, LISS III, and RapidEye) and automated detection techniques to develop landslide susceptibility map and landslide hazard index. They summarized that their presented approach was based on the extensive use of remote sensing data and geospatial tools (e.g., GIS) to characterize landslide susceptibility and hazard. Ray et al. [16] used satellite soil moisture and hydrologic model in combination to develop landslide susceptibility maps at active Cleveland Corral landslide area in California, U.S. Ray et al. [76] used an integrated approach to combine satellite soil moisture and a hydrologic model to develop susceptibility maps at Dhading, Nepal.

5. Landslide monitoring

Landslide monitoring includes all of the activities discussed earlier, such as developing landslide inventory/detection, landslide susceptibility maps, and conducting a landslide hazard analysis. The easiest way to provide geological information to decision-makers and the public is through maps or visualization, which show locations of the landslide events, or where it might occur, thereby providing information on landslide hazard zones [37]. The most effective way to minimize and reduce the impact of landslide hazards and improve risk management is through landslide monitoring and planning [30, 35].

Landslides occur due to the combined effect, such as intense rainfall, topography, and antecedent soil moisture [93]. However, landslides can also be triggered due to external driving forces, such as earthquake, volcano, and excessive surcharge load on the slopes. Landslide hazard causes enormous infrastructural damages and human casualties in mountainous regions [20], and environmental degradation [94]. The combined effect of surface and sub-surface saturation is critical because landslide trigger is not due to only surface layer saturation [92]. Landslide monitoring technique depends on the type and size of the landslide, and the risks involved; it also differs between countries because of their available technology and expertise in landslide monitoring, past experiences with a landslide, and other factors [94]. For example, monitoring the surface displacements of a slope provides essential data for landslide dynamics [94].

Landslide hazard mitigation measures include hazard mapping and assessment, real-time monitoring systems of active and complex landslides, and emergency planning [94]. Landslide monitoring includes a comparison of the areal extent, speed of debris movement, rate of slope movement, surface topography, etc., concerning landslide conditions from different landslide occurrences to assess the activity of a landslide [92]. Timely and high-quality information received from spatial observations is crucial for managers of natural and human-made disasters, particularly in response to emergencies [1]. Landslide monitoring has improved over the years, with better monitoring equipment, automatic measurements done by machines, and less expensive tools [95].

Remote sensing data and techniques can be used for in-depth hazard mapping and monitoring because of their extensive coverage and frequency of observations, especially in high mountainous regions [20, 41, 92, 96]. Stereoscopic air-photo interpretation as far back as the late 1990s has been the most consistent remote sensing tool for landslide monitoring [20]. Combining aerial photography and infrared imagery gives a better result of terrain conditions rather than from either system separately [94].

Coupled with pre-existing landslide inventory maps and synthetic aperture radar (SAR) imagery and interferometric synthetic aperture radar (InSAR) through the integration of auxiliary data (e.g., detailed geological information) can be an effective method to update landslide inventory [1, 20, 97]. Ground-based optical systems (video cameras) limits monitoring movement of active landslides, in case of fog, rain, and darkness [94]. InSAR is useful to monitor prolonged slope movements [20]. Also, InSAR has been widely used in research because of its broad coverage, high spatial resolution, and ability to operate under all weather conditions [52].

Landslide monitoring includes detailed information on topography, geology, groundwater levels, material properties, possible mass movements [93]. Several types of instruments, such as extensometers, inclinometers, piezometers, strainmeters, pressure cells, geophones, tiltmeters, and crack meters, have been used to monitor slope movements and deformation [92, 93]. Recently, the landslide monitoring system has been improved with the development of less expensive computerized equipment [95]. According to Savvaidis [94], and Macek et al. [95], landslide monitoring systems and techniques include:

1. Remote sensing techniques with space-derived information. They are of importance for seismic hazards, landslide hazards, and management of earthquake disasters. Also, remote sensing tools provide surface soil moisture data up to 1–5 cm deep, which has been used to develop landslide susceptibility maps [93].

2. Global positioning system (GPS) technique. It is a flexible and easy operation that uses a series of satellites to determine accuracy in the order of centimeters [92]. A handled GPS provides accurate differential positioning over several kilometers [94].

3. Photogrammetric technique, combined with digital imaging sensors data. It allows early identification of landslide hazard [96]. A photogrammetric technique, which includes interpretation of aerial photography, is a useful technique to identify and map landslides for an extended period [20, 92, 94, 98]. It is also a valuable technique for identifying and describing the 3D overview of the terrain in determining surface information [96].

4. Ground-based conventional surveying techniques measure for absolute displacement computations with the use of different instruments, usually employed in an episodic `monitoring program [94].

