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Anticipating cascading effects of extreme precipitation with pathway schemes - Three case studies from Europe

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ABSTRACT

Extreme precipitation events with high local precipitation intensities, heavy snowfall or extensive freezing rain can have devastating impacts on society and economy. Not only is the quantitative forecast of such events sometimes difficult and associated with large uncertainties, also are the potential consequences highly complex and challenging to predict. It is thus a demanding task to anticipate or nowcast the impacts of extreme precipitation, even more so in situations where human lives or critical infrastructure might be at risk.

In recent years, the term "cascading effects" has been increasingly used to describe events in which an initial trigger leads to a sequence of consequences with significant magnitude. We here analyze three examples for different precipitation types where the initial triggering event generated a cascade of events and impacts, namely a convective precipitation event in the Swiss Prealps, a freezing rain in Slovenia, and a heavy snowfall episode in Catalonia. With the aim to improve process understanding of complex precipitation-triggered events, we assess the prediction of the selected events and analyze the cascading effects that caused diverse impacts. To this end, we use a framework of cascading effects which should ultimately allow the development of a better design risk assessment and management strategies.

Our findings confirm that damage of extreme precipitation events is clearly related to the knowledge of potential cascading effects. Major challenges of predicting cascading effects are the high complexity, the interdependencies and the increasing uncertainty along the cascade. We propose a framework for cascading effects including two approaches: (i) one to analyze cascading effects during past extreme precipitation events, which then serves as a basis for a (ii) more generalized approach to increase the preparedness level of operational services before and during future extreme precipitation events and to anticipate potential cascading effects of extreme precipitation. Both approaches are based on pathway schemes that can be used in addition to numerical models or hazard maps to analyze and predict potential cascading effects, but also as training tools.

1. Introduction

Natural hazards due to high impact weather may have a series of severe effects, often referred to as secondary hazards (e.g. Gill and Malamud, 2014). Extreme precipitation (typically in the form of high intensities, but also extensive freezing rain and heavy snowfall) is one type of high impact weather that in many cases over many different areas of the world acts as a trigger for a sequence of further natural hazards such as floods, landslides, debris flows or snow avalanches (Agel et al., 2015; Frei et al., 2000; Huang et al., 2018; Kunkel, 2003; Lavers and Villarini, 2013; Stoffel and Corona, 2018). These hazards may cause different types of direct and indirect damage, thereby posing a possible threat to human lives, ecosystems, buildings or infrastructure. Disasters occur whenever potentially damaging natural processes/hazards (here in the form of extreme precipitation) interact with elements at risk and their associated physical, socio-economic and environmental vulnerability (Birkmann, 2006). In cases where critical infrastructure is affected or damaged, the negative impacts of these

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natural hazards can be prolonged or intensified (Chang et al., 2007). Critical infrastructure is defined here as systems or assets that are vital to the functioning of society (Setola et al., 2016); any disruption or destruction of critical infrastructure therefore has often serious impacts on health, safety, security or economic well-being (definition by the Government of Canada, cited in Chang et al., 2007).

The prediction of precipitation intensity and type (e.g., snow, hail, freezing rain, or rain) and the complex secondary hazards is often associated with large uncertainty, thereby hampering the anticipation of severe precipitation-induced impacts. In addition, the processes that cause extreme events often interact and are spatially and/or temporally dependent (Zscheischler et al., 2018), posing an important challenge for the prediction. This is the case of e.g. wood-laden flows (i.e., significant amount of wood transported during floods, Ruiz-Villanueva et al., 2018), which are usually formed after heavy precipitation, which triggers processes that deliver woody material to the river (e.g., mass movements or bank erosion) and a flood that eventually transport the wood downstream. The transport of this material may result in an enhanced flood hazard and risk, as wood may clog narrow sections and bridges, leading to a backwater effect and flooding. The complex cascade involved in the triggering and propagation of such flows, as well as their consequences (i.e., clogging, backwater, increased damage), are very challenging to forecast, and very difficult to reproduce numerically or in a laboratory (Mazzorana et al., 2019; Ruiz-Villanueva et al., 2016).

In the area of natural hazards, the term “process chain” is commonly used to refer to a situation where an original hazard triggers a sequence of processes (Han et al., 2007; Mazzorana et al., 2018; Schaub et al., 2013; Somos-Valenzuela et al., 2016; Worni et al., 2013). As a synonym for “process chain”, inter alia, the terms “domino effect”, “cascading disasters/effects”, or “cascade effect” are increasingly used in the context of coupling multiple natural hazards (Delmonaco et al., 2006a,b; Frey et al., 2016; Joyce et al., 2017; Kumasaki et al., 2016; Mehta et al., 2017; Nguyen et al., 2013; Schneider et al., 2014), often from an ecological perspective (Behie et al., 2014; Kinzig et al., 2018; Smith-McKenna et al., 2014). The term “cascading effects” is generally used to describe events, where an initial trigger leads to consequences with significant magnitudes (Pescaroli and Alexander, 2015) and to refer to the fact that hazards are related and that they can influence each other (Kappes et al., 2012). For the last decade, it has been progressively applied in the context of a changing climate, since an increase in air temperatures may lead to a sequence of effects that we need to understand in-depth (Beniston et al., 2018; Huss et al., 2013; Kinzig et al., 2018; Xu et al., 2009). “Cascading effects” should not be confused with “compound events”, a term that recently has been used to refer to the combination of multiple drivers and/or hazards contributing to societal or environmental risks (Zscheischler et al., 2018). “Chain” and “cascade” are similar terms but here “cascade” may be more suitable for precipitation-related hazards and impacts on the human system because of the one-directional and non-mutual nature of many processes along the sequence (e.g. a flood will not control precipitation).

Even though the concept of cascading disasters is often mentioned in hazard and disaster literature, methods considering the entire cascade from the natural trigger (with its predictability days in advance) to the impacts (generating secondary emergencies to society and economy) remain scarce. In addition, most approaches for multiple hazards and interactions do not include the sequence of secondary hazards in the human system when infrastructure is affected (Gill and Malamud, 2014; Kumasaki et al., 2016; Liu et al., 2016; Marzocchi et al., 2012; De Pippo et al., 2008; Tarvainen et al., 2006). In contrast, other studies only focus on cascading effects in human networks such as infrastructure, organizations, and communication systems (Peters et al., 2008), without analyzing natural hazards. However, it is commonly acknowledged that the lack of a holistic approach to forecast multi-hazard situations can lead to and underestimation of risk (May, 2007) and cause errors in managing priorities, increased vulnerability to other hazards or an underestimation of risk (Gill and Malamud, 2014, 2016). For vulnerability assessment, reduction strategies and disaster anticipation, it is hence crucial to understand the chain of possible effects and the related impacts a precipitation event can have (Pescaroli and Alexander, 2015; Schneiderbauer et al., 2017). This is the reason why the Sendai Framework for Disaster Risk Reduction articulates the need for improved understanding of disaster risk in all its dimensions of exposure, vulnerability, and hazard characteristics (UNISDR, 2015). Because it is essential to include the information of potential consequences of a precipitation event in a forecast and multi-hazard tool or platform (such as the one developed by the EU Horizon2020 funded ANYWHERE project, www.anywhere-h2020.eu), a framework to assess possible complex consequences of a triggering precipitation event is urgently needed.

The aim of this study is therefore to assess a new framework to analyze and anticipate precipitation events and their impacts. Note that a probabilistic approach to assess cascading effects and their linkage to derive risk maps can be extremely data-demanding and complex (Delmonaco et al., 2006a), especially for single study regions with limited data availability. We therefore base our study on qualitative descriptions, a method that seems promising for the understanding of a complex process behavior. In recent years, some approaches have been developed to assess and visualize cascading effects including natural hazards as well as the human system such as causality networks (Helbing et al., 2006), branching tree structures (May, 2007), Causal-Loop-Diagrams (Berariu et al., 2015) or hazard/process flow diagrams with several clusters (e.g., natural hazards, technological hazards, and anthropogenic processes; Gill and Malamud, 2016). Our approach is novel in the sense that we analyze the cascade from the predictability of the triggering precipitation event down to the level of impacts (occurred and avoided) in an integrated way. This means that we not only analyze triggering events and related chains of natural hazards (like e.g. in Gill and Malamud, 2014), but we also show how disaster-related impacts progress in time. We follow an adapted framework and terminology introduced by (Gill and Malamud, 2014, 2016; May, 2007; Pescaroli and Alexander, 2015), in order to show the advantage or benefits of understanding an event as a cascade. To do so, we select three case studies, covering three different types of extreme precipitation: (1) a convective rainfall event in the Swiss Prealps, (2) a freezing rain event in Slovenia, and (3) a heavy snowfall event in Catalonia. For these events, we assess predictability of the triggering event and review cascading effects using schemes (May, 2007) to illustrate the single elements and their interdependencies. We discuss the potential of using a framework of cascading effects to anticipate the risk of precipitation-triggered hazards.

2. Methodology and data

The question arises whether a certain complexity is needed to refer to “cascades” or whether a difference exists between “cascades” and complex causal chains, present in most natural hazards. There is no clear answer to that in literature, but Pescaroli and Alexander (2015) suggest that cascading effects are complex, multi-dimensional and evolve over time. Therefore, we here selected characteristic case studies that fulfill the following criteria:

1) cascading effects are “extreme events, in which cascading effects increase in progression over time and generate unexpected secondary events of strong impact. These tend to be at least as serious as the original event, and to contribute significantly to the overall duration of the disaster's effects. These subsequent and unanticipated crises can be exacerbated by the failure of physical structures, and the social functions that depend on them (…)” (Pescaroli and Alexander, 2015: 65).
2) The case studies should cover different precipitation events, including convective rainfall, heavy snow and freezing rain.

Table 1
Forecast data and measurements used to analyze the predictability and the magnitude of the three case studies.

Event	Forecast data	Measurements
Switzerland July 4, 2012 Convective precipitation	- Total precipitation (IFS-HRES[a] and COSMO-2[c]) - CAPE (IFS-HRES[a]) - Meteorological variables for convective indices (Showalter Index, K-index and Deep Convective Index)[b]	- Radar data from the product CombiPrecip[c] (Sideris et al., 2014) - Precipitation records from meteorological stations[c,d] - Precipitation measurements by local residents[e]
Slovenia January 31–February 3, 2014 Freezing rain	- Total precipitation (IFS-HRES[a]) - Most probable precipitation type and meteogram of precipitation type, according to Gascón et al. (2018)	- Daily precipitation[f] - Precipitation type[f]
Catalonia March 8, 2010 Heavy snowfall with wind gusts	- Total precipitation (IFS-HRES[a]) - Fraction of snow (IFS-HRES[a]) - 10 m wind gust (IFS-HRES[a])	- Snow depth from spotter data[g,i] - Maximum wind gust from automatic stations[h,j] - Precipitation estimates from radar and station gauges[h,k]

[a] ECMWF.
[b] GFS.
[c] Swiss Meteorological Office (MeteoSwiss).
[d] Canton Berne, Office of Water and Waste (Amt für Wasser und Abfall).
[e] Personal communication (Flussbau AG, 2012).
[f] SYNOP reports.
[g] Weather observers network (XOM) of the Meteorological Service of Catalonia.
[h] Automatic Weather Stations Network (XEMA) of Catalonia.
[i] To the snow depth (cm) from spotter data a terrain height adjustment and inverse distance interpolation to the radar grid (1 km resolution) is applied. 89 from 113 observations are used after checking valid locations.
[j] For maximum wind gust, point measurements from automatic stations at 10 m above the ground are interpolated using simple inverse distance method.
[k] Precipitation amount from radar and station gauges are blended by ordinary kriging with external drift between officially calibrated radar data and gauge data.

The case studies are assessed using scientific and grey literature (e.g., reports and newspaper articles). As suggested by Pescaroli and Alexander (2015), we focus on the most important factors such as interdependencies and critical infrastructure. These factors need to be addressed in anticipation and risk reduction practices to limit cascading during disaster.

