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Participatory development of storymaps to visualize the spatiotemporal dynamics and impacts of extreme flood events for disaster preparedness

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ABSTRACT

Floods are one of the costliest natural hazards in Switzerland and worldwide. Therefore, society is confronted with questions about protecting people and assets from flood risks. Key instruments are protective measures, land use regulations, spatial planning, and the interventions by civil protection units if flood magnitudes exceed the protection standards. Both prevention and preparedness require risk awareness from professionals, politicians, and the public. Risk awareness is generally high after an event and low after a period without major events. However, the rarity of extreme flood events limits learning from flood events. The training of intervention forces who should manage flood events with magnitudes beyond hitherto observed flood events requires a comprehensive description and visualization of the flood processes and their impacts. To address this, together with stakeholders and civil protection and intervention planning experts, we co-developed a new way to visualize the spatiotemporal dynamics of extreme flood events and thereby communicate their impacts using dynamical flood storymaps. We selected physically plausible precipitation scenarios from reforecasts to develop storylines of extreme river flood events and their socioeconomic impacts in Switzerland. The co-development process revealed which information is relevant to potential users and how it must be presented. It is shown that storylines of extreme events presented as storymaps are a valuable tool to communicate scientific results in a way that allows practitioners to gain relevant information for their work. Therefore, we built an interactive online tool (www.flooddynamics.ch), enabling the user to analyze the spatiotemporal unfolding of flood events in Switzerland from the start of precipitation to the recession of the flood. The visualization includes maps of inundated areas at hourly timesteps and the related impacts in terms of affected persons, buildings, roads, and infrastructure. Such a temporally explicit (dynamic) representation of extreme events in storymaps, in contrast to static hazard maps, which are commonly used today, is favorable for emergency intervention planning and training and thus for awareness creation and better disaster preparedness.

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1. Introduction

Flood risks in Europe are expected to increase due to increasing socio-economic exposure in flood-prone areas [1,2] and the changing climate e.g., [3]. The frequency and intensity of extreme precipitation events are expected to increase in Switzerland with climate change [4]. How flood risk evolves in the future depends on how precipitation and runoff change [5–7], but equally important is how societies respond to and manage the expected environmental changes e.g., [8,9]. To mitigate flood risk, knowledge about flood risks and risk awareness among professionals and the public is essential [10].

Flood risk awareness in Switzerland and other central European countries is generally low [10–13] but increased after a flood event occurred, as shown by Kreibich et al. [14] for particular events in 2002 and in 2006 in Germany and generally by Messner and Meyer [15] and Maidl et al. [12]. The subjective risk perception largely depends on the perceived probability of the natural hazards and on personal experience [12,16]. Both risk awareness and the willingness to invest in flood prevention correlate significantly with personally experienced natural hazard events [12,17,18]. Indeed, there are several examples where public investment in flood protection was only made after an event [19]. Hence, flood protection measures are often reactive measures rather than preventive actions when recent flood experiences and/or memory of flood events are lacking. The review by Andráško [16] shows that private flood protection measures are not widely implemented, and often the responsibility is passed from the homeowners to the authorities.

In addition, a long period without major flood events leads to fading memory (both public and personal memory). Pfister [20] discussed this issue and showed how this leads to an underestimation of natural hazards and low risk awareness. The direct confrontation with the risk increases the relative importance of it, and repeated (indirect) confrontation aids in better recalling previous risk experiences [12,17]. The availability bias brought up by the psychologists Tversky and Kahneman [21] may explain why: we tend to underestimate the probability of an event if we do not remember a similar experience. This ties in with Tulving's [22] distinction between semantic memory, for generalized knowledge, and episodic memory, supporting spatiotemporal relations. We tend to act based on information in the episodic memory rather than in the semantic memory.

The challenge in flood risk management, especially in risk communication, is that extreme flood events are, by definition, very rare. Thus, learning from experience is limited. Imagining an extreme flood event and its impact without previous experience of flood events with similar magnitudes is difficult. Awareness rising thus requires the development of methods that allow for visualizing and imagining the impacts of extreme flood events without suffering the associated losses. This can be achieved with physical models. The goal of flood risk communication with the help of physical model scenarios is comparable to what is traditionally achieved through research of historical events. It shows the range of possible events and, with this makes the unthinkable tangible [20].

In addition, communicating physically plausible extreme weather events is interesting, not only to provide an idea of the possible extreme of weather events today but also to promote the idea of which extreme weather events are possible and more probable with climate change [23–26].

Science communication in the form of narratives or stories offers the advantage of connecting scientific information with peoples' daily experiences and practices, helping to convey scientific content in a more accessible form [18,27,28]. This allows more recipients (users) to give meaning to the information, i.e., to 'translate' abstract information into individual imaginaries, allowing to include the new information into action in the specific form the recipient perceives as meaningful [29]. This is a personal process, and hence the process of gaining new insight happens in the individual social and cultural context, depending, among other factors, on the location [30–32]. This makes maps a helpful tool for communicating complex localized information. Dynamic maps (which include a time component) furthermore may support the learning process because the mental representation of the memory is structured spatially and temporally [33–35].

Storylines or narratives about flood risks embedded in a person's geographic environment appeal to the episodic memory. By this means, they allow the newly learned information to be connected to the personal environment and experiences [23]. The concept of storylines was introduced to flood risk analysis and management by de Bruijn et al. [36]. They suggested applying the approach to facilitate the communication of physically plausible flood events and as a means for stakeholders to analyze critical infrastructure vulnerability and develop emergency response plans. Shepherd et al. [23] defined storylines as "physically self-consistent unfolding of past events, or of plausible future events or pathways". Physically consistent storylines, or "tales of future weather" as Hazeleger et al. [37] call them, complement probabilistic approaches by describing future possible weather events. They are not predictions of future weather; therefore, no probability is assessed. In contrast to probabilistic methods, the focus is on understanding the driving factors of an event and its consequences. This allows the inclusion of qualitative statements from (local) experts. Storylines can include a time component, i.e., the sequence of an event, this is additional information compared to the most commonly used static mapping approaches for natural hazards. Furthermore, isolating single (extreme) events instead of the model ensemble mean is insightful if the physically possible rather than the statistically probable event is of interest [23].

A successful transition from basic research to applied research and to practice is further facilitated by including stakeholders in a development process [26,38]. To collaborate with stakeholders during the entire development process is sometimes called bottom-up in contrast to the top-down approach, where scientists assume the needs of practitioners [39]. It allows scientists and practitioners to learn about each other's needs as well as about technical and scientific limitations. Such collaboration consequently fosters the compilation of application-relevant scientific findings in a form that can be integrated by practitioners in their work and that serves as a basis for decision-makers e.g. [40–43]. User involvement furthermore makes the product and its functionality known among future users [44], who then value the product more because they contributed to it [45].

However, the question is how to involve users in the development. In this process, the following questions arise: How can we transfer the knowledge gained from flood risk and flood impact research into a form that is useful for stakeholders in flood risk management? What are the stakeholder's needs and requirements for such an application? How does the storylines approach support the goals mentioned above?

Our working hypothesis is that the concept of storylines can be incorporated into dynamic storymaps for visualizing the spatiotemporal unfolding of extreme flood events and their impacts on society and provide a valuable means for visualizing targeted information for stakeholders in flood risk management. We selected members of intervention forces and civil protection units involved in emergency management and training as key user groups of the storymaps tool. A second user group is insurance companies.

Therefore, the project aimed to use the existing tools from science as a resource to build an application to assess and communicate flood risks to practitioners in civil protection and flood intervention planning.

Our research questions therefore are:

How can scientific information on extreme precipitation, floods, and flood impacts be conveyed in a way that allows the recipients (the users) to gain relevant information for their practical work?

How can the storyline approach support the communication of scientific information on extreme precipitation, floods, and flood impacts to practitioners in flood management?

2. Methods

With the development of online flood storymaps, we apply the storyline approach to assess and communicate impacts of extreme flood events in Switzerland. This risk communication approach aims at describing and understanding the physical driving factors, their spatiotemporal evolution, and the socio-economic consequences of flood events. The cartographic visualization of the storylines of extreme flood events was developed in a form that meets the needs of the target user group, namely emergency managers in training intervention forces and preparedness planning. The interactive online tool to generate the flood storymaps was therefore co-developed with experts in regional flood intervention, intervention planning, and civil protection. Experts contributed knowledge on which flood indicators are of value to them and in which form such information must be provided to be useful for practical application.

The development is based on two main steps. First, a physical modeling system was developed that simulates the spatiotemporal dynamics of flood events and their impacts based on precipitation and weather information. Second, the way how the modeling results were visualized and published was developed in a participatory approach (Fig. 1). The latter included interviews and workshops for exploration, consolidation, and production. Both steps together lead to the interactive storymaps web tool.

2.1. Physical modeling

The basis of the storymaps tool is a comprehensive model chain that simulates the hydrology of the main rivers and lakes, inundation hydraulics, and flood impacts. The meteorological observational records are relatively short and hence contain only a limited number of extreme events [46]. Therefore, we used extreme precipitation events from two hindcast archives of the European Centre for Medium-range Weather Forecasts (ECMWF) following the UNSEEN (Unprecedented Simulated Extreme Ensemble) [47] approach. Using hindcast archives as a source to select extreme events as scenarios provides a pool of physically plausible weather events. The extreme precipitation events were selected from a combined dataset of 8490 years of hindcasts from ECMWF (ENSext (1998–2017) and SEAS5 (1981–2017) [48,49]). The ECMWF data has a 6-h temporal resolution and was disaggregated to hourly resolution using linear interpolation. The reforecast data was downscaled from a regular 0.4° grid to a spatial resolution of 2 km × 2 km using quantile-mapping [50,51]. Events were selected in a workshop with stakeholders to make a choice that meets the different needs. The selected events were used as input scenarios for the hydrological model DECIPHeR [52], which covers the headwater catchments of the main rivers and lakes in Switzerland north of the Alps, including catchments of the neighboring countries (Fig. 2). For details on the modeling approach, see Zischg [53].