5. Geotechnical methods make use of sensors permanently working on or in the region under consideration, and can also use a telemetric system for real-time transmission of data to a control center [94].

6. Types and role of remote sensing techniques

Several remote sensing data have been used to study landslide processes, including space-borne synthetic aperture radar (SAR) and optical remote sensing, airborne light detection and ranging (LiDAR), ground-based SAR and terrestrial LiDAR, incorporating in situ measurements and observations of environmental factors (**Table 1**). In particular:

- SAR data have been widely used in landslide research because of their broad coverage and high spatial resolution and the ability to operate under all weather conditions. Satellite SAR data used include archived ERS and Envisat ASAR [46], ALOS/PALSAR [52, 99], COSMO-SkyMed constellation [71, 100], TerraSAR-X [72, 101], TerraSAR-X/TanDEM-X [100] and Sentinel-1 [102] and Envisat 2010+ data (22 October 2010–8 April 2012).

- Optical remote sensing images were mainly applied to generate landslide inventory, considering long time-series of Landsat TM/ETM, SPOT 1–5, ASTER, IRS-1C LISS III, and RapidEye between 1986 and 2016 [48]. The ZY-3 [103], and GF-1 [35] high spatial resolution satellite images were used to investigate the landslide cinematics with an image correlation algorithm to SPOT-5 images [104].

- Multi-temporal LiDAR images and ortho-photos can be compared to quantify landscape changes caused by an active landslide [105]. The ground-based terrestrial laser scanner (TLS) LiDAR can produce highly detailed three dimensional (3D) images within minutes, allowing the study of 3D surface changes of landslides [106].

Among the most useful applications derived from the analysis of remote sensing images is the development of digital terrain models (DEMs), such as those generated from Indian remote sensing satellite (IRS) P5 images [107] and TerraSAR-X/TanDEM-X images by InSAR [108]. DEM can then be used to assess erosion, landslide, and topographic multi-temporal differences [107].

Lu et al. [45] used Quickbird remotely sensed data for landslide detection and mapping. They summarized that traditional mapping techniques for landslide detection and mapping, which rely on manual interpretation of aerial photographs and intensive field surveys, are time consuming and not efficient for generating such event-based maps. Guzzetti et al. [33] used aerial photographs, high-resolution DEM (LiDAR), and satellite images (e.g., Landsat-7, IRS, IKONOS-2, Quickbird-2, WorldView-2, and GeoEye-1/2) to develop multi-temporal landslide inventory maps. Holbling et al. [51] used SPOT-5 remotely sensed data for landslide change detection, whereas [52] used ALOS/PALSAR imageries and InSAR techniques for landslide detection. On the other hand, Desrues et al. [54] used LiDAR DEM and satellite images for landslide detection and mapping.

7. Global application

There are several studies conducted using remote sensing data and technologies around the globe. This chapter intends to summarize some of the remote-sensing based research undertaken to address landslide issues from selected countries, which are, mainly, more vulnerable to landslides. The studies have shown that several remote sensing techniques can assist in producing landslide inventory and risk assessment maps by providing information on the morphological features of landslides.

These approaches are very useful mainly in very large geographical areas where landslides are the most common yet highly devastating disasters, such as in Nepal, U.S., Philippines, and in many other countries. In the U.S., landslides caused 25 to 50 deaths each year, whereas extreme rainfall is the most common cause of landslides in the Philippines [109]. Ray and Jacobs [93] studied landslides in California, U.S., Leyte, Philippines and, Dhading, Nepal. They established the relationship between landslides, satellite soil moisture (Advanced Microwave Scanning Radiometer (AMSR-E)), and satellite precipitation (Tropical Rainfall Measuring Mission (TRMM)). In Nepal, Amatya et al. [61] used high resolution optical data for landslide mapping and susceptibility analysis along the Karnali Highway in Nepal.

Light detection and ranging (LiDAR) data open unprecedented possibilities for landslide mapping, with potential opportunities for hazard and risk zonation and landscape evolution modeling [33]. Gorsevki et al. [110] used LiDAR data to detect landslides in the Cuyahoga Valley National Park, Ohio, U.S, to generate a susceptibility map using the artificial neural network (ANN). Martha et al. [30] used a semiautomatic approach to develop landslide inventories from post-event satellite images, which they used for landslide susceptibility, hazard, and risk in the High Himalayan terrain in India. Following the 2004 Typhoon Aere, the object-based image analysis approach (OBIA) was adopted to develop landslide inventory in Xiulan, Taiwan [111].

