Vulnerability of buildings exposed to dynamic flooding

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Abstract. Repeatedly, dynamic flooding causes high loss in many mountain regions all over the world. Dynamic flooding is a group of hazard processes including fluvial sediment transport, debris floods, and debris flows, as well as to some extent flash flood hazards if these are related to mountain catchments. Regardless of the magnitude and frequency, the consequences of dynamic flooding are strongly connected to the vulnerability of elements at risk, such as people, buildings and infrastructure. Several methods to assess physical vulnerability of buildings towards these processes are available. The plethora of methods and approaches, however, makes a comparison between different case studies challenging. Assessment methods can be classified in three categories: vulnerability matrices, vulnerability curves and vulnerability indices. We provide a short review of these methods and discuss their dominance in the scientific debate on mountain hazard risk management over the last decade, giving an emphasis to vulnerability curves. Furthermore, challenges in vulnerability assessment including data requirements, uncertainties, and needs for improved event documentation are outlined.

Key words: *vulnerability, indicators, functions, elements at risk*

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Уязвимость зданий, подверженных динамическим наводнениям

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Аннотация. Неоднократно динамические наводнения приводили к большим потерям во многих горных регионах по всему миру. Динамические наводнения представляют собой группу опасных процессов, включающих транспорт речных наносов, селевые паводки и потоки, а также в некоторой степени ливневые паводки, если они связаны с горными речными бассейнами. Независимо от масштабов и частоты, последствия динамических наводнений тесно связаны с уязвимостью подвергающихся риску элементов, таких как люди, здания и инфраструктура. Существует несколько методов оценки физической уязвимости зданий по отношению к этим процессам. Однако обилие методов и подходов затрудняет сравнение различных тематических исследований. Методы оценки можно разделить на три категории: матрицы уязвимости, кривые уязвимости и индексы уязвимости. В данной статье дается краткий обзор этих методов и обсуждается их доминирующее положение в научных дискуссиях по управлению рисками, связанными с опасностями в горных районах, за последнее десятилетие, особое внимание уделяется кривым уязвимости. Кроме того, излагаются задачи в области оценки уязвимости, включая требования к данным, факторы неопределенности и потребности в улучшении документации событий.

Ключевые слова: *уязвимость, индикаторы, функции, элементы риска*

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Introduction

Mountain areas are high-risk environments threatened by a range of natural hazards, such as dynamic flooding, landslides and snow avalanches. Dynamic flooding is defined as constantly or temporarily flowing watercourses with strongly changing perennial or intermittent discharge and flow conditions, originating within small and steep catchment areas often located in mountain environments [*ONR, 2009*]. Despite their differences in terms of time of onset, duration, frequency and magnitude, dynamic flooding includes a variety of different processes which can be categorised by peak discharge [*Hungr et al., 2001*] or sediment concentration [*Costa, 1984*]. These processes include fluvial sediment transport, debris flows and debris floods. Furthermore, even if defined by space-time scales rather than sediment concentration, flash floods in mountain areas can be included if these are related to torrential catchments [*Borga et al., 2014*]. All these processes are further referred to as “dynamic flooding”.

Dynamic flooding repeatedly results in considerable damage to infrastructure and buildings, despite high investments in hazard and risk mitigation [*Fuchs et al., 2015; Zhang et al., 2018; Zischg et al., 2018; Zou et al., 2018; Schlögl et al., 2019*] which is frequently attributed to both, the effects of climate change leading to changes in frequency and magnitude of events [*Huggel et al., 2019*] and the effects of socio-economic development leading to a higher asset concentration [*Fuchs et al., 2017; Löschner et al., 2017; Röthlisberger et al., 2017*]. Other drivers, such as urbanization, economic degradation, deforestation and overgrazing may additionally influence the impact of natural hazards on mountain communities [*Zimmermann and Keiler, 2015; Klein et al., 2019*]. As the vulnerability of communities experiencing the impact of such dynamics is still less well known [*UN/ISDR, 2015*], there is a need for improved understanding of disaster risk in all its dimensions, above all, exposure and vulnerability.