Depending on the possibilities and shortcomings of different methods, we decided to apply a branching tree structure similar to May (2007), to show how a first trigger evolves into a cascade with several branches, using

(i) an event-based pathway approach, based on particular disasters of three case studies (see Section 3), in order to document the different elements of the cascade (May, 2007)
(ii) a generalized approach to assess "potential cascading effects" that is based upon the results of the first approach and expert knowledge (see Section 4).

To analyze the events of the three case studies, we used several data sets (Table 1). Forecast data from the European Centre for Medium-Range Weather Forecasts (ECMWF) and from the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) are used to assess the predictability of the events.

3. Case studies

In the following, we show the results of the analysis of the three case studies using event-based pathway schemes, that exemplify cascading effects of different types of extreme precipitation events. The first example shows cascading effects of a strong local convective rainfall event in the Swiss Prealps, the second a severe freezing rain event over a large area in Slovenia, and the third an exceptional snow event for the Catalonia region. We focus on the predictability of the triggering events, the subsequent events in the natural and human systems, the resulting losses and the measures that have been taken to mitigate the disaster.

3.1. Case study 1: convective event in the Zulg river catchment, Switzerland (July 4, 2012)

The Zulg river catchment event demonstrates the potential of a local thunderstorm in the Swiss Prealps to cause severe damage in Berne, the capital of Switzerland, 30 km downstream (Fig. 1a and b). While high local rainfall intensities were registered in the Zulg valley, there was no precipitation in Berne, where the situation was critical few hours after the rainfall. The critical element of this event was the instream wood mobilization (Fig. 1c), which caused a partial clogging of a weir (Schwellenmätteli) in Berne and a nearly flooding of the nearby area in the old city.

The triggering rainfall event occurred out of a convective cell over the Zulg catchment in the afternoon July 4, 2012. Very high rainfall intensities within only ~10 km over the upper Zulg catchment, in combination with a low travel velocity of the convective cell, caused high runoff in the river Zulg. A nearby meteorological stations registered 37.3 mm (Marbachegg) for that day, but locally, 100–120 mm were measured by local citizens (Flussbau AG, 2012). The exceptionally high local rainfall intensities of 80–87 mm/h (Flussbau AG, 2012) between 15:15 and 16:30 local time may correspond to a return period of 300 years, while the daily precipitation of that day only relates to a 50–100 year event (Flussbau AG, 2012). The CombiPrecip dataset (a geostatistical combination of rain-gauge measurements and radar estimates) indicates 50–55 mm for this day for the pixel with the highest value, which is probably underestimated due to a calibration problem of the radar (Flussbau AG, 2012). The spatial resolution of the CombiPrecip dataset is 1 km and the temporal resolution is 5 min. The radar data illustrate the very limited spatial distribution of the precipitation (Fig. 1a) as well as the temporal course of precipitation intensity (Fig. 1d).

3.1.1. Forecast evaluation

Convective events are difficult to predict, especially for such high local precipitation intensities within a similar or even smaller area than the spatial model resolution. For this day, no precipitation was predicted by the IFS-HRES forecast for the cells of the Zulg river catchment (base time: July 3, 2012 00:00, Fig. 2a). However, close to the catchment, precipitation of approximately 10 mm was indicated (see orange colors East and Southeast of the study site in Fig. 2a, at a distance of

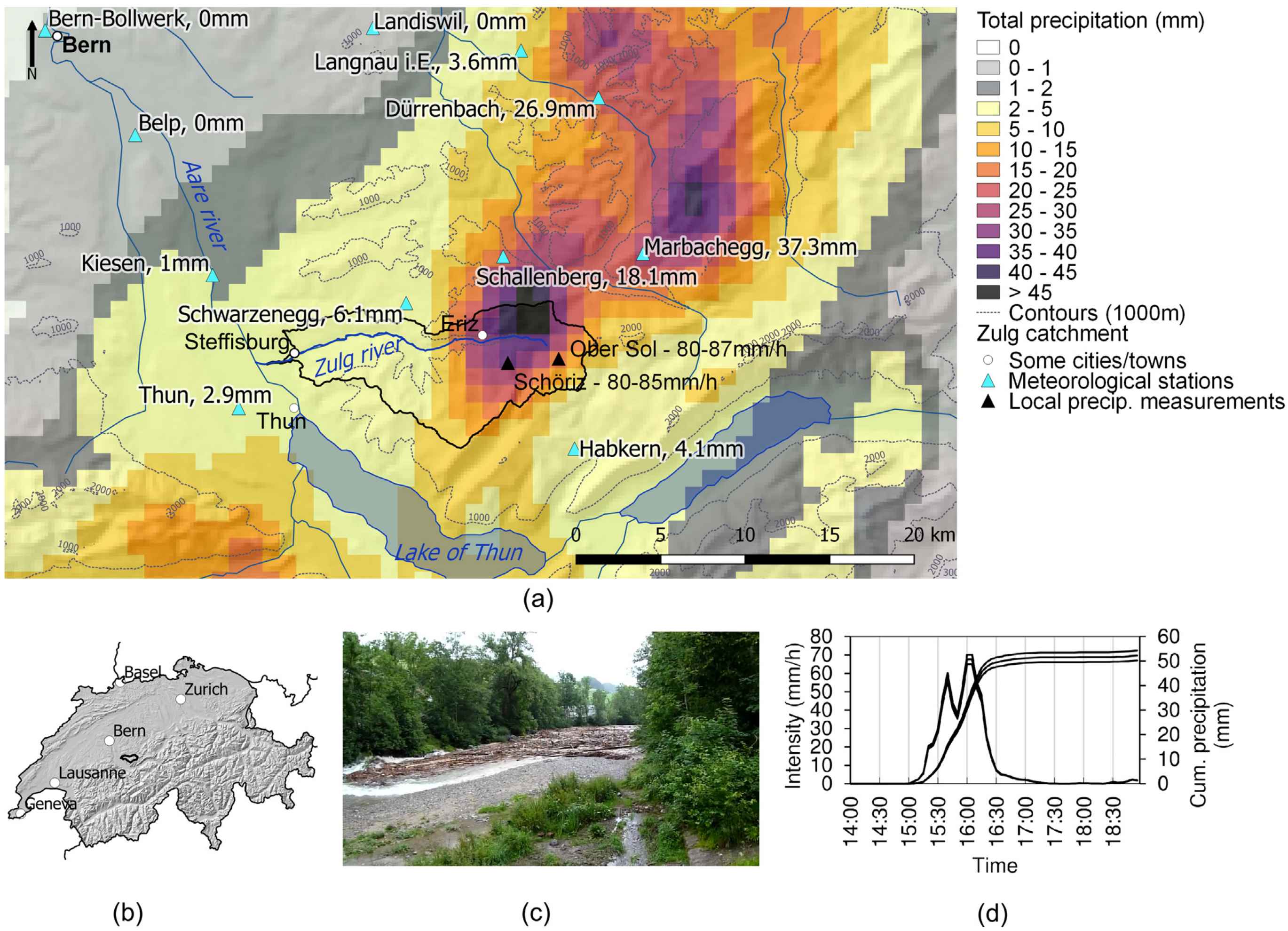

Fig. 1. (a) Map of the study region with the rivers Zulg and Aare, Lake Thun and the catchment of the Zulg river, daily precipitation estimates from the radar network of MeteoSwiss at 1 km resolution from 7 am to 8 pm, stations of the MeteoSwiss network with daily precipitation record in the label name, precipitation estimates by local citizens with precipitation intensities (mm/h); (b) overview map of Switzerland and the study catchment; (c) image of the wood flow in the river Zulg; (d) precipitation intensity and cumulative precipitation from the radar network for the pixel with the largest precipitation estimates (7.81°E, 46.80°N, local time).

10–30 km). In contrast, the higher resolved convection permitting COSMO-2 model – with a grid resolution of 2.2 km – did not indicate any precipitation for 4 July 2012 in this region for the run of 11:00 local time (09:00 UTC, Fig. 2b).

To quantify preconditions for the initiation of convective storms, various thermodynamic and kinematic parameters exist. The commonly used CAPE index expresses the amount of convective potential available energy. The CAPE index from the ECMWF model was low for the event day (not shown here), which is in line with the limited applicability of thermodynamic indices for mountainous regions (such as Switzerland) as previously observed (Graham et al., 2012). More suitable convective indices exist to estimate the potential of an air mass to develop a thunderstorm over mountainous regions, such as the Showalter Index (Showalter, 1953), K-index (George, 1960) and Deep Convective Index (Barlow, 1993). These three indices indicated a high probability for thunderstorm over the Alps (Fig. 2 c-e), based on thresholds given in Huntrieser et al. (1997) or Kunz (2007). In conclusion, the application of convective indices seems promising for the potential development of this type of local precipitation event, especially for cases where the precipitation forecast is not very skillful. It is, however, important to carefully select these convective indices.

3.1.2. *Cascading effects*

Due to the large amount of rain and the high rainfall intensities, runoff of the Zulg river increased rapidly and caused mass movements on the hillslopes, bank erosion and sediment (both organic and inorganic) mobilization along the riverbed causing a sequence of effects (Fig. 3). Discharge in the downstream town of Steffisburg (Fig. 1) reached 222.38 m^3/s, corresponding to a ~100-year event (Flussbau AG, 2012). The hydrograph was very flashy (not shown here), peaking between 17 and 18 h (local time) and lasted only few hours (< 6 h). The flood caused some damage in Steffisburg, flooding some streets and affecting few buildings. The high runoff caused a small local flood of some cellars and destroyed a camping site in the valley floor. Since the people in the camp were informed by a neighbor, the place was evacuated on time and no one was injured. Furthermore, 8 ha of agricultural area and forest were flooded and 2 bridges and a trail were destroyed, as well as parts of the river were undermined. Approximately 1 h later, the flood wave arrived in Berne along the Aare river, where the station located in Schönau registered a peak discharge of 412 m^3/s (~20-year return period according to FOEN, 2018) at around 20:00 local time.

According to available reports (Hunziker Gefahrenmanagement, 2017), the estimated volume of eroded sediment in the Zulg river ranged between 10,000–15,000 m^3, and the mobilized wood volume was between 500 and 700 m^3 (corresponding to ca. 300 tons assuming a wood density equal to 500 kg/m^3). A large quantity of wood was transported down to the river Aare and further on to the city of Berne (approximately 50 tons, around 100 m^3, was extracted at the site called Schwellenmätteli). This site was severely damaged by wood in a previous flood in 2005 causing important damage (FOEN, 2008; Steeb

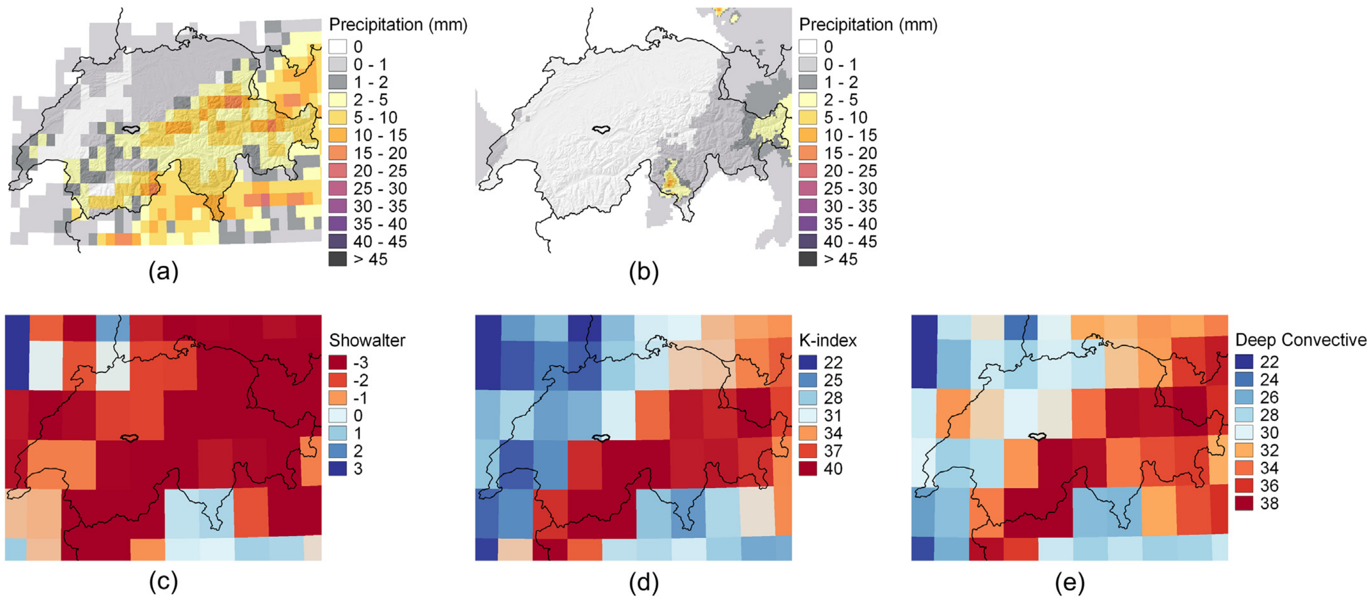

Fig. 2. (a) IFS-HRES precipitation forecast for July 4, 2012 00:00–24:00 UTC (base time: July 3, 2012 00:00 UTC); (b) COSMO-2 precipitation forecast for July 4, 2012 09:00–24:00 UTC (base time: July 4, 2012 09:00 UTC) (c) Showalter Index (°C), (d) K-Index (°C) and (e) Deep Convective Index (°C) for 12:00 UTC (14:00 local time) with the base time July 3, 2012 00:00 UTC. The black polygon indicates the catchment of the Zulg river. Orange to red colors in (c), (d) and (e) indicate threshold exceedance. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