The hydrological model results were used for the hydraulic inundation modeling with the flow simulation environment BASEMENT-ETHZ [54]. This software can simulate river hydraulics in a coupled 1D/2D model. River cross-profile measurements for the 1D module stem from the Federal Office for the Environment, and digital terrain models (DTMs) were provided by the cantons [55–61], the Federal Office of Topography [62], or the Land of Baden-Württemberg (Regierungspräsidium Freiburg/FOEN, [63]. The

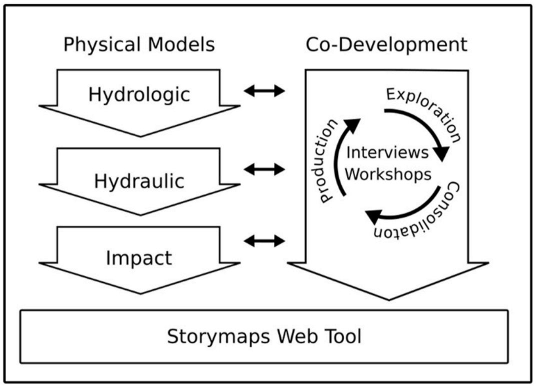


Fig. 1. Schematic illustration summarizing the development process.

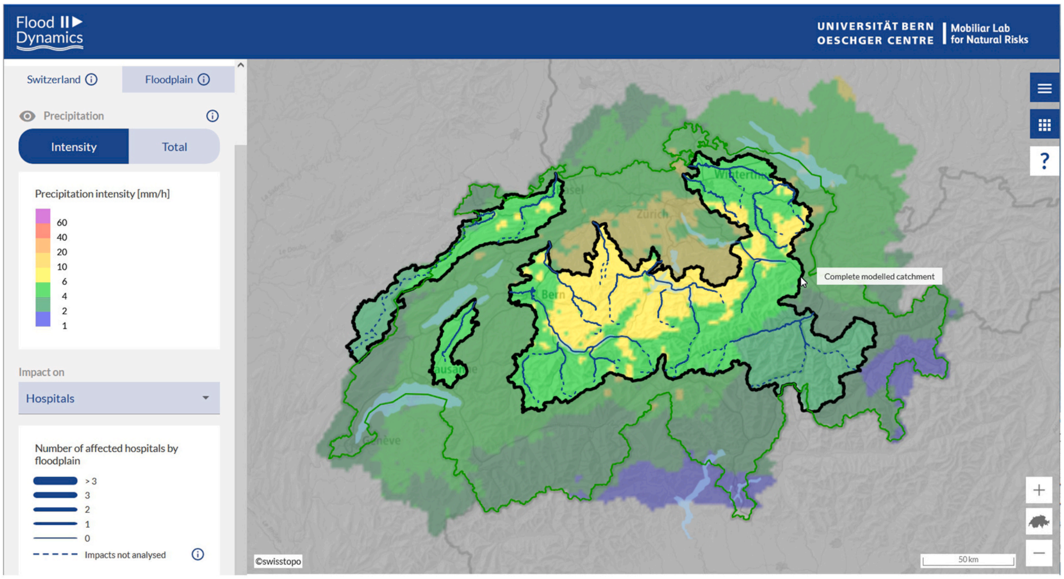


Fig. 2. Screenshot of the online tool. The colored area covers the hydrological domain of Switzerland. The light green line is the border of Switzerland. The areas surrounded in black are the modeled catchments. Solid blue lines show the modeled rivers, and dashed blue lines show rivers that were not included.

computation of the 2D model is based on a triangulated irregular mesh with a maximum mesh size of 200 m^2, built with the meshing module BASEmesh [64]. Applying a single model for Switzerland at this spatial resolution and with a temporal resolution of 1 h is computationally very expensive. Therefore, the modeled domain was subdivided into floodplains that a) are topographically closed, i.e., possible floods in the floodplain are not partitioned by the model boundary, and b) have a significant increase in catchment size due to a confluence with a tributary stream (Fig. 3). The hydrological model was set up to provide hydrographs as input to the hydraulic model at the upper boundary of the floodplains. The hydraulic model was validated by Zischg et al. [65] and Zischg et al. [66].

The 2D model provides the flow depth and velocity per mesh element at an hourly timestep. The flow depth and velocity are the input for the impact model. The impact model contains a dataset of the elements at risk, i.e., a dataset of the buildings including information on the number of residents, workplaces, and building values; a dataset of schools, hospitals, and nursing homes with the number of beds in nursing homes; as well as a dataset of roads. The building dataset was developed by Röthlisberger et al. [67] based

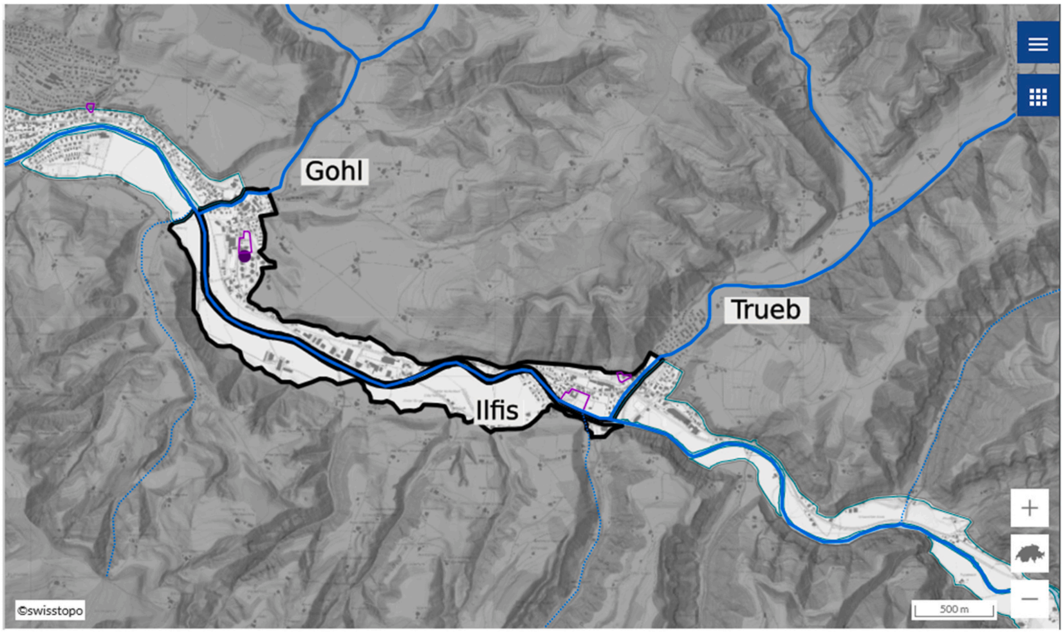


Fig. 3. Screenshot of the online storymaps tool highlighting the floodplain of one river section in black: the domain of one river section of the river Ilfis between the confluence with two tributaries (Trueb and Gohl) to illustrate the construction of sub-regions where tributary streams connect to the main river.

on data from the Federal Office of Topography [68]. Data for retirement and nursing homes stem from the Federal Office of Public Health (FOPH) [69], schools and hospitals are retrieved from swissTLM3D [70]. The number of residents and workplaces is retrieved from data by the Federal Statistical Office [71,72].

The vulnerability model for buildings simulates flood damage to buildings per flooded object. The flow depths are attributed to each building for each timestep following Bermudez and Zischg [73]. We used a flood vulnerability function calibrated with insurance claim data from Switzerland [74]. The maximum flow depth on a building footprint is used to calculate the monetary damage to that building in hourly time steps. The building footprints are used to quantify the number of residents in flooded areas and workplaces as well as to identify critical infrastructure such as schools, hospitals, and retirement and nursing homes within the inundated area. Furthermore, the hydraulic model output is intersected with the road network to estimate the water level and flow velocity on all road segments in a floodplain. Bridges are considered flooded and therefore impassable if the water surface elevation is higher than 1 m below the minimum elevation of the pavement of the bridge segment (following the recommendations of KOHS [75]). Road sections are classified according to whether they are passable by cars and if detour traffic (as an indirect flood impact) is to be expected due to closed nearby road segments. This model chain was set up and calibrated in parallel with the co-development process of the online tool to communicate the results (Fig. 1).

2.2. Co-development

The storymaps online tool was developed in three stages of co-production. During this participatory development process, we iteratively consulted experts and potential users to reconcile their needs with our ideas and technical and financial possibilities, as exemplarily described by Refs. [41,45,76]. Minutes were written for every interview and workshop.

In the first step of co-development (phase “Exploration” in Fig. 1), semi-structured interviews [77] were conducted with 13 possible users and experts in the fields of natural hazards, hydrology, civil protection, fire brigades, national and cantonal governments and from the insurance industry. The aim was to explore possible applications of an online tool depicting storylines of extreme flood events of the rivers of national interest in Switzerland. A particular focus of the interviews was on emergency operations and flood intervention planning and where in this field the interviewee would see storymaps being applied and supportive for practitioners. Based on the results of these exploratory interviews, the potential user group was narrowed (to potential users of higher organizational levels, see also section 3), and the possible functionalities of the tool were concretized in a workshop. The main questions of the interviews and the workshop were the following.