Vulnerability is multidimensional [physical, social, economic, environmental, etc., Fuchs and Thaler, 2018], however, despite a considerable amount of research efforts, only little is known with respect to the physical vulnerability and resilience of elements at risk [*Golz et al., 2015; Schinke et al., 2016; Bozza et al., 2018; Fuchs et al., 2018; Sturm et al., 2018a*]. With respect to methods for an assessment of the physical vulnerability of exposed buildings, some scholars focused on mountain hazards in general [*Papathoma-Köhle et al., 2011*] and some specifically on dynamic flooding [*Papathoma-Köhle et al., 2017*]. Short reviews can be found in many papers and studies such as the ones of Fuchs et al. [*2007*], Akbas [*2009*], Sterlacchini et al. [*2013*], Totschnig and Fuchs [*2013*] Carisi et al. [*2018*] and Milanesi et al. [*2018*] who provide short discussions on functional vulnerability relationships to be used in risk assessment. This paper summarises methods for physical vulnerability assessment as far as dynamic flooding is concerned, with a particular focus on vulnerability curves, on alternative assessment methods and on challenges and recommendations for future research.

The first attempts to assess physical vulnerability to the built environment were vulnerability matrices, a qualitative method to relate hazard intensities to associated consequences such as damage or loss. Over time, these matrices evolved to the more quantitative methods such as vulnerability curves, and, more recently, vulnerability indicators employed for the assessment of physical vulnerability of buildings. The advantages and disadvantages of these three methodological approaches are summarised in Table [*Papathoma-Köhle et al., 2017*].

Table. Overview of existing methods for the assessment of physical vulnerability regarding torrential hazards [*modified from Papathoma-Köhle et al., 2017*]

Method	Advantages	Shortcomings
Vulnerability matrices	Qualitative method, no need for ex-ante data or detailed information	Results may not be translated into monetary loss. Assessment of damage under specific intensities or process characteristics is objective.
Vulnerability curves	The method is quantitative and may "translate" an event into monetary cost	Important characteristics of the natural process (e.g. velocity, duration, direction etc.) as well as the element at risk (number of floors, construction material) are ignored. Highly-demanding in ex-post information
Vulnerability indicators	Characteristics of the element at risk are taken into consideration	The intensity of the process is not considered, demanding in data (detail, amount quality)

Vulnerability functions

Vulnerability functions are a quantitative method for assessing the vulnerability of buildings. They are widely used for assessing risk from hazards such as earthquakes and riverine floods where data is available in a sufficient quantity to create a reliable curve. Vulnerability functions are continuous curves that relate the hazard intensity (X-axis) to the damage state of a building (Y-axis) [*Tarbotton et al., 2015*]. In the case of static (riverine) flooding, intensity on the X-axis is often expressed as the inundation height. In dynamic flooding, however, damage patterns may be different from static inundation. Although the flow height of debris is mostly used as proxy for the hazard intensity [*see Fuchs et al., 2019 for an overview*], other factors such as velocity, orientation and duration of the flow as well as viscosity of the material are also important [*Quan Luna et al., 2011; Rheinberger et al., 2013; Mazzorana et al., 2014; Carisi et al., 2018*]. Such information, however, is rarely measured during event documentation [*Fuchs et al., 2007*], and only little information is available from laboratory experiments [*Zhang et al., 2016; Sturm et al., 2018b*], and effects of these factors on the overall degree of loss remain largely unknown. Moreover, recent studies unveiled limitations during model application with respect to the spatial extent of deposition heights [*Chow et al., 2018; Milanesi et al., 2018*] and resulting loss pattern [*Fuchs et al., 2012*]. Consequently, only a simplified representation of complex damaging processes is repeatedly used in vulnerability assessment, and results are therefore hardly transferable among different case studies [*Cammerer et al., 2013; Papathoma-Köhle et al., 2017; Mosimann et al., 2018*].