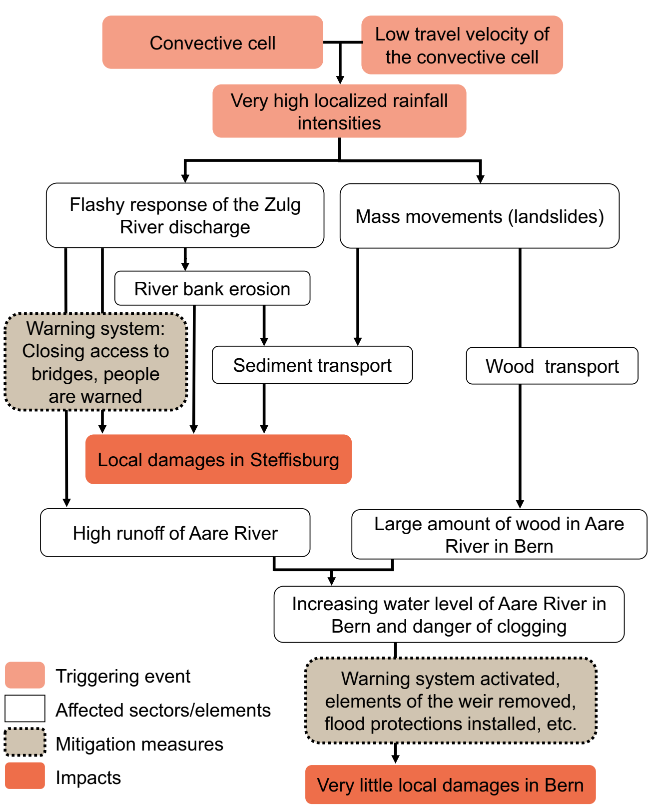

Fig. 3. Scheme of the cascading effects of the slowly moving convective cell over the Zulg catchment.

et al., 2017), therefore, measures were designed to mitigate future impacts, among them the modification of the infrastructure and the installation of a crane equipped with an extraction machine. Without any of these actions, almost certainly, the weir would have been clogged and the nearby Matte neighborhood may would have been flooded again.

For the cascading effects involving wood transport, the wood availability along the riverbed and supply by recruitment processes (e.g., landslides and tributary supply) is a decisive factor. This is clearly shown by the following flood events, for which at similar peak discharge, much less wood was transported (e.g., on July 6, 2015 a peak discharge of 234 m^3/s was recorded in Steffisburg, and around 300 m^3 of transported wood was estimated). Spatio-temporal factors such as the areas affected by intense rainfall, the contributing tributaries, the flood hydrograph and recent history of high flows strongly influence the supply, remobilization and transport regime for wood (Ruiz-Villanueva et al., 2016). The flood in 2012 played a large role in wood delivery, and subsequent events were relatively ineffective in removing wood regardless of their magnitude.

3.1.3. Mitigation measures

Different measures were taken during the 2012 event. At 16:15 h local time, the president of the river authority (Schwellenkooperation Zulg) triggered an alert, based on which the local fire fighters started patrolling along the Zulg river, closing access to bridges and warning population with loudspeakers. Only 15 min later, the river already started flooding buildings. At 17:00, the city of Berne was informed about the heavy load of wood in the Zulg river. In the Swiss capital, flood protections were installed (mobile flood barrier tubes called “beavers”) and when the wood arrived, the crane was ready for use. At 18:00, people living in the low-lying Matte area received a warning via text message (SMS). At 20:15 sirens were activated. Thanks to these preparation works, the wood could constantly be removed from the weir and a flood could be narrowly avoided.

After the event, the responsible institutions concluded that the warning was working well, but there was a dependency on the presence of certain persons, which was identified as a high risk, especially during night and on weekends (Flussbau AG, 2012). As a consequence of the event, a warning and alarm system was installed one year later with a modern radar gauge and a webcam in the upper Zulg river near the Eriz village (Fig. 1). The system automatically sends now prioritized SMS and voice calls to the fire and police departments of Steffisburg fire department. Additionally, the lowering of the outflow from Lake Thun now helps to reduce discharge in the Aare river when there is high runoff in the Zulg river, once the warning system is activated.

3.2. Case study 2: freezing rain in Slovenia (January 31 to February 5, 2014)

Freezing rain refers to the occurrence of rain with a temperature below the freezing point that freezes when it gets in contact with an exposed object or the ground, where it forms a coating of ice (WMO, 2012). These events are most frequent for a continental climate (Carrière et al., 2000). Freezing rain is particularly hazardous for the environment and the society because of the effects it can have on energy supply and transport (Armenakis and Nirupama, 2014; Chang et al., 2007; Cheng et al., 2007; Irland, 2000). This case study shows how an unprecedented and long-lasting freezing rain event in Slovenia caused an extensive disruption of electricity for hundreds of thousands of people, almost leading to a catastrophic situation.

The freezing rain event occurred during several days between January 31 (Friday) and February 5, 2014 (Wednesday) and mainly affected Slovenia, but also neighboring Austria, Croatia, as well as Poland, and had effects up to the Baltic Sea (Forbes et al., 2014). Some days before the event, cold continental air masses were advected from the Northeast (Markosek, 2014). Then a warm air mass flow started from the South at middle levels between 1200 and 2000 m above sea level (Markosek, 2014). At the time when the warm air mass arrived, the surface air was cold with temperatures below 0 °C. During the days of the event, widespread precipitation of 10 to 50 mm occurred, and even exceeded 100 mm (Forbes et al., 2014) to 150 mm locally (Markosek, 2014). Heavy precipitation (rain and snowfall, depending on the region) started on January 30, 2014. The rain then started freezing in the morning of January 31 (at around 03:00 and 06:00 am according to SYNOP reports). In Fig. 4, daily precipitation (06:00 to 06:00 local time) is shown and a symbol indicates where at least one observation of freezing rain was registered during the day. The occurrence of freezing rain continued until February 2 in the afternoon. After a dry day on February 3, some stations reported freezing rain again on February 4 and 5, but less extensively.

3.2.1. Forecast performance

During the winter season, the accurate identification of precipitation type at the ground level is one of the major challenges for forecasters (Ralph et al., 2014). Although the information on the duration, intensity, and spatial extent of freezing rain events is crucial for decision makers, limited attention has been paid to wintertime precipitation type forecasting in Europe until recently (Gascón et al., 2018).

In 2014, the ECMWF Integrated Forecasting System (IFS) cycle 36R4 did not yet include a “precipitation type” parameter. To better represent the winter precipitation-type forecast, the cloud and precipitation physics were improved in the new ECMWF IFS cycle 41R1, operational as of early 2015. Forbes et al. (2014) showed that the improved model with the new physics is in better agreement with measurements, whereas the former model (cycle 36R4) was not able to predict the extent of the freezing rain event, indicating widespread snowfall instead. In a following study, Gascón et al. (2018) showed advantages of using a new product of probability of precipitation type based on ensemble forecasts of instantaneous precipitation type combined with the precipitation rate variable. This new methodology creates tailored products that help reduce the bias of each precipitation type. The product verification shows that the precipitation forecasts skillfully differentiate between rain and snow, but the skill for freezing rain is still moderate. The skillful prediction of freezing rain thus remains a challenge, but will likely improve further in the future.

One of the most important factors in this freezing rain episode was the high precipitation intensity registered during long periods of time (several hours) in many regions of Slovenia. ECMWF conducted a research experiment with the cycle 45R1, that is the operational integrated forecast system (IFS) model version since June 2018, simulating the forecast for this freezing rain episode. An extensive area of freezing rain is observed on the map even 6 days in advance with probabilities < 50% (Fig. 5a), increasing these probabilities to values > 70% 2 to 1 days in advance of event occurrence (Fig. 5b and c). With decreasing lead time, the freezing rain area extends from North Croatia to the center and North of Slovenia in consecutive forecasts, while probabilities of freezing rain increase as well (Fig. 5), matching fairly well with observations from the nearest SYNOP stations. One of the most affected places in the region was the town of Postojna. Meteograms of the probability of precipitation type product for this location are shown in Fig. 6. For long lead times of 150 h (25 Jan, Fig. 6a), probabilities of freezing rain are < 30%, which may not be enough for decision-makers to act but it can be useful for the users to pay attention to the situation of a possible elevated warm layer in the model output in the following days. For January 27 to 29, 2014, the probability of freezing rain increases (between 40 and 70%). For the day before the event (30 Jan, Fig. 6b), the probability of freezing rain and ice pellets increases and reaches 90% for the first half of 31 Jan, when it actually occurred.

This experiment with the freezing rain case study has shown how current products based on the precipitation-type variable from ensemble have been able to forewarn a severe freezing rain episode 7 days in advance, which can help in decision-making for local or regional warnings.

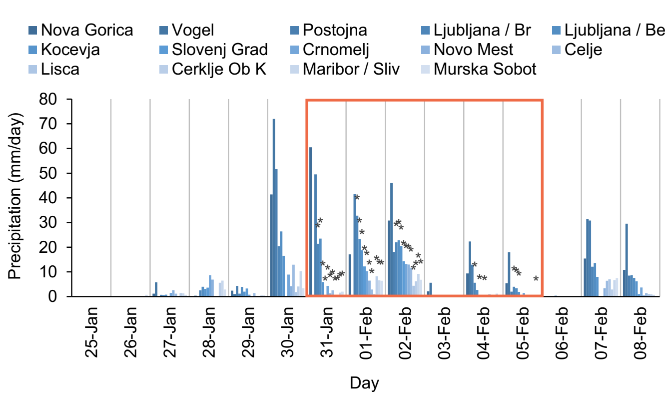

Fig. 4. Daily precipitation (mm/day) for SYNOP stations in Slovenia (reported at 06:00 am). Symbols indicate days where at least one observation for “freezing rain” is reported during the calendar day. The freezing rain started in the morning of the January 31, at around 03:00 to 06:00. Precipitation is cumulative precipitation between 06:00 am and 06:00 am the following day. Freezing rain symbols are set according to the calendar day.

3.2.2. Cascading effects

The freezing rain covered surfaces by a thick layer of ice causing a cascade of diverse effects (see Fig. 7). It was estimated that at least 40% of woodlands, or 500,000 ha have been damaged (Forbes et al., 2014). Fallen trees made many forest roads impassable and coated roads caused numerous car accidents. Also the railway transport was disrupted and villages were cut off for days. Power lines collapsed under the weight of ice and snow or fallen trees and telecommunication installation broke. The power outage affected 250,000 people (IFRC, 2014), corresponding to over 100,000 households. The power outage affected diverse services: water supply, mobile networks, water, heating, radio, television, internet. Schools remained closed in some regions and temperatures in hospitals, schools and retirement homes decreased. Farmers were facing power outages and poor condition of roads, and meadow orchards and crops were affected. Due to the persistence of the situation for several days, massive damage was reported to infrastructure and a state of emergency was proclaimed on February 2 (IFRC, 2014).