- How are flood events managed on different organizational and political levels, and how are responsibilities allocated?
- Is the concept of storylines helpful in developing interactive online tools that show the spatiotemporal unfolding of extreme flood events and their impacts?
- Is the consideration and visualization of the dynamics of flood events (in space and time) useful for emergency preparedness and training of intervention forces?
- What are the most important elements at risk that should be considered in the impact analyses?
- How should the flood hazard be classified and mapped?
- Which flood magnitudes should be considered in the storymaps?

The results are summarized in section 3.

Another round of expert interviews was conducted in the second step (phase “Consolidation” in Fig. 1). Four experts from natural hazards management, the insurance industry, civil protection, and a local command body were interviewed. The aim was to learn from possible future users how they would apply the storymaps tool and which functionalities they would expect. A subsequent workshop was conducted with nine participants from the Mobiliar Lab for Natural Risks, the Federal Office for Civil Protection, natural hazard management consultants, and web user interface development specialists. This workshop aimed at discussing the findings from these interviews and further concretizing the functionalities to be provided in the tool and how the graphical user interface (GUI) was designed. A separate workshop with a hydrologist, a meteorologist, a communication expert, and the co-authors was conducted to select nine precipitation scenarios from a set of extreme events (see section 2.1) on which the storymaps are based. This workshop aimed to select scenarios that meet the needs of the target user groups, considering for example, the regional distribution of the precipitation, return periods, or the duration of the events.

The third stage of development (phase “Production” in Fig. 1) was the consolidation of the GUI and the backend of the storylines online tool. Here, the findings of the first two stages of co-development were implemented. The model chain, which was developed and adapted in parallel to the co-development process of the online platform (see section 2.1), was set up and connected with the GUI.

The workshops conducted in this third phase were held with experts in user experience and web development and, again, experts from hydrology, civil protection, and natural hazards. The focus of these workshops was the design, which means the functionality and usability of the user interface of the online tool. This stage aimed to design the GUI so that the users could handle it intuitively and find the information they were interested in without further help.

In the third stage, the interviews were conducted as user tests with nine potential professional users and with interested laypersons. The focus of the user tests was to obtain feedback on the design of the GUI and if the naming of the different functions etc., are self-explanatory and meet the user’s needs and expectations. The tests were done in two rounds, first, on semi-functional prototypes and, later again, on a functional early version of the online tool. The users were asked, for example, to find flood impact information on their own or perform query tasks like changing the displayed precipitation scenario or displaying the map of the maximum precipitation intensity. While using the prototype, they were asked to comment on what they were thinking and experiencing. This way, a user might reveal sticky information [45], i.e., thoughts and ideas he may not think of afterward.

3. Results

This section first summarizes the results of the co-development process and then describes the resulting tool.

3.1. Co-development process

The first semi-structured interviews revealed that a dynamic online tool to visualize extreme flood scenarios with the help of storymaps could be valuable for the stakeholders and how these institutions are organized regarding flood emergency management. In Switzerland, flood emergency operations are organized across several administrative levels. The administrative levels are from local to national: municipality, canton, and federal. Flood emergency first responders (fire brigades) are organized at the municipality level. Most municipalities, however, collaborate with neighboring municipalities via regionally coordinating command bodies (regional commands). The municipal fire brigades can request assistance from the cantonal civil protection organization if the local forces cannot handle an event because of its severity or long duration. If necessary, the cantons can request assistance from the military. The national and cantonal administrations organize training of coordinators and intervention forces and intervention planning. However, the focus of emergency intervention and preparedness planning is on the first responders at a rather local (municipality) level and rarely on inter-regional coordination. Existing intervention plans and procedures are mainly based on static hazard maps and the experience of individuals. On the municipality level, where fire brigades are responsible for emergency interventions, knowledge from experience on the local natural hazards and the critical infrastructure plays an important role. Training scenarios are also based on static hazard maps, which exist for all municipalities but for residential areas only. However, considerable damage happens outside the covered area [78]. The hazard maps show the maximum flood extent aggregated across flood events up to a return period of 1 in 300 years. In contrast, the storylines of extreme events show a locally and chronologically differentiated picture of the affected areas while one specific scenario unfolds. This allows new perspectives, particularly the time component is frequently mentioned as interesting by the interviewees.

3.1.1. Storyline approach

The interviews and workshops in the explorative and consolidation phase showed that the stakeholders find the principle of storylines for building narratives of flood impacts useful. Although scenarios are used for training, the concept of storylines of possible extreme flood events was new to many interviewees. It was, however, stated that the need for physically plausible simulations of natural hazards, including the temporal unfolding of events, will increase in the future due to the complexity of the impacts of a large-scale flood event. A tool to visualize possible flood evolution scenarios is of interest on the national level because the stakeholders agree that the graphical representation of storylines in the form of storymaps may raise awareness among professionals for possible extreme events and, in connection with expert experience on the local situation, help to prepare for such events.

3.1.2. Dynamics of flood events and storymaps

The interviewees see the time factor introduced and the physically robust origin of the storymaps as valuable information to create realistic storylines for training and emergency response planning. Storymaps may facilitate the imagination of possible future events. Therefore, they may be used to communicate and raise awareness of flood risks as well as for teaching professionals working in the field of flood risk management and flood emergency intervention. It was furthermore mentioned that the tool might be used by regional command bodies and cantonal authorities to reveal weak points in the currently used emergency response procedure. The regional civil protection units find the visualization of the flood dynamics helpful in planning the distribution of resources in space and time during an event.

3.1.3. Elements at risk

The interviewees of fire brigades stated that the number of affected persons, workplaces, and beds in retirement and nursing homes provide essential information for preparing for evacuations and estimating the required places in shelters. The fire brigades stated that the flood impact on the road network is very useful information. With the information about the impassable roads and the roads that must carry additional traffic due to traffic deviations, they realized that the spatial footprint of the flood event is much larger than the flooded areas. The impassable roads lead to the inaccessibility of settlements, neighborhoods, and critical infrastructure. Moreover, the flood impacts on the road network can make fire stations inaccessible, and in such a situation, emergency vehicles and material cannot be used for interventions.

Interviewees from the insurance sector wanted to know about the monetary damages of extreme flood scenarios, preferably about probable maximum losses. This is interesting to compare with their damage estimations.

3.1.4. Classification of flood hazard

The interviewees from the civil protection sector requested two kinds of visual hazard information. The hazard classification that is the easiest to interpret is the flow depth. Thus, the flooding process is visualized as classified flow depths. However, flow depths may be misunderstood in steeper topography because of the hydraulic effect of the flow velocity. Therefore, the representatives from fire brigades requested a hazard classification scheme that considers both flow depth and flow velocity. After some tests, we classified the hazard from the perspective of the vulnerability of pedestrians, cars, and buildings. We classified the flooded areas into four hazard classes, following the method proposed by Costabile et al. [79] and following the definitions of Pregnolato et al. [80] for pedestrians and of Arrighi et al. [81] for cars. We assumed structural damages to buildings when a flood exceeds 1.5 m, according to Zischg et al. [74].

3.1.5. *Flood magnitudes and scenario selection*

The question about the flood magnitudes that should be selected for the storylines raised several discussions. Depending on the field of application, some stakeholders were interested in flood magnitudes that can be managed with temporary interventions such as 1 in 100 years. Others were interested in flood magnitudes far beyond the hitherto observed flood events, which would be interesting to prepare for the worst or for stress tests in the insurance sector. We organized a dedicated workshop on selecting the precipitation scenarios when the models were ready to show some first scenarios. During this workshop, nine precipitation scenarios were selected, showing the spatial variability and events of different severity. Six scenarios with centers of precipitation in different regions of Switzerland with a 1 in 100 years return period, two with a 1 in 300 years return period, and one “worst case scenario” with a 1 in 1000 years return period were selected.

3.1.6. *Functionalities of the tool*

Based on the results of the interviews, we decided to develop a storymaps online tool and refer to it as the “Flood Dynamics” online tool. The goal is to provide a dynamic visualization of extreme river floods in Switzerland and their impacts. Furthermore, the goal is to contribute to the inter-regional and national perspective on the hydraulic system concerning flood evolution and recession. Table 1 summarizes the functionalities of the online tool.

During the second round of semi-structured interviews and workshops (phase “Consolidation” Fig. 1), we received practical inputs on which functions would be interesting to include in the storymaps, e.g., the number of affected people in an area or a visualization of flooded road sections that vary over time and can be queried with the time-slider. The newly introduced time-dependent visualization of storymaps with hourly resolution adds value during the planning phase of training, i.e., the development of scripts for training. For example, it depicts when a particular area or facility will be accessible, and the flood level at each point and time allows for prioritizing resources (personnel and equipment). In addition, it was mentioned that estimating the lead time to the flood will be helpful, e.g., the time lag between the maximum precipitation intensity in the upstream catchment and the flooding in the downstream river reaches. Furthermore, the number of people affected in schools and retirement homes, in combination with detailed accessibility information on the road network, is valuable information to intervention forces which is not available until now. One question brought up was if the data behind the storymaps has the same spatial resolution as the visualization. This is the case. In the hydraulic model, the maximum triangle area of the irregular computational mesh is set to 200 m^2, and in the visualization one pixel covers the area of approximately 200 m^2. Another point of discussion was that it would have to be communicated carefully that the modeled floods are scenarios and cannot be interpreted as predictions of future events, mainly since the exact timing and location of flooding might differ in an actual event.