Hence, the majority of studies on dynamic flooding rely on vulnerability functions with limited data quantity and a high spread in data [*Eidsvig et al., 2014*]. The shape of the final curve depends on the statistical method used (regularly curve fitting based on non-linear regression) and therefore on the type of function selected. In more detail, once individual buildings are represented as points on a XY axis system then a function ensuring the best fit to the data may be chosen, and the associated error statistics such as R^2 (coefficient of determination) or RMSE (Root Mean Square Error) define its reliability. The function with the best fit should minimize the squared differences in data, which is consistent with the classical approach of curve fitting. Recent studies repeatedly computed Weibull distribution functions to mirror the overall relationship between hazard magnitude and observed degree of loss [*Totschnig and Fuchs, 2013; Papathoma-Köhle et al., 2015*].

Uncertainties of aleatory type can be expressed by confidence intervals, which depend on the distribution of errors. These uncertainties are based on the assumption of symmetrically distributed errors around the mean degree of loss, which is hardly confirmed by empirical data. Moreover, the data spread of Weibull functions results in theoretical loss values above one and below zero, which is inconsistent with the definition of vulnerability. The observed loss pattern is characterized by less data with high values (larger degree of loss until complete destruction) than with small values (lower degree of loss), and the data showed a right-skewed distribution [*Totschnig and Fuchs, 2013; Papathoma-Köhle et al., 2015*]. The larger loss values tended to be farther away from the mean degree of loss than the smaller values. Hence, a suitable and stochastically valid probability model should be able to represent this skewness, which requires a parametric assumption and the selection of a probability distribution enabling the statistical treatment of uncertainties. A lack of predictive power of the degree of loss for future events is evident since current approaches were based on spurious error assumptions [*Fox, 2016*].

Furthermore, even if information on the monetary loss per building is required for the computation of vulnerability curves, such data are not always available and the cost of necessary repair works have been used as a proxy instead [*e.g., Holub and Fuchs, 2008; Papathoma-Köhle et al., 2012; Golz et al., 2015; Neubert et al., 2016; Schinke et al., 2016*]. Furthermore, economic values may differ significantly between individual buildings concerning the economic assessment of the overall reconstruction value. Consequently, the degree of loss (the ratio between the monetary loss and the value of the building) is often misleading since some buildings have an remarkably high value due to a high number of floors which influences the degree of loss in a negative way. An alternative approach to calculating loss (e.g. damage/m^2 per affected floor) may be the key to reduce uncertainties in this respect. Moreover, bias may occur as data on monetary loss often also includes additional compensation for the content of buildings or auxiliary buildings in the property, such information has to be excluded before vulnerability computation.

Vulnerability indicators

The use of vulnerability indicators could be useful to qualitatively assess vulnerability since physical vulnerability is dependent on building characteristics. This approach includes the selection of indicators relevant for the occurrence of a loss, the identification of their variables, weighting and finally aggregation in a vulnerability index. One of the first attempts to use such indices was made by Papathoma-Köhle et al. [*2007*] for buildings exposed to landslides in mountain areas. The method was later applied by Kappes et al. [*2012*] without considering the hazard intensity; this was only done by Silva and Pereira [*2014*] by using indicators such as construction material and technique, number of floors, floor and roof structure, etc. A similar approach was also chosen by Mazzorana et al. [*2014*] and Milanesi et al. [*2018*] in order to link the structural resistance of a building to the hazard magnitude. Thouret et al. [*2014*] as well as Ettinger et al. [*2016*] used indicators to assess the physical vulnerability of buildings to debris flows in the Peruvian Andes. Thouret et al. [*2014*] presented results from an analysis of high-resolution satellite imagery based on indicators such as building type, number of floors, percentage and quality of building openings and roof type. Using the same data together with ground truth observation, Ettinger et al. [*2016*] reported vulnerability indices based on indicators such as shape of city block and building density, building footprint, number of stories, as well as distance of buildings from channels and bridges. Finally, Thennavan et al. [*2016*] reported physical vulnerability indices for buildings in Indian Western Ghats hill ranges, based on the method of Papathoma-Köhle et al. [*2007*]. With respect to dynamic flooding, however, Papathoma-Köhle et al. [*2017*] concluded that the fact that the required data are of high resolution and detail makes the use of indicators challenging. In contrast, once also empirical data on damage are available, the interaction of the process with different building characteristics can be studied and empirical weighting may become possible. Nevertheless, additional research is needed for an improved selection of indicators, a better and reliable weighting and aggregation method and for consistent scenarios as a basis of the assessment [*Papathoma-Köhle et al., 2019*]. Moreover, as indicator-based approaches require detailed inventories of elements at risk, alternative ways of data mining such as remotely-sensed data (e.g. Google street view), using questionnaires, and citizen-science increasingly gain importance [*Haworth and Bruce, 2015*].

