CHAPTER FIFTEEN

Snow avalanches

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After seasonally frozen ground, the seasonal snow cover has the second largest extent of any component of the cryosphere. With a mean annual area of approximately 26 million km^2 worldwide (Barry and Thian, 2011), snow cover affects a large part of the populated areas and provides a considerable share of hydroclimatic hazards, above all in mountain regions (Fuchs et al., 2015a). In parallel, snow cover plays an important role as an economic factor in mountain areas (e.g., hydropower, agriculture, tourism, etc.; Callaghan et al., 2011). Correspondingly, snow cover is a determinant of snow avalanches and other hazards in these regions (McClung and Schaerer, 2006; Keiler et al., 2010) as a consequence of its seasonal dynamics and variation. Even though in comparison to other hydroclimatic hazards, such as heavy precipitation and flooding, snow avalanches are relatively limited in their spatial and temporal extent, they cause the majority of winter fatalities both in settlements (e.g., Fuchs et al., 2013, 2017b; Kazakova et al., 2017) and in the tourism and leisure industry (e.g., Badoux et al., 2016; Höller, 2017; Spencer and Ashley, 2011; Walcher et al., in press; Jekich et al., 2016), as well as significant infrastructure loss worldwide (Schweizer, 2008). Therefore, the understanding of temporal and spatial issues of avalanche formation relative to hydroclimate and snowpack development is crucial (McClung, 2005; Schweizer, 2008; Schweizer et al., 2003), in particular for regional avalanche forecasting. Temporal and spatial variability of snow cover and snow pack is strongly related to local and regional temperature regimes and precipitation patterns, hence the hydroclimate (Grünewald et al., 2013). The necessity of involving new and/or innovative methods using remote sensing techniques in identifying areas endangered by snow avalanches is obvious; however, it is not the same for highly-explored regions, such as the Central European mountains or the American

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Rocky Mountains, and relatively unexplored regions, such as mountain areas in artic regions of the Russian Federation. While for the former detailed and extensive documentation of snow avalanches as well as release conditions and triggers can be used to validate remote sensing data and to further develop data processing models (Eckerstorfer et al., 2017), for the latter remote sensing may be used for avalanche detection and forecast only with limited possibilities of validation due to an overall data-scarceness (Fuchs et al., 2017b).

15.1 Hazard characteristics

Snow avalanches are a well-known hazard type and are defined as a sudden release of snow masses and ice on slopes, sometimes containing portion of rocks, soil, and vegetation; and by definition the downhill trajectory exceeds 50 m (Wilhelm, 1975). Avalanche observations are reliable indicators for snow instability, and a relationship between high avalanche risk and high avalanche activity exists (Schweizer et al., 2003). According to the speed of the moving snow, avalanches can be distinguished from creeping and gliding movements of snow.

A number of classifications of snow avalanches exists (Kuroda, 1967; De Quervain et al., 1981; Dzyuba and Laptev, 1984). An international classification used by the majority of scientists and practitioners in the field has become accepted worldwide and classifies avalanches according to their release type, the shape of the trajectory, and the type of movement (De Quervain et al., 1981), see Table 15.1. Various conditions result in a release of avalanches, spanning from heavy snowfall to sudden temperature increase, but the prediction of individual avalanche formation is extremely challenging due to the high spatial variability and transient nature of the snowpack (Schweizer et al., 2003).

Generally, snow avalanches start from terrain that is steeper than about 30°–45° and favors snow accumulation (Wilhelm, 1975). On terrain less than about 15° snow avalanches start to decelerate and finally stop. Snow avalanche formation differs according to different volumes, repeatability and dynamic characteristics (McClung and Schaerer, 2006). While loose snow avalanches are released from a more or less definable point in a comparatively cohesionless surface layer of either wet or dry snow, slab avalanches involve the release of a cohesive slab over an extended plane

Table 15.1 International snow avalanche classification.