Days after the freezing rain event, there was a significant risk of floods due to thawing temperatures, tree debris in the watercourses and expected rainfall. Several local floods were reported (European Commission Joint Research Centre, 2014). Moreover, there were

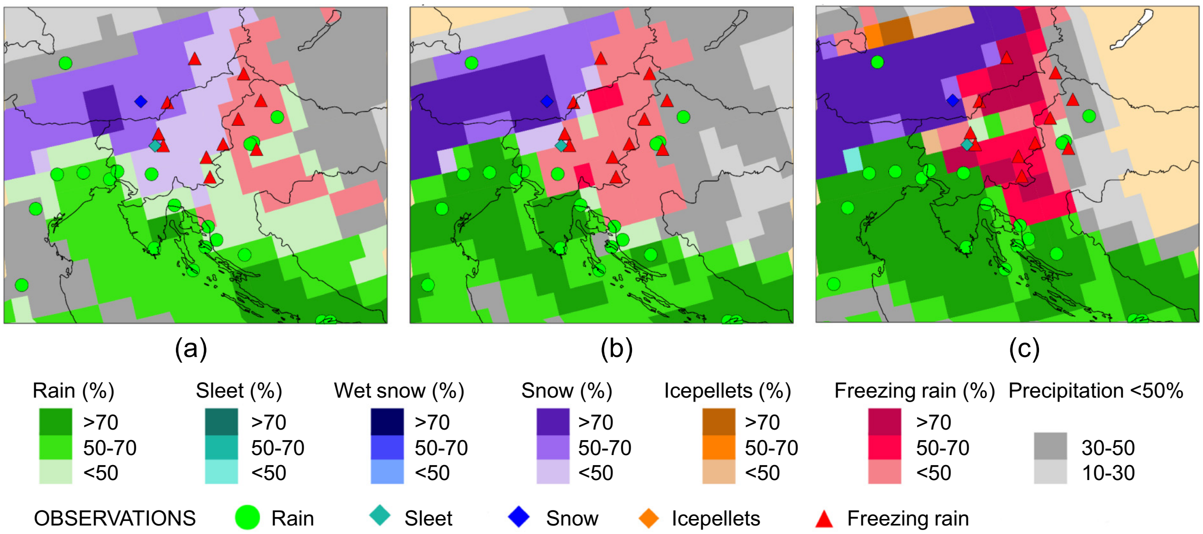

Fig. 5. The most probable precipitation type product generated by ENS model output with a lead time of (a) 150 h (25 Jan, 00:00 UTC), (b) 78 h (28 Jan, 00:00 UTC) and (c) 30 h (30 Jan, 00:00 UTC) before the freezing rain started (31 Jan, 06:00 UTC).

consequences even months to years after the freezing rain event. Fallen trees are particularly vulnerable to bark beetle attacks and neighboring trees can be affected if affected trees are not removed. By the end of 2014, almost half of the fallen conifer trees had been removed (report of Slovenia's Forest Service, cited in de Groot et al., 2018), but due to the remaining wood, a bark beetle outburst occurred in 2015 (de Groot et al., 2018) and 2016 (CIPRA, 2016).

3.2.3. Mitigation actions

Most reports on the Slovenia freezing rain event focus on severe forest damage, but it is worth mentioning that a major disaster due to cascading effects of power disruption was avoided by the fast help from neighboring countries providing generators. Two days after the beginning of the freezing rain (February 2 in the morning), a state of emergency was proclaimed for the entire country. Slovenia requested assistance through the European Union's Civil Protection Mechanisms and in the following days, dozens of generators from Austria, Germany, Czech Republic, and other neighbor countries were provided. Due to the immediate international help ensuring power supply, further cascading effects and impacts were mitigated or avoided. For example, numerous cows would have died without the power supply, since a cow usually only survives a few days without milking. But not only international help, also national agencies and organizations helped mitigate consequences. For example the Slovenian Red Cross started quickly to respond, activating their First Aid teams and volunteers in order to distribute food and non-food relief items, as well as psychological support (IFRC, 2014).

3.3. Case study 3: snowfall in Catalonia (March 8, 2010)

Snowfalls in Catalonia usually occur over the mountainous areas (e.g., Pyrenees and Pre-Pyrenees located in the NE of the Iberian Peninsula), but rarely near the Mediterranean Sea (e.g., the metropolitan area of Barcelona and the coastal area of Girona). The snowfall case of Catalonia on Monday, March 8, 2010 provides an example of how cascading effects of infrequent snowfall together with

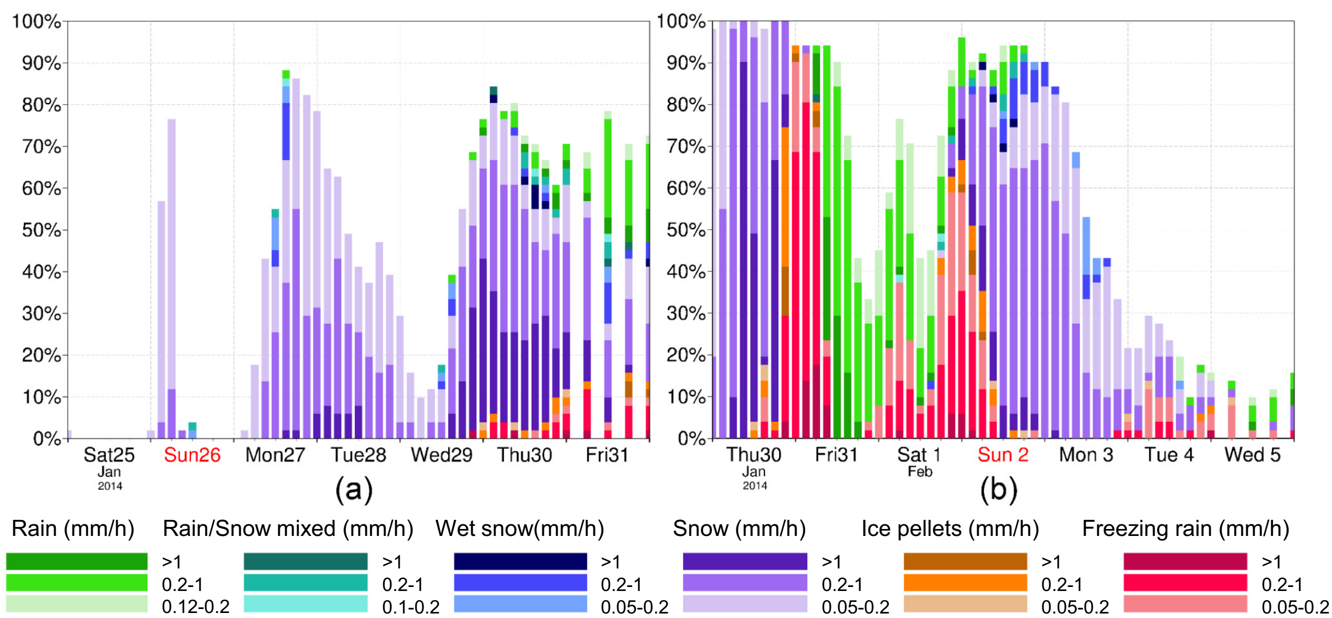

Fig. 6. Meteogram with a lead time of (a) 150 h (25 Jan, 00:00 UTC) and (b) 30 h (30 Jan, 00:00 UTC) before the freezing rain started (31 Jan, 06:00 UTC).

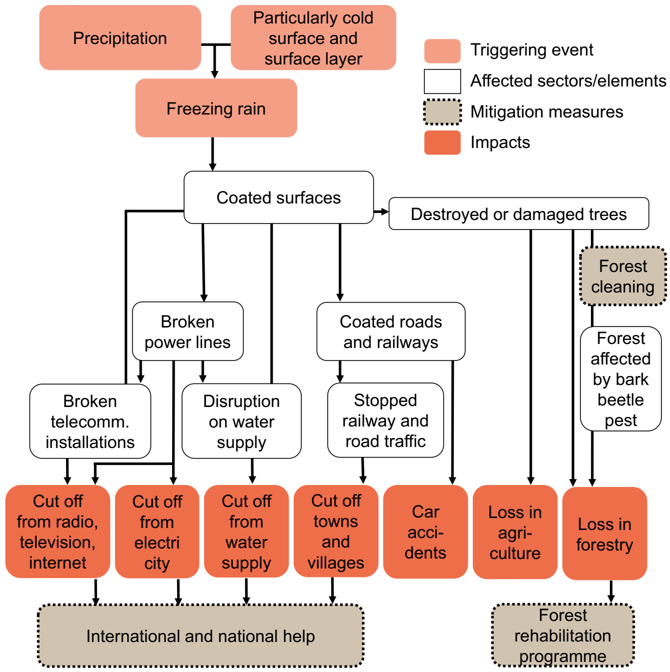

Fig. 7. Scheme of the cascading effects of the freezing rain event in January/February 2014 in Slovenia.

wind gusts and thunderstorms may affect hundreds of thousands of people in a densely populated region.

This event was characterized as an unusual winter thunderstorm (e.g., Llasat et al., 2014). From a meteorological perspective, the widespread and intense snowfall was produced under the presence of a synoptic-scale upper-level trough over Northern Catalonia (which led to a northern flow and advection of cold air, a typical cause of snowfall over the region), and a low-level mesoscale low coming from the Mediterranean Sea (causing advection of humid and warm air, a typical cause of thunderstorms). With the cold depression, snow from the upper levels reached the ground without melting on its way. The cloud development and precipitation was also intensified by convection due to orography and moisture advection at mid- and low-level altitudes. Particularly, this situation set favorable conditions (i.e., 0–2 °C, high humidity, moderate winds) for producing wet snow near the surface. The hotspot of the snowfall event was over the northern coast of Catalonia near Girona, with general snow depths of 20 to 30 cm. Locally up to 60 cm were recorded, as shown in Fig. 8a. In this area, the snowfall was accompanied by increased low-level winds of over 25 m/s (around 90 km/h; Fig. 8b). Daily total precipitation reached over 50 mm (Fig. 8c) with the evolution of the low-level mesoscale low (Bech et al., 2013; Llasat et al., 2014). Although some lightning was also observed over Catalonia, Bech et al. (2013) concluded that it was strongly favored by the presence of tall telecommunication towers, and relatively unrelated to the most active precipitation areas.

3.3.1. Forecast performance

The ECMWF Integrated Forecasting System (IFS) HRES was predicting well the precipitation hotspot along the northern coast of Catalonia (Fig. 8f) with a lead time of one day. Wind gusts did not exceed 90 km/h as predicted by the model, but highest wind speed was measured along the coast according to the forecast (Fig. 8e). The model predicted snow at the coast, but here, a direct comparison with snow depth measurements is difficult due to unknown snow density.

3.3.2. Cascading effects

The city of Barcelona rarely experiences snowfall in March, and the previous snow event that affected the entire city occurred in December 2001. During the event of March 8, 2010, snow covered almost the entire city with snow depths varying between 3 cm near the sea and 20 cm at the Fabra Observatory located on the top of a hill (Bech et al., 2013). The event was special because of the unusual amount of widespread wet snow over the region, winds (particularly in the coastal areas) and the fact that it affected a very densely populated area. Newspapers reported that the event caused a “total collapse” and “chaos” of the city of Barcelona and the region.

In Fig. 9, the cascading effects of this event are illustrated. A widespread breakdown of road and train transport followed the snow event. More than 100 highways were affected by blocked cars in Barcelona, Girona, and Lleida, and numerous roads were closed or controlled with restrictions. For instance, the border with France at La Jonquera was closed, such that hundreds of cars and trucks were blocked on the highway between Girona and the French border (The Telegraph, 2010). In the city of Barcelona, urban buses were suspended (RTVE, 2010), affecting thousands of commuters and students. Several flights in Girona and Barcelona were also deviated or canceled.