In a second workshop (phase “Consolidation” Fig. 1), the decision was taken to focus the development on civil protection and emergency services as the primary user group but to make the tool available online for the interested public as well. The development of the storymaps online tool focuses on applications in flood risk communication, particularly as a physically consistent basis for operational flood emergency exercises. We decided to show the elements at risk that are of interest to the stakeholders and for which geolocated datasets were available (affected schools, hospitals, and retirement homes. No data was available (freely and complete) on where critical infrastructure of emergency services are located). It was decided to include estimates of flood damage on buildings because this information is relevant for building insurers and gives an overview of the flood impacts on a regional and national scale. An issue discussed was if and how the number of residents (working or living) per affected building should be communicated. This information would be valuable to plan evacuation measures, but as it is sensitive personal data, its publication for every single object is not possible, and an aggregation of the data is needed. Therefore, the information is available in the tool as sums of affected residents and workplaces aggregated to geomorphological river sections and their floodplains, respectively, the floodplains of lakes**.** The flooded roads are visualized at the object scale, and no data aggregation was needed because of privacy issues.

Furthermore, it was discussed how the precipitation scenarios should be displayed (color ramp, running precipitation intensities, or the cumulative sum). It was decided to display the precipitation scenarios as intensity maps by default while a scenario runs. The idea behind it is to create maps that resemble the precipitation forecasts issued by the national weather service MeteoSwiss. The user can, however, switch to display precipitation sum, which will also be displayed at the end of a scenario timeline by default.

Table 1
Overview of features of the flood dynamics storymaps online tool.

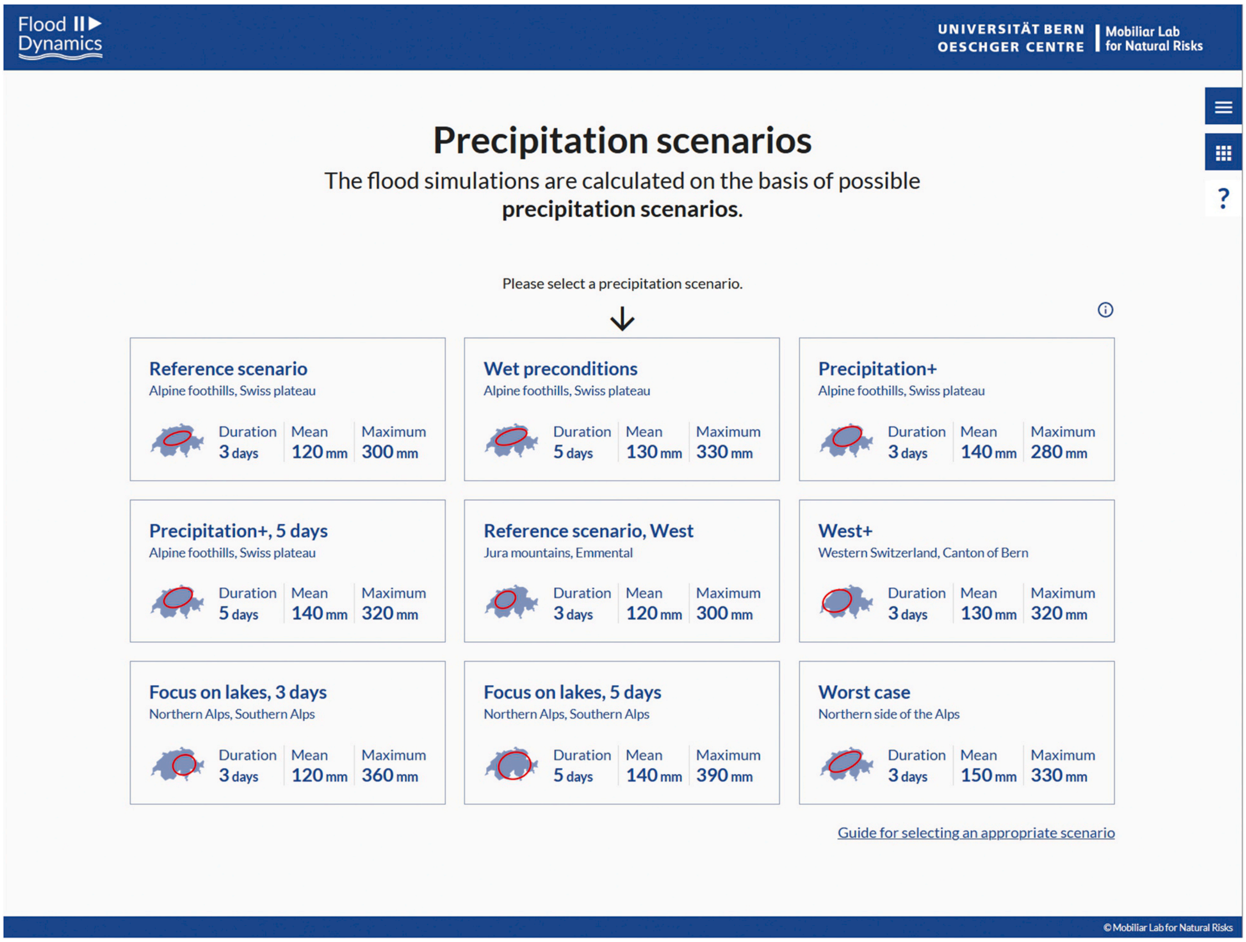
Feature	Possible Application
Interactive animated map	Intuitive communication of flood hazards.
Mapping plausible flood scenarios	Facilitates the imagination of possible flood events for professionals and laypersons.
Visualization of the temporal flood evolution	Input for training scenarios for professionals in flood disaster intervention. Information for the planning of flood disaster management, allowing to estimate the lead time. Flood risk awareness creation.
Regional and national overview of the river system	Input for training scenarios on a regional level or on the national level.
Flood damage estimation	Provides a measure to compare regions and events for governments and building insurers.
Location and number of affected hospitals, schools, and nursing homes	Raise awareness that such critical facilities may be affected.
Number of affected people	Indicative to plan evacuations.
Impact on the road system	Shows if and when an area will be cut off due to impassable roads. For flood intervention planning and training. To be considered when assessing the accessibility of critical services such as hospitals or the emergency services headquarters during flood events.

The third development stage (phase “Production” in Fig. 1) was the production of the user interface and the technical back end. During this stage, the interviews were conducted as user tests on partly functional prototypes of the online user interface. Key topics of these user tests were the user guidance through the tool, i.e., how users find their way to the information they are looking for or how many help texts are needed and where. Some users, for example, found it challenging to understand the choice of the precipitation scenarios. Therefore, a mouse-over function was added to display more information on the spatial and temporal distribution of the precipitation, together with a brief description of the event. Furthermore, a document with an overview of all extreme precipitation events and more information is provided on the website (link in section “data availability”). The results of the user tests were continuously transferred into the development process of the GUI, which was then tested again with potential users.

3.2. *Description of the flood dynamics online tool*

On the entry page of the tool, the user must select one of nine precipitation scenarios (Fig. 4). Subsequently, the user will see a map of Switzerland with the animated precipitation scenario overlaid with a time-slider to visualize the spatiotemporal pattern of the precipitation event. On the same map, the rivers and lakes of national interest are displayed. In the menu pane (Fig. 2), the user can select for which type of elements at risk (buildings, persons, workplaces, damages, schools, hospitals, nursing homes) the quantified impacts of a flood scenario should be displayed. The line width of the displayed river sections varies with time during the event and indicates the magnitude of the selected flood impacts for each river section (Fig. 5). The time-slider at the bottom of the map displays the hours since the onset of the precipitation event and allows pausing or toggling the displayed time step within the scenario.

By zooming in, individual floodplains can be displayed in more detail (Fig. 6). A regional overview of more than one floodplain can be displayed, as well as a detailed view, which allows visualizing every single road and building within a floodplain. On the detailed zoom level, the visualization of the event changes to a detailed map, and the precipitation pattern is no longer visible. Instead, the scenario can be displayed as flood depth or vulnerability-based hazard classes (see section *Classification of flood hazard*). The storymaps also highlight the location of critical infrastructure on the map, namely schools, hospitals, and retirement and nursing homes (Fig. 7),