Zone	Criterion	Characteristic and denomination	
Origin	Manner of starting	From a point	From a line
		Loose snow avalanche	**Slab avalanche**
	Position of failure layer	Within the snowpack	On the ground
		Surface-layer avalanche	**Full-depth avalanche**
	Liquid water in snow	Absent	Present
		Dry-snow avalanche	**Wet-snow avalanche**
Transition	Form of path	Open slope	Gully or channel
		Unconfined avalanche	**Channeled avalanche**
	Form of movement	Snowdust cloud	Flowing along ground
		Powder snow avalanche	**Flowing snow avalanche**
Deposition	Surface roughness of deposit	Coarse	Fine
		Coarse deposit	**Fine deposit**
	Liquid water in deposit	Absent	Present
		Dry deposit	**Wet deposit**
	Contamination of deposit	No apparent contamination	Rock debris, soil, branches, trees
		Clean deposit	**Contaminated deposit**

Source: After De Quervain, M.R., De Crécy, L., Lachapelle, E.R., Lossev, K., Shoda, M., Nakamura, T., 1981. Avalanche Atlas. Illustrated International Avalanche Classification. UNESCO, Paris; Fuchs, S., Keiler, M., Sokratov, S. 2015a. Snow and avalanches. In: Huggel, C., Carey, M., Clague, J.J., Kääb, A. (Eds.), The High-Mountain Cryosphere: Environmental Changes and Human Risks. Cambridge University Press, Cambridge.

of weakness. Slab avalanche activity is highest soon after snow storms because of the additional load on the existing snow layers (Schweizer et al., 2003). The existence of a weak layer below a cohesive slab layer is a prerequisite for the development of dry slab avalanches. This weak layer is either a result of the metamorphism inside the snow pack or a buried surface hoar. Crystals formed by kinetic grain growth such as surface hoar or depth hoar (Fruehauf et al., 2009) together with changes in response to temperature and water vapor gradients variability can also be accompanied by the formation of a solid and icy layer on top of the snow pack, restricting the connection of new-fallen snow with the older snow below the solid layer, and often forms the horizon at which the snow masses start to move downhill. Differently to the causes of snow avalanche release, the mechanism of avalanche movement and corresponding distances and forces are rather well described (Fuchs et al., 2015a).

Flow velocities of snow avalanches vary between 50 and 200 km/h for large dry snow avalanches, whereas wet avalanches are considerably denser and slower (20–100 km/h, McClung and Schaerer, 2006). If the avalanche path is steep, dry snow avalanches may generate a powder cloud. Depending on the type of avalanche the moved amount of snow is variable, and in combination with the high velocities the induced damage may vary significantly (Fuchs et al., 2013).

Besides natural triggering by overloading or internal weakening of the snowpack, snow avalanches can also be triggered artificially—unlike most other rapid mass movements—through localized, rapid, near-surface loading by, for example, people (usually unintentionally) or intentionally by explosives used as part of avalanche control programs or industrial activities (Mokrov et al., 2000). Occasionally, snow avalanches have also been triggered by large earthquakes (Stethem et al., 2003). While naturally released avalanches mainly threaten buildings and infrastructure, human-triggered avalanches are the main threat to recreationists in mountain areas.

15.2 Remote sensing of snow avalanches

In operational avalanche forecasting, avalanche formation is usually assessed heuristically by weighting avalanche-contributing factors such as terrain, precipitation, wind, temperature, and snow stratification (Bründl et al., 2010), that is, the complex interaction between terrain, snowpack, and meteorological conditions (Schweizer et al., 2003). These data are generally measured at specific accessible but isolated points such as weather stations, snow profiles, or avalanche activity observations (Bühler, 2012). On-site testing of snow pack properties in the field, terrain-based reconnaissance of avalanche activity and dynamics, and modeling of both are used to assess avalanche formation and run-out. However, for defining the release conditions, the monitoring of snow accumulation and the modeling of both snowpack properties and stability still are major areas of research (Bründl et al., 2010) because snow pack characteristics vary substantially within close adjacency to a measurement location (Schweizer et al., 2008). Moreover, field-based approaches require weather conditions to allow measurement campaigns and snow stability to assess the often remote avalanche starting zones and to study snow parameters in situ. Therefore, temporal and spatial data gaps result, leading to some uncertainties and biased statistical analysis in snow avalanche hazard and risk assessment (Eckerstorfer et al., 2016; Keiler et al., 2006).

To overcome these challenges, remote sensing techniques spanning from ground-based devices over airborne systems to spaceborne imagery are increasingly used. Given repeated measurements, remote sensing of snow avalanches allows for a comprehensive and unbiased monitoring in a temporarily consistent and spatially continuous way. While remote sensing of snow cover already has a long history (Scherer et al., 2013), remote sensing of snow avalanches is only recently becoming mature (Eckerstorfer and Bühler, 2015). Nevertheless, in contrast to other hydro-climatic hazards such as river flooding, the spatial extent of areas affected by snow avalanches is relatively small (Fuchs et al., 2015b; Jongman et al., 2014), which limits the some remote sensing methods to those that only provide a medium-to-small resolution.