In the coastal forest areas of Girona, wet snow combined with strong winds damaged the power line distribution, pulled down 36 high voltage power transmission towers, and caused hundreds of trees to fall down. Consequently, > 450,000 people or 200,000 households (RTVE, 2010) were affected by power outage over the following days. Forest losses from this event were quite substantial as well (150,000 ha, Llasat et al., 2014). Furthermore, the failure of a high voltage cable and falling trees caused several trains to stop. As a result, about 500 people (The Telegraph, 2010) were trapped in trains and train stations and had to be transported to sport centers to stay overnight.

The event had a major societal impact in Catalonia by generating some subsequent and unexpected secondary events of strong impact as illustrated in Fig. 9 (solid boxes in an event-based pathway scheme). There were a raised number of activities sharing the event pictures and videos on social networks and an exceptional amount of news articles reported in regional newspapers (Llasat et al., 2014).

3.3.3. Mitigation actions

Three days before the event, the Meteorological Service of Catalonia issued a first meteorological warning, as well as two press releases (Vilaclara et al., 2010). The day before the event (Sunday midday, March 7, 2012), the Civil Protection of Catalonia issued warnings for snow, wind and storm surges, including advice for municipalities and citizens (Generalitat de Catalunya, 2010). Some preventive works (e.g., reinforced fleet, taking boats out of the water, closure of some areas) were carried in the ports due to high waves (up to 8 m, Berghaenel, 2012) induced by strong winds near the coast. The advices for citizens were mostly regarding travelling by car, such as avoiding travelling if possible, otherwise consulting forecasts and road state, driving carefully, and exercise special caution driving large vehicles. The Meteorological Service of Catalonia also considered observations from spotters (Servei Meteorològic de Catalunya, 2018), which was extremely helpful for the correction of the forecast at the beginning of the event (Vilaclara et al., 2010). In Barcelona, 19 snowplows were working to ensure access to hospitals, firefighter centers and other key facilities. Blocked people were rescued from their cars on the highway and the coast was closed due to high waves. Weeks to months after the event, the regional government approved 23.5 Mio. Euro for forest cleanup operations, damage repair due to fallen trees, and reducing wildfire risks in the presence of dead trees (Llasat et al., 2014). In the above scheme of the cascading effect (Fig. 9), the mitigation actions are illustrated with dashed boxes.

4. A generalized approach to anticipate future freezing rain events

From the three case studies, we select the freezing rain event as an example to create a generalized pathway scheme. We create this graphic scheme based on the historical scheme (Section 3.2) and literature

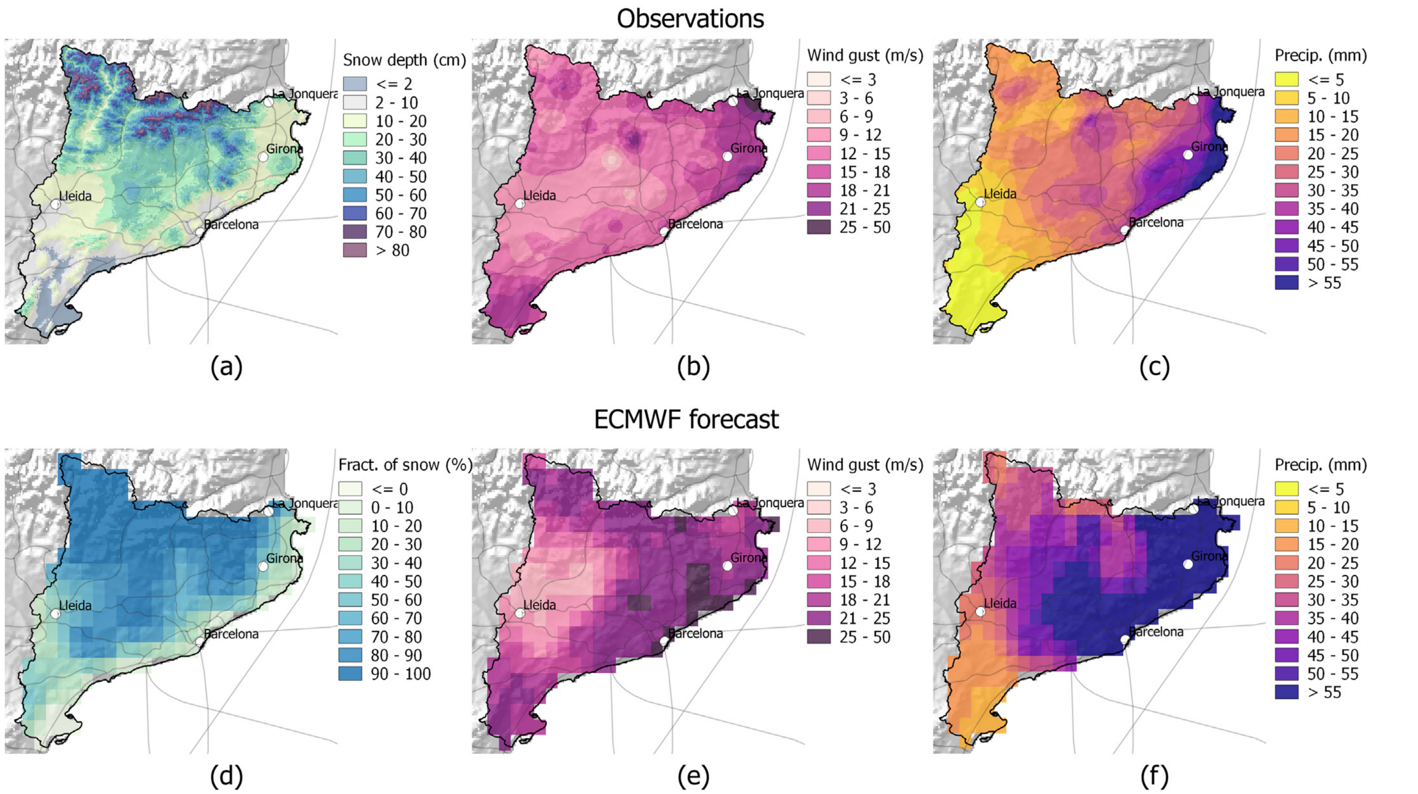

Fig. 8. (a) Snow depth (cm) from spotter data; (b) maximum wind gust (m/s) from automatic stations at 10 m above ground for the March 8, 2010 (08/03/2010 00:00 to 09/03/2010 00:00); (c) Precipitation (mm) from radar and station gauges. Forecast from ECMWF from March 7, 2010 00:00 am (for March 8, 00:00 am to March 9, 00:00 am UTC) for (d) fraction of snow of total precipitation; (e) maximum wind gust; and (f) total precipitation.

on similar events (Armenakis and Nirupama, 2014; Chang et al., 2007), complemented with experience by the co-authors (expert knowledge). The purpose of this approach is to visualize the prediction and the potential effects of future freezing rain event in relation to the occurrence time and to identify critical infrastructure and interdependencies that might cause major social and economic loss (Fig. 10).

The scheme illustrates that freezing rain can have a variety of effects, with the most common and severe being the loss of electrical power and related hazards (such as lack of heating affecting human health by fires, carbon monoxide poisoning or dropping temperatures in houses). Orange arrows indicate sectors affected by power outage and highlight the complex dependencies of the system on power supply. A blackout clearly acts as a source of amplification and power supply can therefore be identified as a critical infrastructure.

Complex interdependencies are not only related to power supply, but also appear between the different sectors, and increase the potential for cascading effects and disasters to occur (Pescaroli and Alexander, 2016). For example, road and train traffic is affected by diverse failures in the system: train lines and roads can be blocked by coated surfaces causing car accidents, but also by fallen trees or failing traffic lights. Traffic backup and cut off cities can then have further impacts on e.g., health or food supply.

The generalized scheme (Fig. 10) is also able to show the temporal dimension of an event cascade. Prior to the event occurrence, we placed “medium range forecast” and “nowcast”. Both forecast types are crucial elements for anticipating cascading effects of freezing rain events. Destroyed or damaged trees and a blackout due to affected power plants and/or power grid may happen very quickly after the event, affecting almost instantaneously money transfer, houses and buildings (including e.g. hospitals), communication, and traffic (including airports, trains, and roads). Severe consequences of a blackout to animal husbandry or food supply occur hours or days after an event and further sectors such as forestry or agriculture may be affected days to month after, if mitigation actions are insufficient.

5. Discussion

5.1. Benefits and challenges of pathway schemes

In the study reported here, we have demonstrated event-based pathway schemes to analyze case studies, based on which we designed a generalized pathway scheme for potential future events. Table 2 summarizes the main benefits and limitations of both approaches.

Event-based pathway schemes have been useful for an event analysis (with the possibility to analyze single branches or pathways separately) and may be a powerful tool to visualize the complex effects of a natural hazard for non-experts. Generalized pathway schemes, based on findings from past events, have several benefits; i) its potential to fill the gap of missing models for cascading events by the combination with expert knowledge, ii) its strength to identify complex interdependencies, effects that are not obvious and critical infrastructure (e.g. power disruption or transport systems) that could lead to loss of life and economic damage and thereby would be of help to anticipate future events (Chang et al., 2007).

One clear shortcoming of both schemes is the difficulty to represent the spatial extent of the event. In addition, the schemes can get complex and difficult to understand if complex interactions and interdependencies are considered. An additional challenge results from the need to include a series of boundary conditions (such as wood availability and supply or soil saturation in case 1). Key boundary conditions should be included in a scheme of potential cascading effect, since they have the potential to alter or increase the impact of the event. Key preconditions are e.g. the robustness of the infrastructure, disposition of emergency equipment and materials as well as the vulnerability and resilience of a society (Pescaroli and Alexander, 2016).

Different possibilities exist to include pathway schemes in risk

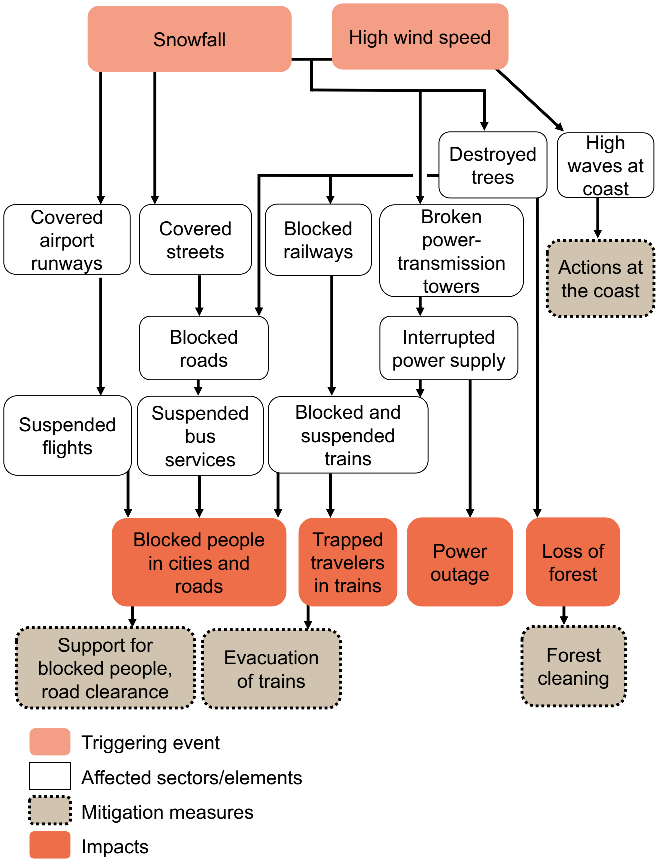

Fig. 9. Event-based pathway scheme of the cascading effects of the snowfall event with strong wind gusts on Monday, March 8, 2010 in Catalonia.

management, i.e. as a complement to existing maps and early warning systems. Generalized pathway schemes can also be used for an improved long-term planning. The example of the bark beetle outbreak in Slovenia shows quite clearly how economic impacts and losses in forestry can occur years after the freezing rain event. Generalized pathway schemes have different applications such as disaster management, warning and communication to a broad public, coordination of international collaboration and education of citizens or decision takers (May, 2007).