Precipitation scenarios

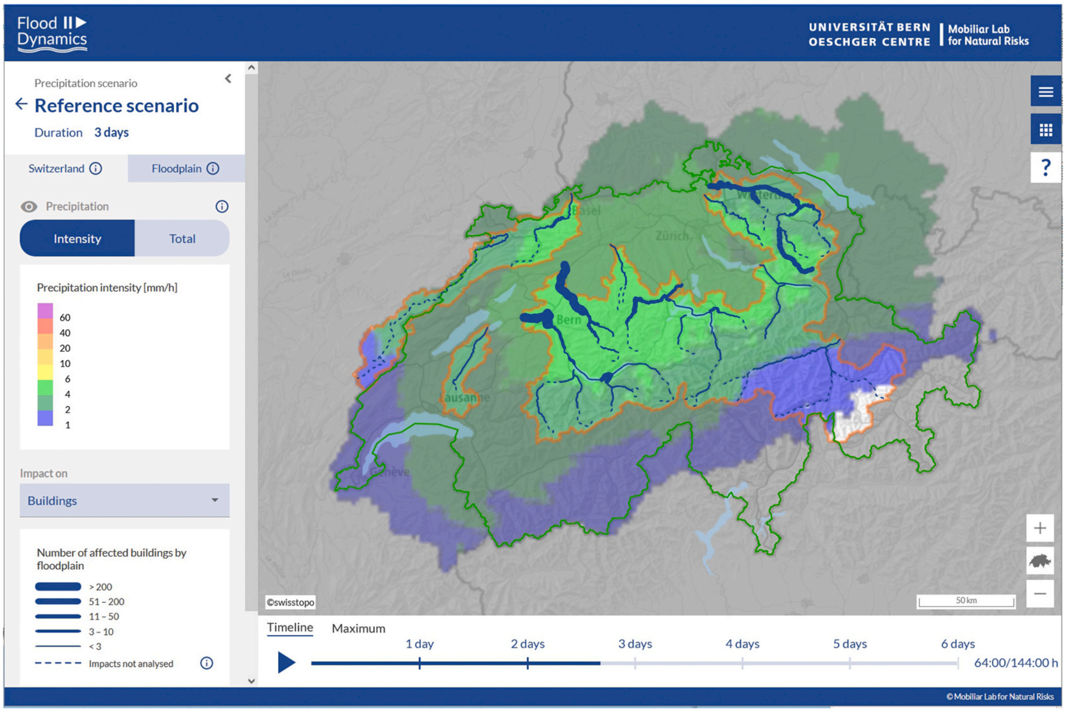
The flood simulations are calculated on the basis of possible **precipitation scenarios.**

Please select a precipitation scenario.

Scenario	Region	Duration	Mean	Maximum
Reference scenario	Alpine foothills, Swiss plateau	3 days	120 mm	300 mm
Wet preconditions	Alpine foothills, Swiss plateau	5 days	130 mm	330 mm
Precipitation+	Alpine foothills, Swiss plateau	3 days	140 mm	280 mm
Precipitation+, 5 days	Alpine foothills, Swiss plateau	5 days	140 mm	320 mm
Reference scenario, West	Jura mountains, Emmental	3 days	120 mm	300 mm
West+	Western Switzerland, Canton of Bern	3 days	130 mm	320 mm
Focus on lakes, 3 days	Northern Alps, Southern Alps	3 days	120 mm	360 mm
Focus on lakes, 5 days	Northern Alps, Southern Alps	5 days	140 mm	390 mm
Worst case	Northern side of the Alps	3 days	150 mm	330 mm

Guide for selecting an appropriate scenario

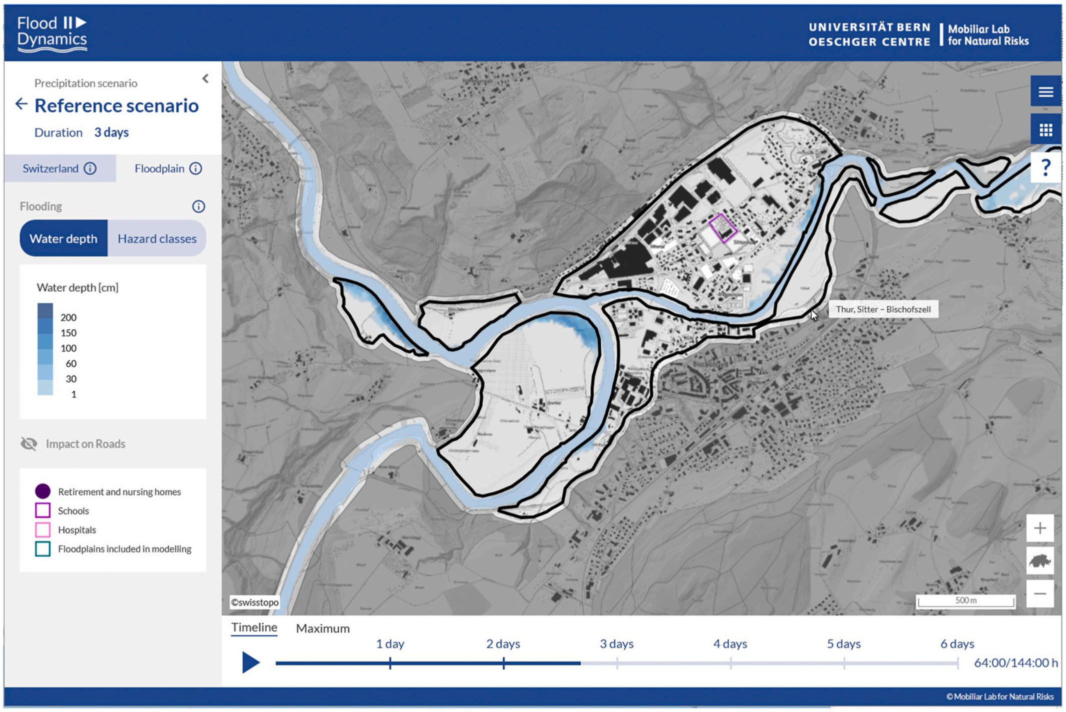
Fig. 4. Screenshot of the entry page of the flood dynamics tool showing the nine precipitation scenarios available for selection. For each scenario, the duration (days), the mean amount of precipitation (in mm) over hydrological Switzerland, and the local maximum precipitation (in mm) are indicated. An icon displays the region with the center of the precipitation.



Precipitation scenario
Reference scenario
Duration 3 days

64:00/144:00 h

Fig. 5. Overview of the hydrological domain of Switzerland with a precipitation event ("Reference Scenario") depicted. The menu pane on the left shows the precipitation intensity's color code and the flood impact (line width) legend on the selected object at risk (buildings in this example).



Precipitation scenario
Reference scenario
Duration 3 days

64:00/144:00 h

Fig. 6. Detailed view of one floodplain surrounded in black (confluence of Thur and Sitter at Bischofszell in this example). The flooded area indicates flood depth. The menu pane on the left shows the color code for the flood depth and a legend for highlighted critical infrastructure in the floodplain.

or show a classification of inundated road sections (Fig. 8). The flood hazard classes are consistent with the classification of the flooded roads. The detailed base map and the flood visualization at hourly time steps provide a high-resolution picture of how the flood and the resulting impacts evolve (Figs. 6–8).

Additionally, statistics on the flood impacts aggregated for Switzerland or a selected floodplain are provided. Estimations on the following flood impacts are evaluated over time: the damage restoration costs on buildings as calculated by the vulnerability model, the number of people in an area or in affected schools and retirement homes, and the length of inundated road sections including an estimation of whether and how a road is useable or not (Fig. 9).

4. Discussion

4.1. Application of the online tool

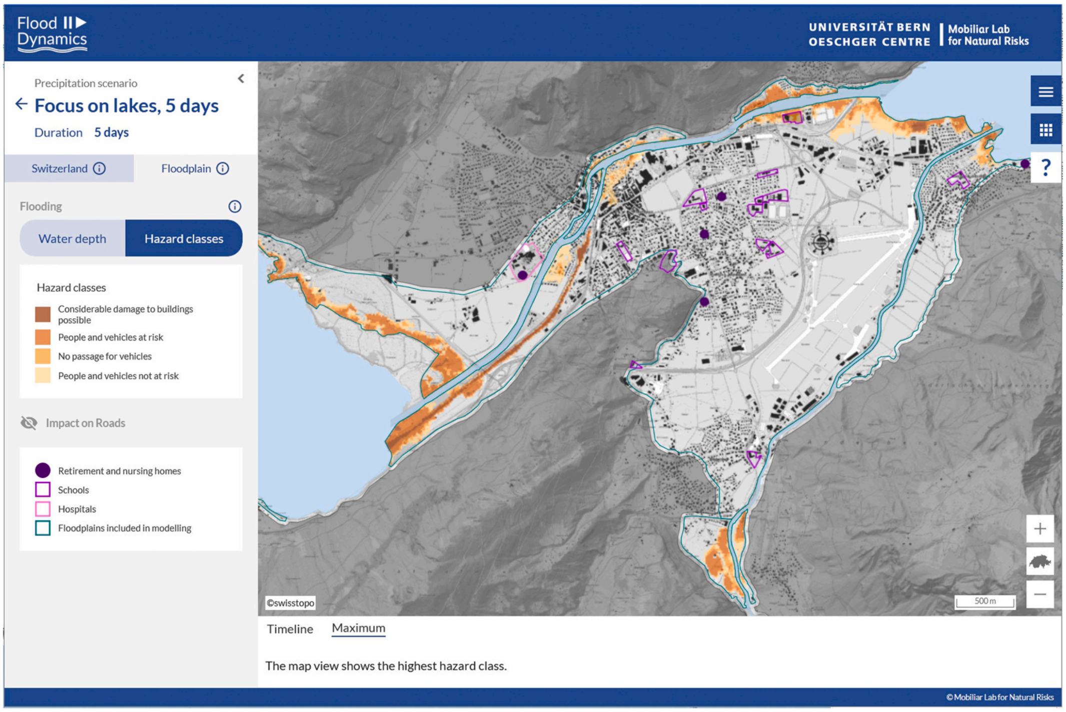
The flood storymaps depict nine flood scenarios along Switzerland's major rivers and lakes. The development of a storymap starts with selecting a precipitation scenario that results in flood events with substantial regional impact. The simulations show that extreme floods can occur in multiple regions nearly at the same time and hence can cause an overwhelming situation for emergency services. The online tool's national and regional overview function draws attention to a national and regional perspective on flood hazards and points to the need to coordinate different levels of intervention forces during long-lasting and widespread flood events.