Remote sensors can either be passive or active. Passive optical sensors make use of the reflected sunlight either in the visible electromagnetic spectrum, or in the near infrared and shortwave infrared part. In contrast, LiDAR (light detection and ranging) and radar (radio detection and ranging) sensors are actively emitting radiation and measure the reflection from the surface. LiDAR is based on the visible and near infrared and radar on the microwave region of the spectrum, the latter having the advantage of acquiring data also during darkness (e.g., polar night, nighttime) and bad weather conditions (Eckerstorfer et al., 2016). According to this differentiation the applicability and informative value of remotely-sensed data on snow avalanches differs.

15.2.1 Passive sensors

Optical remote sensing using passive sensors is based on measurement of the reflective properties of snow and is therefore dependent on solar radiation as a primary energy source. As a result, the use of passive sensors is restricted by daylight, weather conditions, and cloud cover. The size and spatial extent of snow avalanches can be detected by using contrast differences between avalanche deposits and surrounding (undisturbed) snowpack, due to snow properties such as increased snow depth, snow density, and surface roughness causing cast shadows. The assessment of these snow properties, however, is influenced by sensor illumination and observation angles as well as different atmospheric conditions caused by altitude variations, limiting avalanche detection using optical sensors (Scherer et al., 2013; Eckerstorfer et al., 2016). Moreover, coarse resolution sensors have the disadvantage of recording many overlaying signals in one pixel (e.g., different snow types, snow-free patches, rocks, cast shadow) particularly in alpine areas with complex terrain (Bühler, 2012).

15.2.1.1 Ground-based passive sensors

Time-lapse photography may be used in order to obtain dynamic information on avalanche activity, as shown by Christiansen (2001) for the development of the snow cover in avalanche-starting zones or Van Herwijnen and Simenhois (2012) and Hendrikx et al. (2012) for snow gliding. Results may be linked to meteorological data in order to better understand underlying process behavior, and can further be used to improve our understanding of avalanche dynamics, as recently shown with respect to the release time and size of wet snow avalanches by Van Herwijnen et al. (2013).

Techniques of photogrammetry may also be used to assess spatiotemporal snow distribution, as shown by Wirz et al. (2011) and Gauthier et al. (2014), for a discussion see Westoby et al. (2012). Most of the studies report the reconstruction of high-resolution topography using commercially available digital single-lens reflex (SLR) cameras in combination with low-cost 3D modeling software, which makes the entire procedure highly affordable in comparison to the use of airborne or even most of the spaceborne sensors.

The use of ground-based passive sensors provides nearly real-time data; however, the spatial coverage is relatively limited. According to Eckerstorfer et al. (2016), application ranges vary between a few meters to several hundreds of meters with a temporal resolution between minutes and days (mostly depending on the power input available). A further shortcoming is the often missing spatial orientation and scale, which demands postprocessing and georeferencing.

15.2.1.2 Airborne passive sensors

Airborne aerial imagery has been used for decades in geosciences for documentation and monitoring, as well as for topographic mapping of snow avalanches (Akif'eva, 1980). Two facts reduce the applicability with respect to snow avalanches: (1) the relatively high costs for obtaining suitable georeferenced images through aerial surveys; and (2) the fact that most of the aerial imagery is recorded during summertime when the visibility and the flight conditions are better compared to wintertime. As such, operational use of spatially inclusive and comprehensive images is limited. Nevertheless, after large avalanche events such as those that occurred in some regions in the European Alps in 1999 surveys are commissioned, sometimes executed by the respective national air force, and the resulting images can at least be used to map the outline of snow avalanche release and run-out of specific events (Fuchs and McAlpin, 2005). Moreover, Korzeniowska et al. (2017) recently reported on the use of near-infrared aerial imagery for regional snow avalanche detection, based on object-based image analysis.