5.2. A framework of cascading effects

The three case studies confirm that it is indispensable to understand potential cascading effects before, during, and after an extreme precipitation event. Impacts were mitigated and avoided because key actors had an adequate understanding on the cascade of events, the critical elements or infrastructure (e.g. clogging of a weir in case 1 or power outage in cases 2 and 3) such as the most vulnerable elements (e.g. flood exposure of the Matte neighborhood area in Berne in case 1, farmers depending on electricity in case 2). For example, people in charge of natural risks and civil protection in the city of Berne (case 1) were aware of the clogging related to wood transport and made the crane operational in time to remove an element of the weir. In Slovenia (case 2), the international help with capacitated people could provide power generators to key institutions. In Barcelona (case 3), detailed warnings for traffic were released the day before and during the event and coastal areas were closed due to a risk of storm surges. Also for long-term management, it is important to know the potential cascading effects month to years after the event happened (e.g. risk for bark beetle pest in case 2 or forest fire in case 3 as a consequence of destroyed and fallen trees).

The case studies also show that a framework of cascading effects might be a useful tool in real-time risk management, even if the predictability of the triggering effect is limited (e.g. cases 1 and 2) and

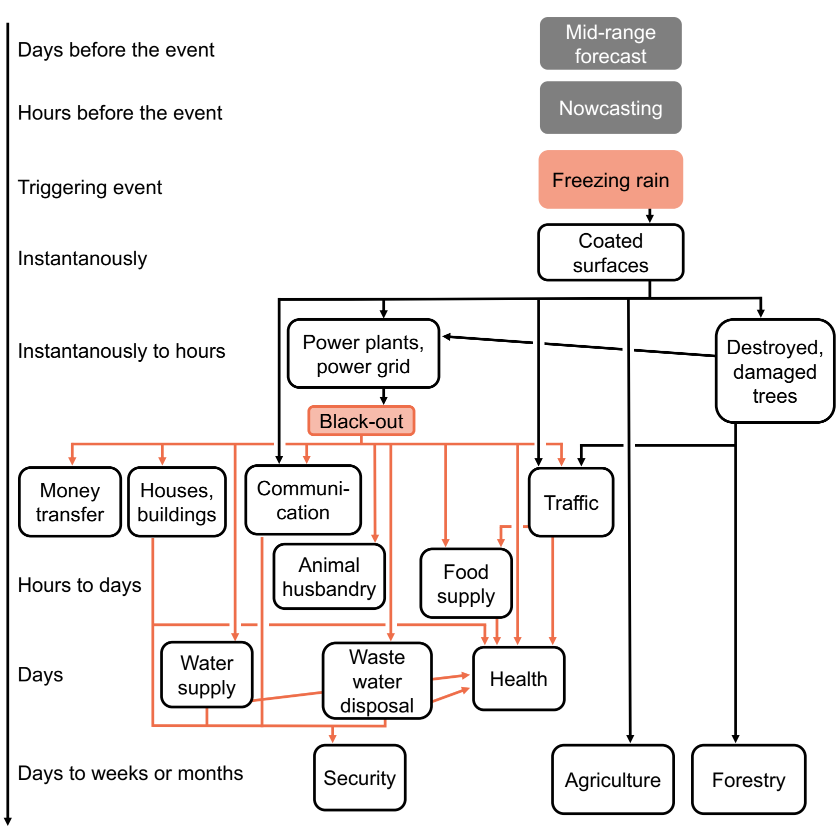

Fig. 10. Generalized pathway scheme of potential cascading effects of a freezing rain event. The cascade starts with the medium range forecast days in advance and the nowcasting, followed by the triggering event (freezing rain). The arrows show cascading effects on different sectors. The effects of electric power disruption are indicated by orange arrows to show the complex impacts of a disrupted critical infrastructure. The sectors are arranged according to their occurrence time before/after the triggering event. Industry and tourism are not considered here, but would mainly be affected days or weeks after the event. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Most important challenges and benefits of schemes of cascading effects.

	Benefits	Challenges
Event-based pathway schemes to analyze past events	• Branches and single pathways can be analyzed (May, 2007) • Represent strong tools to visualize complex effects of a triggering event • Offer different applications	• It is difficult to consider spatial extent
Generalized pathway schemes to analyze potential cascading events	• Complement numerical models • Interdependencies and critical infrastructure can be identified • The temporal dimension can be included • Can be combined with forecasts, early warning systems and maps • Are useful for long-term disaster planning • Offer different applications	• It is difficult to consider spatial extent • Key boundary conditions need to be included • The design of complex interdependencies is challenging • Schemes can get complex and difficult to understand

therefore hampering hazard anticipation. While the snowfall event in Barcelona was expected days in advance, both the convective precipitation in the Zulg river catchment and the freezing rain in Slovenia were difficult to predict. Substantial efforts are now being invested to improve the algorithms and the forecast of precipitation type with promising results for freezing rain (Gascón et al., 2018). Nevertheless, some precipitation events, such as convective precipitation in the Alps in summer, will remain uncertain in the future, hampering the operational prediction of cascading effects in some study sites or seasons. In order to overcome this problem, research efforts such as the EU funded H2020 ANYWHERE innovation project, aim at building a proof-of-concept Multi-Hazard Early Warning System (MH-EWS) to integrate information provided by state-of-the-art algorithms with less conventional data sources (e.g. radar, satellite imagery, social media information) to boost the predictive capabilities of models at the onset of a dangerous event. Although ANYWHERE is still ongoing, it holds promise for providing a comprehensive platform for the investigation of high-impact weather with a more data-driven approach.

As illustrated in case study 2, the forecast of a severe event may be quite uncertain for the medium range (e.g., 7 days), posing a challenge for the anticipation of cascading effects. A probability of occurrence of < 50% (Fig. 5a) for a severe event might be too low to take “expensive” actions. Mitigation actions for cascading effects therefore need to be a function of different factors of a forecasted or anticipated severe event such as its lead-time, occurrence probability and projected severity (in terms of intensity, extent, and duration). If the forecast predicts a severe freezing event 7 days in advance but with a low probability, professional emergency warning and response organizations need to be aware of a possible forthcoming severe cascading event – but no costly measures should be taken. Only few days before the event and according to the likelihood of occurrence, expensive actions (e.g. providing generators, warning public, mobilizing volunteers) need to be initiated.

A further challenge in assessing cascading effects is the increasing uncertainty along the cascade, schematically illustrated in Fig. 11. Uncertainty rises along the cascade because of the growing complexity and error propagation and the increasing influence of uncertain boundary conditions, but also due to limited knowledge. This is a commonly known phenomenon and described in IPCC WP2 as a “cascade of uncertainty” to refer to a process whereby uncertainty accumulates throughout the process of climate change prediction and impact assessment (IPCC WP2, Chapter 2.6.4. Aggregation and the Cascade of Uncertainty in IPCC WP2 report IPCC, 2014). The increasing uncertainty not only represents a challenge for modeling, but also for visualizing (Pappenberger et al., 2013) and communicating potential cascading effects to public planners and decision makers. The pathway scheme of cascading effect may be used to illustrate how the uncertainty is growing along the cascade and could be used to specifically explain and communicate the possible range of impacts of a certain triggering event and the uncertainty that needs to be accepted (Sword-Daniels et al., 2018) and included into natural hazard assessment (Beven et al., 2018).

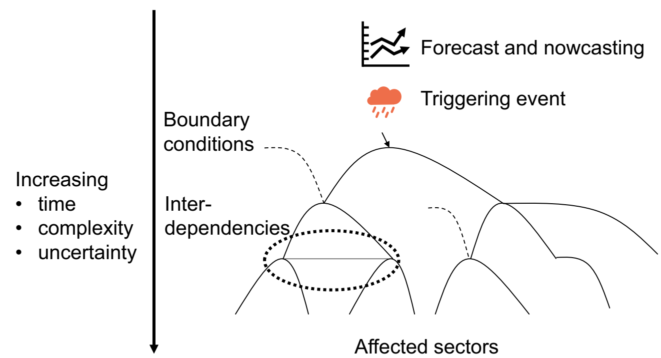

Fig. 11. Scheme of challenges of cascading effects. The triggering event forecast is already related to uncertainty (depending on the precipitation type, situation etc.). Along the cascade with increasing time and complexity, the uncertainty increases significantly. Interdependencies appear where several elements are interconnected and key boundary conditions control the cascade at certain points.

Interestingly, the three case studies indicate that the limited awareness of cascading effects may lead to dangerous situations. In the case of Catalonia, the civil protection issued a warning and suggested to travel only if urgently needed. Despite of clear contingency plans and recommendations to citizens one day in advance, thousands of people were travelling when the event occurred and numerous accidents happened (Amaro et al., 2010). Also case study 1 showed that a campsite close to the river was only evacuated thanks to a neighbor. This is in line with the observation that people living in mountainous regions are often not sufficiently aware of cascading effects of a thunderstorm in headwater catchments and related impacts along the river network (e.g. Scolobig et al., 2012) and tourist might be even less so conscious. It would be worthwhile to analyze hazard events more in-depth and unravel reasons for people's limited awareness for cascading effects (e.g. why did they travel despite of a warning?). Further research should focus on the potential of these schemes to better inform citizens about the possible cascading effects, impacts and uncertainties of an event, with the aim to raise the self-preparedness of the exposed population (e.g. a role-playing game ANYCaRE training tool, developed by ANYWHERE. Scholle et al., 2017).

In conclusion, a framework of cascading effects may help to further understand the complexity of natural hazards as well as natural and human systems and to assess vulnerability of these systems, which is crucial for risk reduction strategies (Mazzorana et al., 2018, 2019). Such a framework is especially supportive to show impacts that are not obvious, difficult to model or that might happen years after the event occurred. Despite of the challenges described above, a framework of cascading effects has a great potential to show critical infrastructure and complex interdependencies that need to be integrated into risk management decisions, mitigation and preparation strategies, as well as response and recovery. Decision makers greatly benefit from lessons learnt during past events; it is therefore vitally important to document the effects of complex interactions that would be likely ignored and/or underestimated. This paper is an effort in this direction but we hope that, in the future, there might be more effective ways of collecting knowledge from domain experts and distilling it into actionable insights.

6. Conclusions

In this work, we have presented three case studies to assess the applicability of a framework of cascading effects for anticipating precipitation-induced hazards prior the event occurrence. The analysis of the case studies using event-based pathway schemes showed that the knowledge of the decision makers on the system is crucial when it comes to anticipate hazards, and to prioritize resource allocation for mitigation and disaster risk reduction. But also the public's knowledge of possible cascading effects is a key element in hazard anticipation. Event-based pathway schemes of cascading effects support this key understanding of the natural and human systems and help detect the key contributing factors of a disaster: the triggering event, complex interdependencies, and interactions within the system and boundary conditions. Pathway schemes serve to identify critical infrastructure, that would intensify or prolong impacts and resulting damages/losses when affected.

The findings from the three case studies also confirm that it is not only difficult to forecast triggering events but also very challenging to model possible cascading effects for certain regions and hazard situations. To fill this gap, we suggest generalized pathway schemes of cascading effects. Such schemes are suitable to anticipate risk prior to event occurrence and to illustrate and forecast possible cascading effects of triggering events that are either predicted or occurring. Complex interactions between single hazards or impacts can be disentangled, but the schemes might get complex and difficult to understand when interdependencies are included. These schemes can complement forecast and multi-hazard models and can help deal in a graphical way with the growing uncertainty along the cascade, that needs to be accepted and communicated to affected citizens. Since the pathway schemes of cascading effects have difficulties to represent a spatial extent, they might be combined with risk maps or sequences of risk maps. In general, there are different aspects to consider when using a framework of cascading effects with pathway schemes:

- Such schemes should be adapted to different needs of the region and end users. For the experts, first responders and decision makers, it could be helpful to include critical infrastructures, complex interdependencies or time scales. For citizens, a simpler scheme is more convenient and has a great potential to complement text or map based warnings.
- A scheme of cascading effects in combination with forecast models could help anticipate natural hazards by preventing (e.g. wood monitoring and removal in a river bed), long-term planning (e.g. forest management), warning (e.g. showing not only a warning for a region of the triggering event, but also possible consequences) but also informing and rising awareness of the complexity of cascading consequences (e.g. news, social media, apps, schools, civic centers, institutions). A real-time constant update of the scheme would help mitigate or even avoid further steps along the sequence of potential events.