The dynamic (i.e., time-resolved) visualization of the precipitation, the flood dynamics, and the flood impacts for the main Swiss rivers is new. It may show situations where a closer collaboration across regional command bodies could be favorable. For such applications, the storymaps complement the existing static hazard maps.

The precipitation scenarios contain hourly values (for potential evapotranspiration, temperature, and precipitation) disaggregated from six-hourly time steps. This process smoothed peak values within the six-hourly resolution. Therefore, the model chain based on these precipitation scenarios is suitable for generating storylines on a medium to a large spatial scale. Intensive small-scale precipitation events that affect mainly the local surface runoff and small rivers and lakes are not well represented in the storymaps. Consequently, the presented tool focuses on the main rivers of Switzerland, and small rivers and surface runoff are not considered. However, these small rivers, creeks, and surface runoff are important local flood sources in many municipalities. Floods in small rivers and due to surface runoff occur mainly during local-scale weather events like thunderstorms. These phenomena are not considered in the continental-scale weather simulation models. As soon as convection-resolving models are available, these local-scale hazard processes could, in principle, be implemented in the impact modeling chain.

4.2. Road information

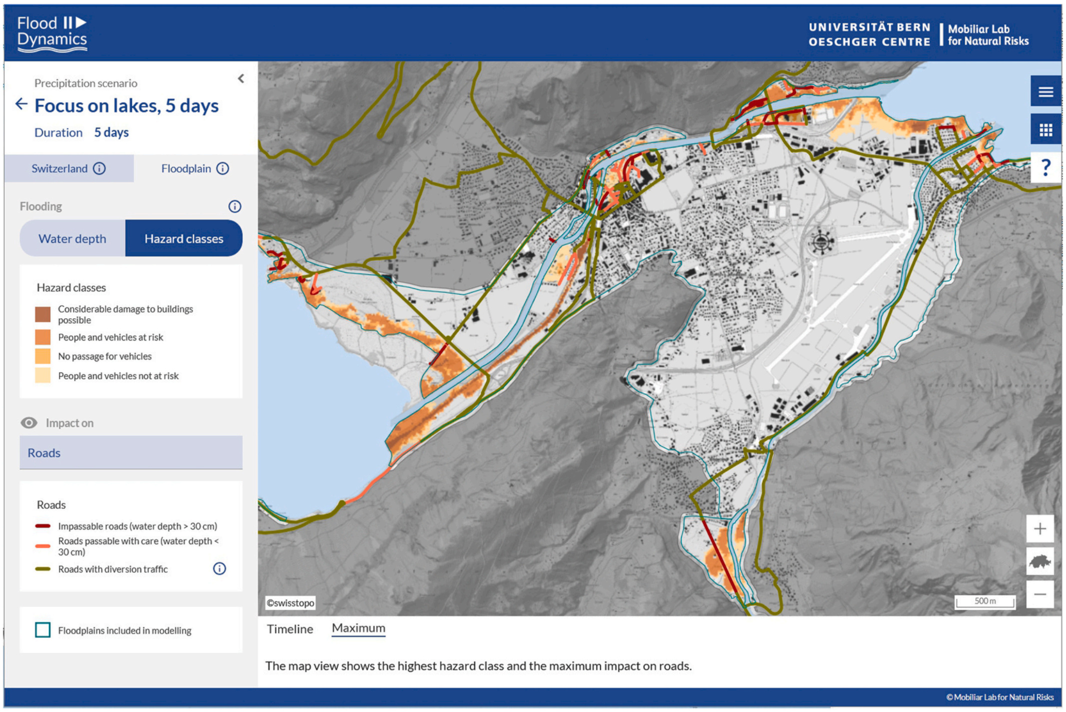
The visualization if a road is passable or not draws attention to the issue that the intervention forces have difficulties reaching some



Precipitation scenario
Focus on lakes, 5 days
Duration 5 days

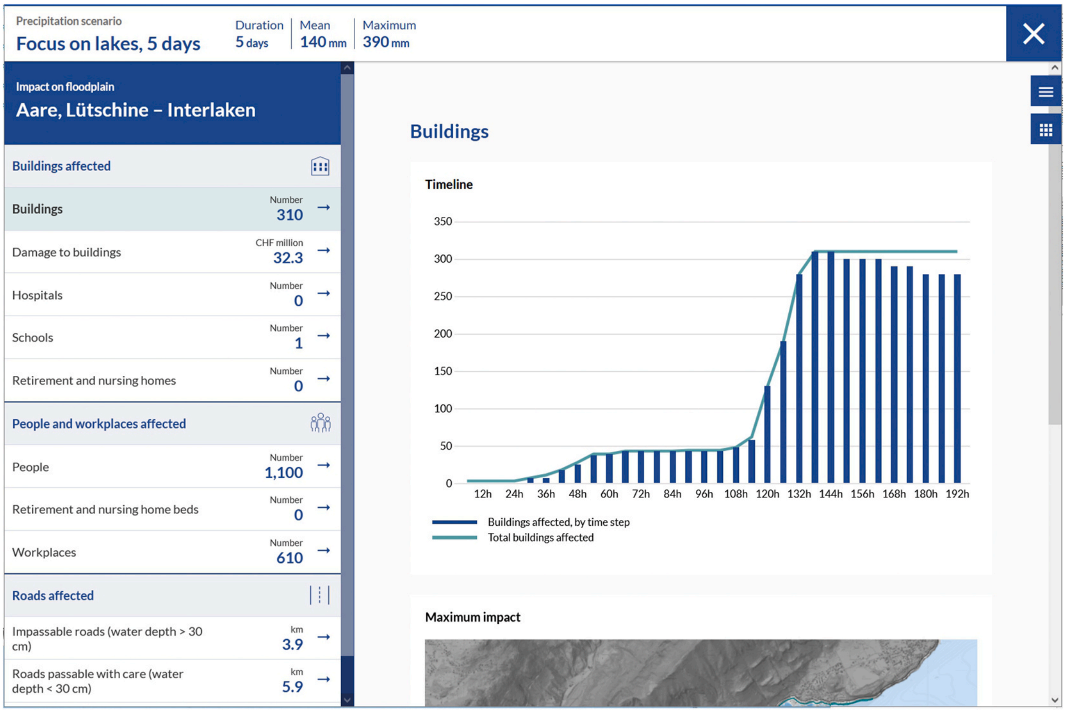
The map view shows the highest hazard class.

Fig. 7. Screenshot of the online tool showing flooded areas in the floodplain as hazard classes at Interlaken between the Lakes of Brienz and Thun; critical infrastructure is highlighted. The menu pane on the left shows the color code with a description of the hazard classes and a legend for the highlighted critical infrastructure in the floodplain.



The map view shows the highest hazard class and the maximum impact on roads.

Fig. 8. Screenshot of the online tool showing flooded areas as hazard classes and the impacts on roads. The menu pane on the left shows the color code with a description of the hazard classes and a legend for the color code of the flood impact on roads.



Buildings affected	
Buildings	Number 310
Damage to buildings	CHF million 32.3
Hospitals	Number 0
Schools	Number 1
Retirement and nursing homes	Number 0
People and workplaces affected	
People	Number 1,100
Retirement and nursing home beds	Number 0
Workplaces	Number 610
Roads affected	
Impassable roads (water depth > 30 cm)	km 3.9
Roads passable with care (water depth < 30 cm)	km 5.9

Fig. 9. Screenshot of the online tool showing a graph with the aggregated numbers for flood impacts over time in one floodplain (the Aare and the Lütschine at Interlaken in this example) for the scenario "Focus on lakes, 5 days". The "damage to buildings" is selected and displayed. In the menu pane on the left other objects at risk can be selected for a detailed view.

Table 2
Overview of the aggregated flood impacts within the modeled domain of the online tool.

Scenario	Number of Buildings affected	Damage to buildings [millions CHF]	Affected hospitals	Affected schools	Retirement and nursing homes	Retirement and nursing home beds	Affected persons	Affected workplaces	Impassable roads [km]	Roads passable with care[a] [km]	Roads with diversion traffic [km]
Reference scenario	3100	920	0	18	4	260	12000	7400	110	95	520
Wet preconditions	4400	1177	0	28	6	440	17000	11000	140	130	740
Precipitation +	5800	1717	0	41	6	440	23000	25000	200	180	1200
Precipitation +, 5 days	4300	1388	0	27	6	470	18000	17000	140	120	770
Reference scenario, West	2400	874	0	16	6	430	10000	11000	88	75	450
West +	2700	1160	0	14	4	340	12000	7600	90	70	420
Focus on lakes, 3 days	2000	583	0	18	3	160	8400	15000	65	81	730
Focus on lakes, 5 days	5200	1570	1	45	7	380	25000	35000	210	140	1000
Worst case	19000	5490	1	97	19	1300	80000	75000	600	440	3000

[a] Roads passable with care: road section is flooded, but the water depth is < 30 cm.

areas during some events and may motivate to prepare for such cases (e.g., inter-regional cooperation and strategic allocation of material or shelter locations). Furthermore, including roads where diversion traffic must be expected is an example of an indirect flood impact. This example shows that such indirect impacts can affect much larger areas than the direct flood impact. This is most pronounced in mountainous regions or on lake shores where a blocked road section can lead to large detour routes or even the complete cut-off of an area.