To overcome the shortcomings of commercial aerial photography, the recent technical progress with respect to remotely piloted aircraft systems (“drones”) may be promising. Eckerstorfer et al. (2015) reported on creating a high-resolution orthophoto mosaic to compute both avalanche debris outline and avalanche debris volume for a test site in Norway. More frequently, drones have been used to gather accurate snow depth data, which can be used in the case of available high-resolution digital elevation models to compute the spatial distribution of snow depth. This information can be further used in combination with expert knowledge for avalanche forecast (Bühler et al., 2016), but until now not as a stand-alone-method for an assessment of an avalanche hazard and risk. Nevertheless, due to restrictions by air traffic control in many countries, the potential of such systems may not be fully used. As such, even if the aerial survey can be preprogrammed and in principle the vehicle could undertake missions under fully autonomous flight mode, regulatory authorities regularly require contact flight which limits the operating distances considerably.

At the same time, however, the number, versatility, and reliability of alternative platforms to be used in large-scale aerial photography have been increasing (Aber et al., 2010). Unmanned aerial vehicles including platforms such as ultralite vehicles, kites, blimps, or remote-controlled model aircrafts are nowadays also used to carry small commercial cameras or other inexpensive sensors, often sufficient to provide quickly needed information in emergency situations (Kerle, 2013)—which is information on the event size and a rough estimation of affected persons or buildings, without any standardized georeferencing. Thus, a standard for application on snow avalanche hazard and risk is outstanding.

15.2.1.3 Spaceborne passive sensors

Satellite remote sensing is widespread in natural hazard management, in particular because of the short temporal orbiting and spatial coverage, ranging from low to very high resolution (Bello and Aina, 2014). Nevertheless, so far only a few studies on snow avalanches are available, while for other hazard types affecting larger areas the use of spaceborne sensors is largely adopted (Kerle, 2013).

Snow avalanches are visually recognized in satellite images as rough surface characterized by a line-shaped pattern oriented in the aspect direction of the terrain (Larsen et al., 2013). Two recent studies showed the potential for automated avalanche detection using such texture features. The main challenges were related to overillumination and underexposure in parts of the imagery, caused by mountain topography in combination with a low solar angle in high latitudes leading to a lack of visual contrast between the avalanche debris and the surrounding snowpack (Lato et al., 2012; Larsen et al., 2013). Lato et al. (2012), as well as more recently Eckerstorfer et al. (2016), provided an overview on possible platforms to be used in spaceborne avalanche research, concluding that so far, most of the high-resolution data available is relatively expensive in comparison to the expected outcomes. The exception is the recently launched Sentinel satellites of the European Earth Observation Program “Copernicus” which should allow for analyzing snow avalanches using the visible as well as near and shortwave infrared spectrum, with data being free-of-charge.

15.2.2 Active sensors

Active sensors are based on the emission of radiation and the reflection measurement from the illuminated surface. Platforms use ground-based and airborne LiDAR and ground-based, air-, and spaceborne radio detection and ranging (radar) sensors.

15.2.2.1 Ground-based active sensors

Prokop et al. (2008, 2015) report on possibilities of snow avalanche assessment using ground-based LiDAR based on earlier studies on spatial snow depth measurements (Prokop, 2008). The principle of the applied LiDAR sensor was to collect 3D data from temporally changing landscape surfaces and to measure the height differences in order to achieve information on extent and volume of the snow masses. The study had clearly shown the potential for assessing both mass loss in the avalanche starting zone and mass gain in the run-out area with a horizontal resolution of decimeters given a measurement distance of several hundred meters. Due to the relative fast development of LiDAR sensors and a parallel technological software development, recent studies expect an increase in ground-based LiDAR applications with respect to millimeter-scale range accuracy in natural hazard management (Deems et al., 2013), such as the study of Deems et al. (2015) reporting on the mapping of snow distribution and snow depth in avalanche starting zones.

A similar principle in measuring height differences allows ground-based radar detection for snow avalanches (Martinez-Vazquez and Fortuny-Guasch, 2008). As reported in Eckerstorfer et al. (2016), snow avalanches represent a significant physical change in the backscattering, leading to temporal decorrelation in the data, and can therefore be spatially assessed. Nevertheless, physical changes in the snowpack may also lead to similar decorrelation, which makes a distinction challenging. Fast application times and acquisition intervals below 30 seconds together with a horizontal resolution of meters at a distance of 1 km, in contrast, are reported as added values of this method, given good calibration, co-registration filtering, and processing of images (Caduff et al., 2015). Moreover, radar allows for measurement independent of weather and light conditions with measurement ranges between 50 m and around 18 km (Eckerstorfer et al., 2016). As for ground-based LiDAR, these techniques require image acquisition before and after an avalanche event, so that they are usually only applied in experimental settings where the measurement data is available.