Cascading effects of extreme precipitation occur in most regions of the world, but depend on the geographic setting (e.g. vegetation, elevation, topography). We suggest that a framework of cascading effects may be applied to other regions and used to analyze past or potential dangerous events, to assess possibilities and limitations in forecasting such events or to identify critical infrastructure. Whereas the cascade of natural hazards might be transferable to other regions with a similar geographical setting, the local physical (e.g., proximity to disaster, power generation and transmission) or social vulnerability (e.g. decision making process in risk management) has to be carefully assessed.

We here assessed precipitation-triggered cascading effects, but other natural hazards can trigger similar sequences of effects and impacts. We suggest that the scheme may also be used for other types of weather and climate induced hazards such as droughts, storms, heatwaves, even earthquakes or volcanic eruptions. Future research may also focus on the combination of hazard and risk maps with cascading effects. It is also crucial to assess cascading effects in long-term planning, because not only the frequency and intensity of extreme events might increase due to a changing climate, but also the human system gets more interconnected and complex and current forecast models might not be robust against changing conditions.

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References

Agel, L., Barlow, M., Qian, J.-H., Colby, F., Douglas, E., Eichler, T., 2015. Climatology of daily precipitation and extreme precipitation events in the Northeast United States. J. Hydrometeorol. 16, 2537–2557. https://doi.org/10.1175/JHM-D-14-0147.1.

Amaro, J., Llasat, M.C., Aran, M., 2010. The social impact of the snowfall of 8 March 2010 in Catalonia. In: Plinius Conference on Mediterranean Storms, (Corfu Island Greece).

Armenakis, C., Nirupama, N., 2014. Urban Impacts of Ice Storms: Toronto December 2013. Nat. Hazards 1291–1298. https://doi.org/10.1007/s11069-014-1211-7.

Barlow, W., 1993. A new index for the prediction of deep convection. In: 17th Conference on Severe Local Storms. American Meteorological Society, St. Louis, MO, pp. 129–132.

Bech, J., Pineda, N., Rigo, T., Aran, M., 2013. Remote sensing analysis of a Mediterranean thundersnow and low-altitude heavy snowfall event. Atmos. Res. 123, 305–322. https://doi.org/10.1016/j.atmosres.2014.08.009.

Behie, A.M., Kutz, S., Pavelka, M.S., 2014. Cascading effects of climate change: do hurricane-damaged forests increase risk of exposure to parasites? Biotropica 46, 25–31. https://doi.org/10.1111/btp.12072.

Beniston, M., Farinotti, D., Stoffel, M., Andreassen, L.M., Coppola, E., Eckert, N., Fantini, A., Giacona, F., Hauck, C., Huss, M., Huwald, H., Lehning, M., López-Moreno, J.-I., Magnusson, J., Marty, C., Morán-Tejéda, E., Morin, S., Naaim, M., Provenzale, A., Rabatel, A., Six, D., Stötter, J., Strasser, U., Terzago, S., Vincent, C., 2018. The European mountain cryosphere: a review of its current state, trends, and future challenges. Cryosph 12, 759–794. https://doi.org/10.5194/tc-12-759-2018.

Berariu, R., Fikar, C., Gronalt, M., Hirsch, P., 2015. Understanding the impact of cascade effects of natural disasters on disaster relief operations. Int. J. Disaster Risk Reduct. 12, 350–356. https://doi.org/10.1016/j.ijdrr.2015.03.005.

Berghaenel, R.P., 2012. Temporal de nieve con tormenta del 8 de marzo de 2010 en Cataluña [WWW Document]. URL. https://www.tiempo.com/ram/13534/temporal-de-nieve-con-tormenta-del-8-de-marzo-de-2010-en-cataluna/, Accessed date: 18 November 2018.

Beven, K.J., Aspinall, W.P., Bates, P.D., Borgomeo, E., Goda, K., Hall, J.W., Page, T., Phillips, J.C., Simpson, M., Smith, P.J., Wagener, T., Watson, M., 2018. Epistemic uncertainties and natural hazard risk assessment – Part 2: What should constitute good practice? Nat. Hazards Earth Syst. Sci. 2769–2783. https://doi.org/10.5194/nhess-18-2741-2018.

Birkmann, J., 2006. Indicators and criteria for measuring vulnerability: theoretical bases and requirements. In: Birkmann, J. (Ed.), Measuring Vulnerability to Natural Disasters. United Nations University Press, pp. 55–77 ISBN-13: 978-92-808-1202-2.

Carrière, J.-M., Lainard, C., Le Bot, C., Robart, F., 2000. A climatological study of surface freezing precipitation in Europe. Meteorol. Appl. 238, 229–238.

Chang, S.E., McDaniels, T.L., Mikawoz, J., Peterson, K., 2007. Infrastructure failure interdependencies in extreme events: power outage consequences in the 1998 ice storm. Nat. Hazards 41, 337–358. https://doi.org/10.1007/s11069-006-9039-4.

Cheng, C.S., Auld, H., Li, G., Klaassen, J., Li, Q., 2007. Possible impacts of climate change on freezing rain in south-central Canada using downscaled future climate scenarios. Nat. Hazards Earth Syst. Sci. 7, 71–87. www.nat-hazards-earth-syst-sci.net/7/71/2007/.

CIPRA, 2016. Heisshunger auf Wald [WWW Document]. URL. https://www.cipra.org/de/news/heisshunger-auf-wald, Accessed date: 27 November 2018.

De Pippo, T., Donadio, C., Pennetta, M., Petrosino, C., Terlizzi, F., Valente, A., 2008. Coastal hazard assessment and mapping in Northern Campania, Italy. Geomorphology 97, 451–466. https://doi.org/10.1016/j.geomorph.2007.08.015.

Delmonaco, G., Margottini, C., Spizzichino, D., 2006a. ARMONIA Methodology for Multi-Risk Assessment and the Harmonisation of Different Natural Risk Map (Deliverable 3.1.1). Rome. (Armonia project).

Delmonaco, G., Margottini, C., Spizzichino, D., 2006b. Report on New Methodology for Multi-risk Assessment and the Harmonisation of Different Natural Risk Maps (Deliverable 3.1). Rome. (Armonia project).

European Commission Joint Research Centre, 2014. Floods in Slovenia (2014-02-11) [WWW Document]. Eur. Comm. Jt. Res. Cent dataset. URL. http://data.europa.eu/89h/208a9349-41d1-40d6-a30e-7b4d0fe18616, Accessed date: 27 November 2018.

Flussbau AG, 2012. Hochwasser vom 4. Juli 2012 in der Zulg - Ereignisanalyse 9.11.2012 - Jahresschlussrapport ZSO Steffisburg-Zulg. Bern.

FOEN, 2008. The Floods of 2005 in Switzerland - Synthesis Report on the Event Analysis.

FOEN, 2018. Hydrodaten [WWW Document]. URL. https://www.hydrodaten.admin.ch, Accessed date: 24 October 2018.

Forbes, R., Tsonevsky, I., Hewson, T., Leutbecher, M., 2014. Towards predicting high-impact freezing rain events. ECMWF Newsl. 141, 15–21.

Frei, C., Davies, H.C., Gurtz, J., Schär, C., 2000. Climate dynamics and extreme precipitation and flood events in Central Europe. Integr. Assess. 1, 281–299.

Frey, H., Huggel, C., Schneider, D., Schaub, Y., García Hernández, J., Portocarreo, C., 2016. Prozesskaskaden und ihre Modellierung. Agenda FAN. 2. pp. 3–7.

Gascón, E., Hewson, T., Haiden, T., 2018. Improving predictions of precipitation type at the surface: description and verification of two new products from the ECMWF ensemble. Weather Forecast. 33, 89–108. https://doi.org/10.1175/WAF-D-17-0114.1.

Generalitat de Catalunya, 2010. Protecció Civil activa la fase d'alerta del pla Neucat i el Procicat per l'estat de la mar i del vent [WWW Document]. URL. https://govern.cat/salapremsa/notes-premsa/25962/proteccio-civil-activa-fase-dalerta-neucat-procicat-lestat-mar-vent, Accessed date: 18 November 2018.

George, J.J., 1960. Weather Forecasting for Aeronautics. Academic Press, New York and London.

Gill, J.C., Malamud, B.D., 2014. Reviewing and visualizing the interactions of natural hazards. Rev. Geophys. 52, 680–722. https://doi.org/10.1002/2013RG000445.

Gill, J.C., Malamud, B.D., 2016. Hazard interactions and interaction networks (cascades) within multi-hazard methodologies. Earth Syst. Dyn. 7, 659–679. https://doi.org/10.5194/esd-7-659-2016.

Graham, E., Koffi, E.N., Mätzler, C., 2012. An observational study of air and water vapour convergence over the Bernese Alps, Switzerland, during summertime and the development of isolated thunderstorms. Meteorol. Zeitschrift 21, 561–574. https://doi.org/10.1127/0941-2948/2012/0347.

de Groot, M., Ogris, N., Kobler, A., 2018. The effects of a large-scale ice storm event on the drivers of bark beetle outbreaks and associated management practices. For. Ecol. Manag. 408, 195–201. https://doi.org/10.1016/j.foreco.2017.10.035.

Han, J., Wu, S., Wang, H., 2007. Preliminary study on geological hazard chains. Earth Sci. Front. 14, 11–23.

Helbing, D., Ammoser, H., Kühnert, C., 2006. Disasters as Extreme Events and the Importance of Network Interactions for Disaster Response Management. In: Albeverio, S., Jentsch, V., Kantz, H. (Eds.), Extreme Events in Nature and Society. The Frontiers Collection, Springer, Berlin, Heidelberg.

Huang, W., Yang, Z., He, X., Lin, D., Wang, B., Wright, J.S., Chen, R., Ma, W., Li, F., 2018. A possible mechanism for the occurrence of wintertime extreme precipitation events over South China. Clim. Dyn. 0, 1–18. https://doi.org/10.1007/s00382-018-4262-8.

Huntrieser, H., Schiesser, H.H., Schmid, W., Waldvogel, A., 1997. Comparison of traditional and newly developed thunderstorm indices for Switzerland. Weather Forecast. 12, 108–125.

Hunziker Gefahrenmanagement, 2017. Schwemmholz Zulg. Untersuchungen zum Schwemmholzaufkommen in der Zulg und deren Seitenbächen. Gemeinde Steffisburg.

Huss, M., Sold, L., Hoelzle, M., Stokvis, M., Salzmann, N., Farinotti, D., Zemp, M., 2013. Towards remote monitoring of sub-seasonal glacier mass balance. Ann. Glaciol. 54, 75–83. https://doi.org/10.3189/2013AoG63A427.

IFRC, 2014. Emergency Plan of Action - Final Report Slovenia: Extreme Winter Conditions.

IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. (Geneva, Switzerland).

Irland, L.C., 2000. Ice storms and forest impacts. Sci. Total Environ. 262, 231–242.

Joyce, J., Chang, N., Harji, R., Ruppert, T., Singhofen, P., 2017. Cascade impact of hurricane movement, storm tidal surge, sea level rise and precipitation variability on flood assessment in a coastal urban watershed. Clim. Dyn. 51, 383–409. https://doi.org/10.1007/s00382-017-3930-4.

Kappes, M.S., Keiler, M., von Elverfeldt, K., Glade, T., 2012. Challenges of analyzing multi-hazard risk: a review. Nat. Hazards 64, 1925–1958. https://doi.org/10.1007/s11069-012-0294-2.

Kinzig, A.P., Ryan, P., Etienne, M., Allison, H., Elmqvist, T., Walker, B.H., 2018. Resilience and regime shifts: assessing cascading effects. Ecol. Soc. 11.

Kumasaki, M., King, M., Arai, M., Yang, L., 2016. Anatomy of cascading natural disasters in Japan: main modes and linkages. Nat. Hazards 80, 1425–1441. https://doi.org/10.1007/s11069-015-2028-8.

Kunkel, K.E., 2003. North American trends in extreme precipitation. Nat. Hazards 29, 291–305.