4.3. Precipitation scenarios

It is important to keep in mind that the shown precipitation scenarios are selected examples of plausible extreme events. They are, however, not equally extreme for all catchments. For example, the Emme River section at Burgdorf experiences large flood magnitudes in most of our selected storylines. In contrast, even in our "worst case" storymap, when severe flood impacts are shown in most river sections, minimal impact appears along the Broye River and no flood impact at all along the river Wigger. However, we know from past events that the rivers Broye or Wigger can be affected by floods [82–84]. If and where floods are simulated in the online tool depends on one hand on the selected precipitation scenario. On the other hand, local factors such as river morphology, the exposure of people and objects at risk, and flood protection measures play an important role. The return periods used to describe the precipitation scenarios are given for the hydrological domain of Switzerland. A different return period would be attributed at the local level for individual catchments and another return period again for the river runoff. The reference scenario, for example, was attributed a return period of 100 years but leads to more damaged buildings than the scenario "west +" with a return period of 300 years (Table 2). Table 2 shows the variability of the flood impacts related to the selected storylines and scenarios. Such amounts of information are difficult to convey without visualization. This supports both research questions, namely that storylines visualized as storymaps allow to communicate large amounts of complex scientific information. Understanding and interpreting the storymaps correctly needs some background knowledge. This is why professional users are the main targeted user group.

4.4. Multiple scales

The flood dynamics tool presented here provides a dynamic view and promotes a national perspective without losing the view of local details. This multi-scale application was valued by the first users of the tool. Users were satisfied with the ability to show the impacts at the national and local scales with many details.

4.5. User feedback

After the online tool was officially released and published, we received feedback from users who started including it in teaching for commanders of civil protection organizations. Furthermore, local political decision-makers and professionals in the field of hydraulic engineering reported being interested and evaluating potential applications. They stated that the tool would be used in risk communication and teaching during courses for professionals. The main conclusion from the feedback was that the tool allows for visualizing the 'unthinkable', namely extreme flood events that go far beyond the hitherto experienced ones. Moreover, they stated that the dynamic perspective of the tool eases the understanding of flood events.

The proposed model chain uses the results of weather forecast models to simulate flood events and their impacts on selected aspects of societal activities and infrastructure. Thus, the presented co-development method could, in principle, also be applied to develop impact-based early warning systems. Impact forecasts and impact-based warnings aim at giving specific information to defined target groups enabling them to protect themselves in case of a forecasted extreme weather event [85]. Such warning systems "translate" the weather forecast to impact forecasts. The impact information is expected to support decision-making at the onset of a potentially catastrophic hazard event. The design and setup of impact-based warning systems, e.g., the development of warning messages dedicated to specific user groups with specific vulnerabilities to extreme weather events, requires involving the potential users in a participatory process. Thus, the presented approach with stakeholder participation can be an example of co-developing and co-designing impact-based warning systems. A co-production approach is easing the choice of the assets at risk and their vulnerability to floods that determine the content of the impact-based warnings (e.g., impacts of floods on buildings), the content of the warning message (where and when will people and buildings be affected in the next 24 h), or the content of the message that recommends actions for flood prevention when a flood event is forecasted (what has to be done?).

As the hazard classification scheme differs from the hazard maps scheme officially used in Switzerland, some stakeholders argued against this new visualization because it might undermine the official communication effort about the importance of the hazard maps for land use planning purposes. These official hazard maps are widely accepted among professionals. They are, however, rarely used among the public [12,86]. In contrast to the presented approach of visualizing storylines of flood scenarios, these hazard maps summarize many possible scenarios. There is always a trade-off between using well-known concepts and linkages with existing tools and innovation. We avoided the transfer of the concept of static hazard maps to the dynamic hazard maps because of the risk of misinterpretation. When asking experts, they may judge the new tool from the perspective of integrating it into their daily tasks. Innovative functions must be explained well before asking potential users for the potential benefits. In this case (hazard classes), the proposed new way of mapping hazards in relevant categories for vulnerability (bottom-up classification of hazard intensities) was judged as useful from one part of the expert's pool and not useful by the other part. Vulnerability information is relevant to give behavioral instructions. Other participatory investigations have shown that there is demand for actionable impact communication [87,88].

4.6. Limitations and future developments

However, there are some limitations. First, the tool shows only a limited number of scenarios. Thus, not all river reaches are covered by the simulated floods. Furthermore, the storymaps tool is online and publicly available. It has however not been evaluated how users other than the targeted users perceive and interpret the presented storymaps. They might find it a useful tool for flood risk communication and (public) awareness creation. The risk of misinterpretation might, however, be larger than with professional users. Moreover, the model chain itself has the same limits as most natural hazards simulation models. They neglect certain relevant processes, for example, the transport and clogging of bridges due to large woody debris, lateral and riverbed erosion, sediment transport, and finally, any human intervention during an event. This was also criticized by several users. Although the hydraulic model bases on very high spatial resolution, some local hydraulic structures might be neglected because they are not represented in the digital elevation models. Further uncertainty is given by the initial conditions we assumed at the onset of the extreme precipitation events to simulate the runoff. The hydrological initial conditions are a relevant source of variability and may have a larger effect on peak floods than the meteorological forcing [89]. The role of the initial conditions of the hydrological model must therefore be further analyzed for their impact on peak runoff and flood generation.

It must be carefully communicated that the selected scenarios are extreme scenarios. They are physically plausible, meaning they could potentially occur, but it is not expected that any of the scenarios will occur exactly as shown. The presented scenarios can, however, still give an impression of possible flood magnitudes and the regional extent and timing of precipitation-driven extreme flood events.

Further development of the online tool could include the public (non-experts) as an additional user group. Therefore, an investigation into how people interpret the storymaps, which additional information is needed, and how it must be provided to add value, for example, for flood risk awareness creation.

For professional users, integrating more information on the locations of more critical infrastructure would be helpful. The provided information was integrated based on the needs of the interrogated potential users and the availability of complete national data and, as such, may be seen as examples to demonstrate the feasibility and the usefulness of such information integrated into dynamic storymaps.

Some stakeholders requested a functionality to interactively insert virtual flood defenses and test their effects on the flood hazard. This functionality of evaluating the effects of mobile flood protection measures on the flood impacts should be in the focus of future developments.

5. Conclusions

In this study, we asked how scientific information on extreme precipitation, floods, and flood impacts can be conveyed in a way that allows stakeholders in flood risk management to gain relevant information for their practical work in preparedness raising. We assessed how the storyline approach can support the communication of flood impacts information to practitioners in flood management. The study shows that storylines are a helpful concept to explore and communicate plausible extreme flood events. We apply this concept and combine it with mapping to yield storymaps. Our storymaps apply the concept of storylines with the help of dynamic (time-resolved) maps. They depict plausible extreme flood events rather than the most probable event. Storymaps of extreme flood events complement the commonly used official hazard maps, which are static and are based on events with return periods from decades to centuries (probability-based) with a focus on municipalities. The presented multi-scale flood storymaps provide impact information aggregated across the river system as well as information on local processes and impacts. This is relevant additional information for practitioners in flood intervention and flood intervention planning.

The close collaboration with stakeholders in an iterative co-development process guided the selection and preparation of the content and visualization of information of physically plausible flood storylines. The online tool https://flooddynamics.floodrisk.ch/en, which results from this process, combines physically plausible storylines of extreme flood events with mapping for nine storylines. The storylines of extreme flood events are shown in storymaps that visualize the spatiotemporal unfolding of these flood events and their impacts. The storylines, on the one hand, contribute plausible time sequences of flood processes and their impacts on society. The time-resolved maps, on the other hand, make large amounts of complex information more easily accessible. The storymaps visualize the model chain that simulates the whole process chain from precipitation to river runoff, flooding, and flood impacts.

In summary, the storyline concept can well be combined with mapping. Dynamic maps are particularly suited to this application because they allow for including the temporal component.

The co-development process allowed to design the storymaps online tool for the stakeholders' specific needs. The involvement of stakeholders was crucial for selecting the precipitation scenarios, the considered types of elements at risk, the classification of the flood hazards, the functionality of the tool, and its useability. Consequently, the information on extreme precipitation, flood risks, and flood impacts provided by research can be purposely used in practice to prepare and train for extreme flood events.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

"The data and the presentedtool “Flood Dynamics” can be viewed and interactively browsed at https://flooddynamics.floodrisk.ch/en. The document mentioned in section 3.1, with an overview of all extreme precipitations events for selecting the precipitation scenario of the flood impact storyline, is available at https://www.hochwasserrisiko.ch/en/text_howadyn/menuitem/findings/

Entscheidungshilfe_Szenarienauswahl_en.pdf."

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References

[1] S. Fuchs, V. Röthlisberger, T. Thaler, A. Zischg, M. Keiler, Natural hazard management from a coevolutionary perspective: exposure and policy response in the European Alps, Ann. Assoc. Am. Geogr. 107 (2017) 382–392, https://doi.org/10.1080/24694452.2016.1235494.

[2] Z.W. Kundzewicz, S. Kanae, S.I. Seneviratne, J. Handmer, N. Nicholls, P. Peduzzi, R. Mechler, L.M. Bouwer, N. Arnell, K. Mach, R. Muir-Wood, G.R. Brakenridge, W. Kron, G. Benito, Y. Honda, K. Takahashi, B. Sherstyukov, Flood risk and climate change: global and regional perspectives, Hydrol. Sci. J. 59 (2013) 1–28, https://doi.org/10.1080/02626667.2013.857411.

[3] L. Alfieri, F. Dottori, R. Betts, P. Salamon, L. Feyen, Multi-model projections of river flood risk in Europe under global warming, Climate 6 (2018) 6, https://doi.org/10.3390/cli6010006.