15.2.2.2 Airborne active sensors

According to Eckerstorfer et al. (2016) there are few studies only showing the successful use of LiDAR airborne detection of snow avalanches, providing only little information on LiDAR performance. Vallet et al. (2000) reported on snow volume measurements within an accuracy of

20–30 cm, while Chrustek and Wezyk (2009) concluded that the method has some advantages compared to traditional ground-based devices for avalanche mapping in smaller mountain regions where the avalanche frequency is closely related to changes in the local terrain.

Airborne radar remote sensing of snow avalanches seems to be so far restricted to rescue operations for avalanche victims and an associated sensor development (e.g., Instanes et al., 2004; Fruehauf et al., 2009; Jaedicke, 2003).

15.2.2.3 Spaceborne active sensors

Spaceborne remote sensing using active sensors using the radar technology traces back already two decades, when Wiesmann et al. (2001) reported on the detection of avalanche debris on synthetic aperture radar images, taking some of the avalanches during the 1999 winter in Switzerland as an example. Further applications include those of Bühler et al. (2009) who applied change detection on the backscattering information of data acquired on different dates to show the potential of spaceborne avalanche detection. However, as also shown by Malnes et al. (2013), the validation of results needs comprehensive fieldwork and/or optical airborne data due to a high percentage of false classification with respect to the avalanche outlines. The challenge of temporal availability, together with high acquisition costs have largely been solved since the Sentinel 1 satellite of the European "Copernicus" program is operational (Eckerstorfer et al., 2016), nevertheless, the ground resolution of the radar sensor may still be too low. Other higher-resolution satellites include the TerraSAR-X (Germany) and the Cosmo-SkyMed (Italy), both offer relatively moderately-priced or free-of-charge data in the case of scientific use.

15.3 Snow avalanche risk

The general advantages of remotely sensed data on natural hazards (e.g., a safe data acquisition with high temporal and spatial resolution) are opposed to the needs for a reliable assessment of risk, that is, spatially explicit data on hazard, exposure, and vulnerability. The concept of risk, defined in its broadest way as hazard times consequences, has been introduced in disaster management since experiences suggested that elements at risk (such as buildings, infrastructure lines) and vulnerability should be increasingly considered within the framework of hazard management to reduce losses. Starting in the 1990s as the United Nations International Decade for Natural Disaster Reduction (United Nations General Assembly, 1989), the primary focus was shifted from hazards and their consequences to the physical and socioeconomic dimensions of risk and toward a wider understanding, assessment, and management of natural hazards. This highlighted the integration of approaches to risk reduction into a broader context between sciences and humanities (Fuchs et al., 2011). If snow avalanche risk is considered by the potential exposure of a system, resulting from the convolution of hazard and consequences during a certain period of time at a certain location, it becomes obvious that risk is not static (Fuchs et al., 2015a, 2013). The main challenge of risk assessment is rooted in the system dynamics driven by both geophysical and social forces, stressing the need for an integrative management approach (Bründl et al., 2010).

Exposure and vulnerability to snow avalanches, however, are characteristics of risk that have—to our knowledge—not been successfully assessed quantitatively using remote sensing techniques because of two reasons: temporal and spatial scale and scale-dependency. These issues have currently been discussed for other hazard types (such as floods, where usually larger areas are affected, which makes a general assessment of exposure and vulnerability possible). However, due to the discussed limited spatial extent of snow avalanches, together with the fact that they often occur during a period of limited availability of remote sensing data, exposure and vulnerability can only barely be assessed so far at the necessary resolution.

15.3.1 Exposure

The temporal variability and spatial extent of exposure has an important influence on the assessment of avalanche risk (Fuchs et al., 2015b), even if this risk is comparatively low compared to other hydroclimatic hazards (Fraefel et al., 2004; Fuchs et al., 2015b, 2017b). In many avalanche-prone regions, socioeconomic developments in the human-made environment have led to an asset concentration and a shift in urban and suburban population. Long-term changes in building numbers and values exposed to snow avalanches show a significant increase in numbers and values in many regions (Campbell et al., 2007; Gardner and

Dekens, 2007; Keiler, 2004; Shnyparkov et al., 2012). These can be so far only roughly assessed using multitemporal remotely sensed data, whereas classical (governmental) object-based and georeferenced data turned out to be very accurate in terms of information content needed in risk assessment (Fuchs et al., 2015b).