Landslide mapping in the Cameron Highlands area in Malaysia is complicated due to dense vegetation and weather conditions. However, researchers used airborne synthetic aperture radar (AIRSAR) and WorldView-1 satellite data to develop a landslide inventory map for the Cameron Highlands [112, 113]. Also, Bui et al. [34] used synthetic aperture radar (SAR) data for landslide detection and susceptibility mapping in Cameron Highlands, Malaysia. In China, an area near the Three Gorges Reservoir (TGR) along the Yangtze River, which is one of the most landslide-prone regions in the world, was studied using ZY-3 high resolution satellite images to develop landslide inventory map [103].

In Italy, rainfall-induced landslides are serious threats to the population [114]. Since landslides are a national threat and distributed throughout the nation, it is not possible to analyze and monitor landslides using in situ measurements alone. Several researchers have studied landslides using remotely sensed data and technologies (e.g., [102, 115, 116]). Several researchers have also used cartographic thematic and optical data with Persistent Scatterer Interferometry (PSI) to identify slow to very slow moving landslides in a different region of Italy [117–122]. Boni et al. [115] developed a new methodology to update the landslide state of activity (LAMBDA) using multi-temporal A-DInSAR data at north-western Italy.

Bozzano et al. [46] used field surveys and remote sensing techniques to investigate more than 90 landslides affecting a small river basin in Central Italy. Bardi et al. [116] used GB-InSAR data to monitor the rapid movement of earth flows over the Capriglio landslide in the northern Apennines, Italy. InSAR data were used to conduct a multi-temporal assessment of landslide activity in the basin of Abruzzi, Italy [44]. Fayne et al. [57] used Landsat-8 imagery in identifying potential locations and timing of newly triggered landslides in Italy.

Satellite-born landcover panchromatic images and shuttle radar topography (SRTM) elevation data were used to monitor landslide clusters over a vegetated landscape in Itaoca, Brazil [123]. Landslide is one of the natural hazards that occur each year in Indonesia. Hayati et al. [124] used interferometric synthetic aperture radar (InSAR) data to monitor the slow-moving landslide in Ciloto, Indonesia. The sensors provided useful data in obtaining continuous and area-based information for landslide affected areas. Bravo-Carvajal et al. [125] used SPOT satellite images to develop landslide inventory and susceptibility maps at the village of Nueva Colombia in the state of Chiapas. Also, in northern Pakistan, the SPOT-5 satellite was used to develop a landslide inventory [126]. Shroder and Weihs [127] used ASTER elevation data and Landsat 7 images for landslide mapping at northeastern Badakhshan, Afghanistan. Rainfall-induced landslides are frequent in the mountainous region of Bangladesh. For example, Das and Raja [128] used ASTER elevation data and Landsat 8 images to develop a landslide susceptibility map at Chittagong city, Bangladesh. Singhroy et al. [64] used Landsat TM and SAR images in combination to interpret the retrogressive slope failures on the Shale banks of the Saskatchewan river in Canada. Singhroy et al. [64] used SAR images to identify flow slides on sensitive marine clays in the Ottawa Valley of Canada.

8. Summary and conclusions

Natural disasters such as hurricanes, earthquakes, tsunami, and landslides have been on the rise, causing damage to property and human lives, especially in mountainous regions. Major causes of landslides are conditioning factors, such as lithology, relief, geological structure, geomechanical properties, weathering, and triggering factors such as precipitation, seismicity, temperature change, and static and dynamic loads. Conventional methods for landslide studies mainly rely on the visual interpretation of aerial photographs and field investigation in combination. However, these methods are time consuming and cost-ineffective. On the other hand, remotely sensed data at high spatial and temporal resolutions and advanced techniques could be used for landslide studies at a range of scales, which can reduce the time and resources required for the studies.

This chapter has reviewed the use of remotely sensed data and advanced technologies used for landslide inventory/detection, developing landslide susceptibility maps, conducting a landslide hazard analysis, and monitoring landslide events and slope movement at a range of scales. More robust technologies and high-resolution data are essential to reduce the impact of landslides threats on human lives, properties, and environments. In addition, we also need to develop advanced technologies, which can improve landslide assessment, prediction, and mitigations. According to Singhroy [129], our primary challenge is to have an advanced technology and/or high-resolution data to recognize and interpret detailed geomorphic characteristics of large and small landslides and determine whether or not failure is likely to occur. Although the use of high spatial resolution radar and LiDAR data are very helpful in conducting landslide studies, satellite products at high spatial and temporal resolutions are still limited. In the future, if real-time remotely sensed products at high spatial and temporal resolutions are available, especially in remote and hardly accessible terrain, it would be helpful to study landslide dynamics at a range of scales.

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Conflict of interest

The authors declare no conflict of interest.

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