Kunz, M., 2007. The skill of convective parameters and indices to predict isolated and severe thunderstorms. Nat. Hazards Earth Syst. Sci. 7, 327–342. www.nat-hazards-earth-syst-sci.net/7/327/2007/.

Lavers, D.A., Villarini, G., 2013. The nexus between atmospheric rivers and extreme precipitation across Europe. Geophys. Res. Lett. 40, 3259–3264. https://doi.org/10.1002/grl.50636.

Liu, B., Siu, Y.L., Mitchell, G., 2016. Hazard interaction analysis for multi-hazard risk assessment: a systematic classification based on hazard-forming environment. Nat. Hazards Earth Syst. Sci. 16, 629–642. https://doi.org/10.5194/nhess-16-629-2016.

Llasat, M.C., Turco, M., Quintana-Seguí, P., Llasat-Botija, M., 2014. The snow storm of 8 March 2010 in Catalonia (Spain): a paradigmatic wet-snow event with a high societal impact. Nat. Hazards Earth Syst. Sci. 14, 427–441. https://doi.org/10.5194/nhess-14-427-2014.

Markosek, J., 2014. Severe freezing rain in Slovenia. The European Forecaster 38–42.

Marzocchi, W., Garcia-Aristizabal, A., Gasparini, P., Mastellone, M.L., Di Ruocco, A., 2012. Basic principles of multi-risk assessment: a case study in Italy. Nat. Hazards 62 (2), 551–573.

May, F., 2007. Cascading disaster models in postburn flash flood. In: Butler, B.W., Cook, W. (Eds.), The Fire Environment—Innovations, Management, and Policy; Conference Proceedings. US Department of Agriculture, Forest Service, Fort Collins, CO, pp. 443–464.

Mazzorana, B., Ruiz-Villanueva, V., Marchi, L., Cavalli, M., Gems, B., Gschnitzer, T., Iroumé, A., Valdebenito, G., 2018. Assessing and mitigating large wood-related hazards in mountain streams: recent approaches. J. Flood Risk Manag. 11, 207–222. https://doi.org/10.1111/jfr3.12316.

Mazzorana, B., Picco, L., Rainato, R., Iroumé, A., Ruiz-Villanueva, V., Rojas, C., Valdebenito, G., Iribarren-Anacona, P., Melnick, D., 2019. Cascading processes in a changing environment: disturbances on fluvial ecosystems in Chile and implications for hazard and risk management. Sci. Total Environ. 655, 1089–1103. https://doi.org/10.1016/j.scitotenv.2018.11.217.

Mehta, M., Shukla, T., Bhambri, R., Gupta, A.K., Dobhal, D.P., 2017. Terrain changes, caused by the 15–17 June 2013 heavy rainfall in the Garhwal Himalaya, India: a case study of Alaknanda and Mandakini basins. Geomorphology 284, 53–71. https://doi.org/10.1016/j.geomorph.2016.11.001.

Nguyen, H.T., Wiatr, T., Fernández-Steeger, T.M., Reicherter, K., Rodrigues, D.M.M., Azzam, R., 2013. Landslide hazard and cascading effects following the extreme rainfall event on madeira Island (February 2010). Nat. Hazards 65, 635–652. https://doi.org/10.1007/s11069-012-0387-y.

Pappenberger, F., Stephens, E., Thielen, J., Salamon, P., Demeritt, D., vanAndel, J.S., Wetterhall, F., Al, L., 2013. Visualizing probabilistic flood forecast information: expert preferences and perceptions of best practice in uncertainty communication. In: Hydrocarb. Process. 146. pp. 132–146. https://doi.org/10.1002/hyp.9253.

Pescaroli, G., Alexander, D., 2015. A definition of cascading disasters and cascading effects: Going Beyond the “toppling dominos” Metaphor. planet@risk 3 (1), 58–67.

Pescaroli, G., Alexander, D., 2016. Critical infrastructure, panarchies and the vulnerability paths of cascading disasters. Nat. Hazards 82, 175–192. https://doi.org/10.1007/s11069-016-2186-3.

Peters, K., Buzna, L., Helbing, D., 2008. Modelling of cascading effects and efficient response to disaster spreading in complex networks. Int. J. Crit. Infrastrucutres 4, 46–62. https://doi.org/10.1504/IJCIS.2008.016091.

Ralph, F.M., Rauber, R.M., Jewett, B.F., Kingsmill, D.E., Pisano, P., Pugner, P., Rasmussen, R.M., Reynolds, D.W., Schlatter, T.W., Stewart, R.E., Tracton, S., Waldstreicher, J.S., 2014. Improving short-term (0–48 h) cool-season quantitative precipitation forecasting: recommendations from a USWRP workshop. In: Cool-Season Quantitative Precipitation Forecasting Workshop. American Meteorological Society, Boulder, Colorado, pp. 1619–1632. https://doi.org/10.1175/BAMS-86-11-1619.

RTVE, 2010. La mayor nevada en 50 años paraliza Cataluña y deja sin luz a 200.000 hogares [WWW Document]. URL. http://www.rtve.es/noticias/20100308/mayor-nevada-50-anos-paraliza-cataluna-deja-sin-luz-200000-hogares/322750.shtml, Accessed date: 18 November 2018.

Ruiz-Villanueva, V., Piégay, H., Gurnell, A.M., Marston, R.A., Stoffel, M., 2016. Recent advances quantifying the large wood dynamics in river basins: new methods and remaining challenges. Rev. Geophys. 54, 611–652. https://doi.org/10.1002/2015RG000514.

Ruiz-Villanueva, V., Mazzorana, B., Bladé, E., Bürkli, L., Iribarren-Anacona, P., Mao, L., Nakamura, F., Ravazzolo, D., Rickenmann, D., Sanz-Ramos, M., Stoffel, M., Wohl, E., 2019. Characterization of wood-laden flows in rivers. Earth Surf. Process. Landf. https://doi.org/10.1002/esp.4603.

Schaub, Y., Haeberli, W., Huggel, C., Künzler, M., Bründl, M., 2013. Landslides and new lakes in deglaciating areas: a risk management framework a risk management framework. In: Landslide Science and Practice. Springer, Berlind, Heidelberg, pp. 31–38. https://doi.org/10.1007/978-3-642-31313-4.

Schneider, D., Huggel, C., Cochachin, A., Guillén, S., García, J., 2014. Mapping hazards from glacier lake outburst floods based on modelling of process cascades at Lake 513, Carhuaz, Peru. Adv. Geosci. 35, 145–155. https://doi.org/10.5194/adgeo-35-145-2014.

Schneiderbauer, S., Calliari, E., Eidsvig, U., Hagenlocher, M., 2017. The most recent view of vulnerability. In: Poljansek, K., Ferrer, M., De Groeve, T., Clark, I. (Eds.), Science

for Disaster Risk Management 2017: Knowing Better and Losing Less. Publications Office of the European Union, Luxembourg, pp. 68–82.
Scholle, P., Schäfer, C., Habdank, M., Pottebaum, J., Ruin, I., Terti, G., Capone, F., Venier, S., Lorini, V., Marras, I., Pylkkö, P., Sancho, D., Tesfai, I., Brune, M., Rodehutskors, N., Nowak, R., Sempere-Torres, D., 2017. Supporting Innovation for Self-preparedness and Self-protection: Good Practices, Approaches, Guidelines and Constraints (Deliverable. 5.1). "ANYWHERE Project", available on http://www.anyshwere-h2020.eu/.
Scolobig, A., De Marchi, B., Borga, M., 2012. The missing link between flood risk awareness and preparedness: findings from case studies in an Alpine. Nat. Hazards 63, 499–520. https://doi.org/10.1007/s11069-012-0161-1.
Servei Meteorològic de Catalunya, 2018. Vigilància meteorològica [WWW Document]. URL. http://www.meteo.cat/observacions/xom_vigilancia, Accessed date: 18 November 2018.
Setola, R., Rosato, V., Kyriakides, E., Rome, E., 2016. Managing the complexity of critical infrastructures - A modelling and simulation approach. In: Studies in Systems, Decision and Control. 90 SpringerLink. https://doi.org/10.1007/978-3-319-51043-9.
Showalter, A.K., 1953. A stability index for thunderstorm forecasting. Bulletin Am. Meteorol. Soc. 34, 250–252.
Sideris, I.V., Gabella, M., Sassi, M., Germann, U., 2014. The CombiPrecip experience: development and operation of a real-time radar raingauge combination scheme in Switzerland. In: International Symposium Weather Radar and Hydrology, pp. 7–9 Washington, DC, USA.
Smith-McKenna, E.K., Malanson, G.P., Resler, L.M., Carstensen, L.W., Prisley, S.P., Tomback, D.F., 2014. Cascading effects of feedbacks, disease, and climate change on alpine treeline dynamics. Environ. Model. Softw. 62, 85–96. https://doi.org/10.1016/j.envsoft.2014.08.019.
Somos-Valenzuela, M.A., Chisolm, R.E., Rivas, D.S., Portocarrero, C., Mckinney, D.C., 2016. Modeling a glacial lake outburst flood process chain: the case of Lake Palcacocha and Huaraz, Peru. Hydrol. Earth Syst. Sci. 20, 2519–2543. https://doi.org/10.5194/hess-20-2519-2016.
Steeb, N., Rickenmann, D., Badoux, A., Rickli, C., Waldner, P., 2017. Large wood recruitment processes and transported volumes in Swiss mountain streams during the extreme flood of August 2005. Geomorphology 279, 112–127. https://doi.org/10.1016/j.geomorph.2016.10.011.
Stoffel, M., Corona, C., 2018. Future winters glimpsed in the Alps. Nat. Geosci. 11, 458–460. https://doi.org/10.1038/s41561-018-0177-6.
Sword-Daniels, V., Eriksen, C., Hudson-Doyle, E., Alaniz, R., Adler, C., Schenk, T., Vallance, S., 2018. Embodied uncertainty: living with complexity and natural hazards. J. Risk Res. 21, 290–307. https://doi.org/10.1080/13669877.2016.1200659.
Tarvainen, T., Jarva, J., Greiving, S., 2006. Spatial pattern of hazards and hazard interactions in Europe. In: Schmidt-Thomé, P. (Ed.), Natural and Technological Hazards and Risks Affecting the Spatial Development of European Regions, Special Paper 42. Geological Survey of Finland, pp. 83–91.
The Telegraph, 2010. Barcelona hit with heaviest snowfall in 25 years. [WWW Document]. URL. http://www.telegraph.co.uk/news/worldnews/europe/spain/7401422/Barcelona-hit-with-heaviest-snowfall-in-25-years.html, Accessed date: 18 November 2018.
UNISDR, 2015. Sendai framework for disaster risk reduction 2015–2030. [WWW Document]. URL. www.unisdr.org.
Vilaclara, E., Segalà, S., Andrés, A., Aran, M., 2010. Operational warnings issued by the SMC in the 8th March snow event in Catalonia. In: Plinius Conference on Mediterranean Storms, (Corfu Island Greece).
WMO, 2012. International Glossary of Hydrology. World Meteorological Organization (WMO), Geneva.
Worni, R., Huggel, C., Stoffel, M., 2013. Glacial lakes in the Indian Himalayas - from an area-wide glacial lake inventory to on-site and modeling based risk assessment of critical glacial lakes. Sci. Total Environ. 468, 71–84. https://doi.org/10.1016/j.scitotenv.2012.11.043.
Xu, J., Grumbine, R.E., Shresta, A., Eriksson, M., Yang, X., Wang, Y., Wilkes, A., 2009. The melting Himalayas: cascading effects of climate change on water, biodiversity, and livelihoods. Conserv. Biol. 23, 520–530. https://doi.org/10.1111/j.1523-1739.2009.01237.x.
Zscheischler, J., Westra, S., van den Hurk, B.J.J.M., Seneviratne, S.I., Ward, P.J., Pitman, A., AghaKouchak, A., Bresch, D.N., Leonard, M., Wahl, T., Zhang, X., 2018. Future climate risk from compound events. Nat. Clim. Chang. https://doi.org/10.1038/s41558-018-0156-3.