To give an example, while in many rural and urban settlements of the European Alps the total number of buildings exposed to snow avalanches had almost tripled since the 1950s, the proportional increase in the number of buildings was significantly lower than the proportional increase in the building value (Fuchs et al., 2017a). Buildings inside hazard-prone areas showed a lower average value than buildings outside those areas (Fuchs et al., 2015b). Nevertheless, the total amount of buildings exposed to snow avalanches is only minor in the Eastern European Alps compared to other mountain hazards (only approximately 4% of exposed buildings are exposed to snow avalanches, including multihazard risk, see Fig. 15.1), an issue that was also recently addressed for the Western Alps (Röthlisberger et al., 2017).

Another example of exposure of settlements to snow avalanches also illustrates the discussed dilemma: Grab and Linde (2014) used daily Moderate Resolution Imaging Spectroradiometer snow cover images for a 7-year period to establish the frequency and spatial extent of snowfalls across a test site in Southern Africa. In addition, a digital shape file containing the location, name, and district attributes of villages affected was used to assist in the construction of a village exposure to snow index. Hence, in this example, exposure to avalanches was not directly measured using remote sensing, but this information was gathered by merging the

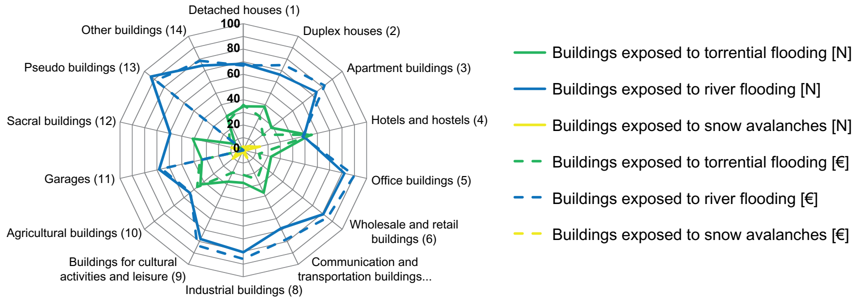

Figure 15.1 Radar chart of exposed buildings in the Eastern European Alps (Republic of Austria) to different types of mountain hazards. *Courtesy of Fuchs, S., Keiler, M., Zischg, A., 2015b. A spatiotemporal multi-hazard exposure assessment based on property data. Nat. Hazard. Earth Syst. Sci. 15, 2131, with permission.*

respective information on snowfall adjacent to villages and roads with ground-based geographic information system (GIS) data.

Short-term fluctuations in exposure supplemented the underlying long-term dynamics, in particular with respect to temporary variations of population movements or commuting citizens in settlements and of vehicles on the infrastructure network (Zischg et al., 2005; Keiler et al., 2005) as well as with respect to different management strategies (Fuchs et al., 2007; Holub and Fuchs, 2008). By implementing a quantifying fluctuation model it was proven by Keiler et al. (2005) how strong variations affect avalanche risk in mountain resorts. Similarly, Margreth et al. (2003), as well as Hendrikx and Owens (2008), were pointing to the dynamics in avalanche exposure on traffic infrastructure, and Fuchs et al. (2013) addressed the multiple temporal scales of exposure on high alpine traffic routes. Such information, however, is only barely available when only using remote-sensing data.