Laboratory experiments supporting vulnerability assessment

Despite the numerous studies on the physical vulnerability of buildings, there is still a gap concerning the interaction between the hazard process and the building envelope. Numerical modelling based on laboratory experiments may be used to overcome this gap [*Gems et al., 2016*]. The information acquired may replace or complement empirical data, as shown by some scholars for static inundation [*Armanini et al., 2011; Scheidl et al., 2013; Mazzorana et al., 2014; Zhang et al., 2016*]. However, similar studies focusing on dynamic flooding in mountain catchments are still scarce. Regarding laboratory experiments, a remarkable effort to study and quantify the interaction between buildings and dynamic flooding has been made by Sturm et al. [*2018a, b*]. They used a 1:30 scaled fan model including building stock to capture the process impact pressure on the building envelope under different scenarios. The results of the measurements not only provided information on flow heights and impact pressure per building, but they also demonstrated the importance of scale in vulnerability assessment: while some of the buildings acted as protective shields for neighbouring buildings, they redirected the flow and finally increased the damage for other buildings. Moreover, it was shown that windows and other openings reduce the impact pressure on the walls decreasing at the same time the probability of a wall to collapse. Finally, Milanesi et al. [*2018*] studied the stability thresholds and the collapse mechanisms of traditional alpine masonry buildings exposed to hyperconcentrated flows using limit analysis, and the results were compared to the results of finite element analysis. Such studies can enhance the knowledge on building retrofitting and local structural protection, as shown by Holub et al. [*2012*] with respect to an idealised hazard-proof residential building in the Austrian Alps.

Conclusion and the way forward

The reliability of vulnerability curves is based on available empirical data related to the damage pattern of buildings following the impact of dynamic flooding. A thorough and standardised post-event documentation is necessary to increase the overall preciseness of such curves and to compute multiple curves for different building types as well as for buildings with common characteristics (e.g. buildings with basement, brick buildings, reinforced concrete buildings). Vulnerability indicators may be used to supplement vulnerability curves and to overcome the current scarceness in data.

The predictive power of vulnerability curves together with vulnerability indices could be enhanced using complementary empirical data based on a classification of elements at risk. In particular, a building-type based approach that uses dependencies between hazard and damage patterns for specific building categories can be helpful to estimate potential damage costs prior to disastrous events, provided it will be extended for dynamic flooding [*e.g., Golz et al., 2015; Schinke et al., 2016*].

Additionally, no physical vulnerability assessment is complete without the consideration of buildings of special use and infrastructure (critical infrastructure). So far, buildings such as hospitals or those related to other critical infrastructure cannot be included in the traditional vulnerability curves based on residential or commercial buildings. Moreover, studies of vulnerability curves for roads or other transport networks are also limited [*Unterrader et al., 2018; Schlögl et al., 2019*], and future research should be conducted in this direction. Finally, yet importantly, a significant challenge is the fact that vulnerability curves are often site-specific and therefore not always transferable among case studies.

The recent advances in vulnerability assessment methods for buildings threatened by dynamic flooding presented in this paper clearly show that there is still a need for further research in this field. Existing vulnerability curves may be improved with the availability of additional damage data and alternative methods such as indicator approaches may be used alone or in combination to shed light on the interaction between natural processes and elements at risk. All this knowledge will contribute to the enhanced assessment of risk, to target-oriented mitigation and to the design of suitable risk reduction strategies.

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