15.3.2 Vulnerability

Vulnerability, broadly defined, is the potential for loss (Fuchs and Thaler, 2018a), and includes elements of exposure (people, places, infrastructure at risk from a hazard), sensitivity (the degree to which the people, places, or infrastructure are harmed), and coping (the skills, resources, and opportunities of people and places to survive, absorb the impacts, and manage the adverse outcomes). Despite the growing amount of studies recently published (see for an overview, e.g., Fuchs and Thaler, 2018b), current approaches are still driven by a divide between natural and social sciences, leading to different research methods, concepts, and results. Whereas social scientists tend to view vulnerability and resilience as representing the set of socioeconomic factors that determine people's ability to cope with stress or changes (e.g., Cutter et al., 2003; Fekete and Hufschmidt, 2014), natural scientists and engineers often view both terms focusing on the likelihood of occurrence of specific hazards, and associated impacts on the built environment (e.g., Papathoma-Köhle et al., 2017). The assessment of physical, social, economic, and institutional vulnerability requires social and economic data of certain spatial and temporal resolution, not necessarily corresponding to the available resolution of geophysical and climatic data used in snow avalanche hazard assessment. With respect to snow avalanche risk, population density and land use are maybe the most prominent direct drivers for vulnerability in mountain regions. Apart from the overall population number, it is also the population distribution and composition, such as the level of urbanization and household size, as well as the increasing effects of counterurbanization (Kaltenborn et al., 2009; Löffler and Steinicke, 2006) which define the level of vulnerability to mountain hazards (Fuchs, 2009; Papathoma-Köhle and Thaler, 2018). However, as noted by Papathoma-Köhle et al. (2011), studies focusing on the vulnerability assessment of communities and buildings to snow avalanches are significantly fewer in number than similar studies regarding other disaster types, probably due to lack of sufficient data on avalanche damages to exposed elements, and to our knowledge none of the available studies is based on remotely sensed data.

15.4 Conclusions

It has been shown in the previous sections that a variety of remote sensing platforms exist that are potentially suitable for the detection of snow avalanches. Depending on the purpose and availability of resources, these include passive and active, as well as optical, LiDAR, and radar sensors. So far, however, the detection of snow avalanches can hardly be accomplished by only using such data, mainly because of the lack of reliability of ground-based proof, and the overall challenges in professional avalanche forecast (Bründl et al., 2010; Schweizer et al., 2003). Instead, remotely sensed data may be used in addition to traditional data sources in the evaluation of snow avalanche hazard and risk, and provide some advantages that have to be further assessed in future research. Overall, remote sensing techniques are relatively safe in comparison to in situ field measurements, in particular during periods of high avalanche danger or during bad-weather conditions. Remotely sensed information may therefore support the ongoing improvements in operational avalanche forecasting, but will so far not replace ground-based fieldwork and data collection, statistical data analysis, and modeling.

It has been reported by Eckerstorfer et al. (2016) that a minimum spatial resolution of 30 m is needed to successfully detect avalanches using remote sensing platforms with only minor omission and commission errors. Nevertheless, a spatial resolution of 30 m is not fine enough to assess exposure or even elements of vulnerability in a reliable manner.

A minimum temporal resolution of a few days would be optimal to eliminate detection uncertainties, which may be due to heavy snowfall in the target region or changes of physical snow properties leading to changes in the reflection behavior of the snow pack.

There has been certain development towards detection of snowpack properties using remote sensing. As such, remote sensing may support the detection of snow avalanche hazard and risk as some basic information needed for further computing hazard and risk may be gathered (Veitinger and Sovilla, 2016). Depending on the scale and accessibility of the area, the geographical location, the latitude, and altitude, remotely-sensed information can be fed into the traditional ground-based assessment, and, given accurate validation techniques of snow avalanche detection using available sensors, may then be further developed toward a semi-automated and automated hazard classification. The highest potential is offered by the recently launched Sentinel satellites, but also by a further application of terrestrial LiDAR and LiDAR scans using remotely piloted aircraft systems. These options, however, require a snow-free high-resolution digital elevation model so that snow masses can be computed precisely. Moreover, in data-scarce and remote areas when data are available with high temporal resolution, remote sensing of snowpack and snow avalanches may also be used to build up an avalanche cadaster based on hindcasting (Frauenfelder et al., 2010). The combination of remotely-assessed relief parameters together with climatic parameters has shown to be promising for small-scale snow avalanche hazard estimation in remote regions and was used to compile small-scale maps of snow avalanche activity, repeatability, and the factors of the snow avalanches formation (Kotlyakov, 1997).

To conclude, the currently available remote sensing data of high resolution required for snow avalanche assessment are still expensive and rarely have sufficient temporal resolution. The algorithms for automated detection of either positions or the timing of snow avalanches are still underdeveloped and require expert control, comparable to the workload needed during traditional field surveys. However, the appearance of new platforms such as remotely piloted aircraft systems or new satellites such as the Sentinel generation, together with a gradual increase in available snow avalanches data from different regions, can eventually fill the existing gaps between the requirements of operational snow avalanches forecasts and the data availability.

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