[4] CH2018, CH2018 – Climate Scenarios for Switzerland, National Centre for Climate Services, Zurich, 2018. Technical Report, https://www.nccs.admin.ch/nccs/de/home/klimawandel-und-auswirkungen/schweizer-klimaszenarien/technical-report.html.

[5] M.I. Brunner, D. Farinotti, H. Zekollari, M. Huss, M. Zappa, Future shifts in extreme flow regimes in Alpine regions, Hydrol. Earth Syst. Sci. 23 (2019) 4471–4489, https://doi.org/10.5194/hess-23-4471-2019.

[6] L. Keller, A.P. Zischg, M. Mosimann, O. Rössler, R. Weingartner, O. Martius, Large ensemble flood loss modelling and uncertainty assessment for future climate conditions for a Swiss pre-alpine catchment, Sci. Total Environ. 693 (2019), 133400, https://doi.org/10.1016/j.scitotenv.2019.07.206.

[7] R. Muelchi, O. Rössler, J. Schwanbeck, R. Weingartner, O. Martius, River runoff in Switzerland in a changing climate – changes in moderate extremes and their seasonality, Hydrol. Earth Syst. Sci. 25 (2021) 3577–3594, https://doi.org/10.5194/hess-25-3577-2021.

[8] A.P. Zischg, Floodplains and complex adaptive systems — perspectives on connecting the dots in flood risk assessment with coupled component models, Systems 6 (2018) 9, https://doi.org/10.3390/systems6020009.

[9] K.M. de Bruijn, B.A. Jafino, B. Merz, N. Doorn, S.J. Priest, R.J. Dahm, C. Zevenbergen, J.C.J.H. Aerts, T. Comes, Flood risk management through a resilience lens, Commun. Earth Environ. 3 (2022) 1–4, https://doi.org/10.1038/s43247-022-00613-4.

[10] W.J.W. Botzen, J.C.J.H. Aerts, J.C.J.M. van den Bergh, Dependence of flood risk perceptions on socioeconomic and objective risk factors, Water Resour. Res. 45 (2009), https://doi.org/10.1029/2009WR007743.

[11] A. Glaus, M. Mosimann, V. Röthlisberger, K. Ingold, How flood risks shape policies: flood exposure and risk perception in Swiss municipalities, Reg. Environ. Change 20 (2020) 120, https://doi.org/10.1007/s10113-020-01705-7.

[12] E. Maidl, B. Wiederkehr, M. Buchecker, Ergebnisbericht über die Bevölkerungsbefragung «Leben mit Naturgefahren», Eidg, Forschungsanstalt für Wald, Schnee und Landschaft WSL, Birmensdorf, 2016. https://www.wsl.ch/de/publikationen/ergebnisbericht-ueber-die-bevoelkerungsbefragung-leben-mit-naturgefahren.html. (Accessed 26 February 2023).

[13] T. Terpstra, J.M. Gutteling, Households' perceived responsibilities in flood risk management in The Netherlands, Int. J. Water Resour. Dev. 24 (2008) 555–565, https://doi.org/10.1080/07900620801923385.

[14] H. Kreibich, I. Seifert, A.H. Thieken, E. Lindquist, K. Wagner, B. Merz, Recent changes in flood preparedness of private households and businesses in Germany, Reg. Environ. Change 11 (2011) 59–71, https://doi.org/10.1007/s10113-010-0119-3.

[15] F. Messner, V. Meyer, Flood damage, vulnerability and risk perception - challenges for flood damage research, in: J. Schanze, E. Zeman, J. Marsalek (Eds.), Flood Risk Manag. Hazards Vulnerability Mitig. Meas., Springer Netherlands, Dordrecht, 2005, pp. 149–167, https://doi.org/10.1007/978-1-4020-4598-1_13.

[16] I. Andráško, Why people (do not) adopt the private precautionary and mitigation measures: a review of the issue from the perspective of recent flood risk research, Water 13 (2021) 140, https://doi.org/10.3390/w13020140.

[17] G. Wachinger, O. Renn, C. Begg, C. Kuhlicke, The risk perception paradox — implications for governance and communication of natural hazards, Risk Anal. 33 (2013) 1049–1065, https://doi.org/10.1111/j.1539-6924.2012.01942.x.

[18] V.J. Cortes Arevalo, L.N.H. Verbrugge, R.-J. den Haan, F. Baart, M.C. van der Voort, S.J.M.H. Hulscher, Users' perspectives about the potential usefulness of online storylines to communicate river research to a multi-disciplinary audience, Environ. Commun. 13 (2019) 909–925, https://doi.org/10.1080/17524032.2018.1504098.

[19] L. Thomi, A. Zischg, H. Suter, Was macht Hochwasserschutzprojekte erfolgreich? eine Evaluation der Risikoentwicklung, des Nutzens und der Rolle privater Geldgeber, Mobiliar Lab, University of Bern, Bern, 2015. https://plattform-renaturierung.ch/wp-content/uploads/2018/02/ThomiZischgSuter2015_WasmachtHWS-Projekte_erfolgreich_MobiliarOeschgerCenter.pdf.

[20] C. Pfister, The "disaster gap" of the 20th century and the loss of traditional disaster memory, GAIA - Ecol. Perspect. Sci. Soc. 18 (2009) 239–246, https://doi.org/10.14512/gaia.18.3.10.

[21] A. Tversky, D. Kahneman, Judgment under uncertainty: heuristics and biases, Science 185 (1974) 1124–1131, https://doi.org/10.1126/science.185.4157.1124.

[22] E. Tulving, Episodic and semantic memory, in: Organ. Mem., Academic Press, New York, 1972, pp. 381–402.

[23] T.G. Shepherd, E. Boyd, R.A. Calel, S.C. Chapman, S. Dessai, I.M. Dima-West, H.J. Fowler, R. James, D. Maraun, O. Martius, C.A. Senior, A.H. Sobel, D. A. Stainforth, S.F.B. Tett, K.E. Trenberth, B.J.J.M. van den Hurk, N.W. Watkins, R.L. Wilby, D.A. Zenghelis, Storylines: an alternative approach to representing uncertainty in physical aspects of climate change, Clim. Change 151 (2018) 555–571, https://doi.org/10.1007/s10584-018-2317-9.

[24] T.G. Shepherd, Storyline approach to the construction of regional climate change information, Proc. R. Soc. Math. Phys. Eng. Sci. 475 (2019), 20190013, https://doi.org/10.1098/rspa.2019.0013.

[25] W. Krauß, S. Bremer, The role of place-based narratives of change in climate risk governance, Clim. Risk Manag. 28 (2020), 100221, https://doi.org/10.1016/j.crm.2020.100221.

[26] J. Sillmann, T.G. Shepherd, B. van den Hurk, W. Hazeleger, O. Martius, J. Slingo, J. Zscheischler, Event-based storylines to address climate risk, Earth's Future 9 (2021), https://doi.org/10.1029/2020EF001783.

[27] S.J. ElShafie, Making science meaningful for broad audiences through stories, Integr. Comp. Biol. 58 (2018) 1213–1223, https://doi.org/10.1093/icb/icy103.

[28] S. Razavi, P. Gober, H.R. Maier, R. Brouwer, H. Wheater, Anthropocene flooding: challenges for science and society, Hydrol. Process. 34 (2020) 1996–2000, https://doi.org/10.1002/hyp.13723.

[29] T.G. Shepherd, E.A. Lloyd, Meaningful climate science, Clim. Change 169 (2021) 17, https://doi.org/10.1007/s10584-021-03246-2.

[30] R.A. Bradford, J.J. O'Sullivan, I.M. van der Craats, J. Krywkow, P. Rotko, J. Aaltonen, M. Bonaiuto, S. De Dominicis, K. Waylen, K. Schelfaut, Risk perception – issues for flood management in Europe, Nat. Hazards Earth Syst. Sci. 12 (2012) 2299–2309, https://doi.org/10.5194/nhess-12-2299-2012.

[31] E. Lechowska, Approaches in research on flood risk perception and their importance in flood risk management: a review, Nat. Hazards 111 (2022) 2343–2378, https://doi.org/10.1007/s11069-021-05140-7.

[32] B. Marschütz, S. Bremer, H. Runhaar, D. Hegger, H. Mees, J. Vervoort, A. Wardekker, Local narratives of change as an entry point for building urban climate resilience, Clim. Risk Manag. 28 (2020), 100223, https://doi.org/10.1016/j.crm.2020.100223.

[33] J.M. Curiel, G.A. Radvansky, Mental maps in memory retrieval and comprehension, Memory 10 (2002) 113–126, https://doi.org/10.1080/09658210143000245.
[34] J. Mallow, J. Bernarding, M. Luchtmann, A. Bethmann, A. Brechmann, Superior memorizers employ different neural networks for encoding and recall, Front. Syst. Neurosci. 9 (2015), https://doi.org/10.3389/fnsys.2015.00128.
[35] T. Pathman, C. Coughlin, S. Ghetti, Space and time in episodic memory: effects of linearity and directionality on memory for spatial location and temporal order in children and adults, PLoS One 13 (2018), e0206999, https://doi.org/10.1371/journal.pone.0206999.
[36] K.M. de Bruijn, N. Lips, B. Gersonius, H. Middelkoop, The storyline approach: a new way to analyse and improve flood event management, Nat. Hazards 81 (2016) 99–121, https://doi.org/10.1007/s11069-015-2074-2.
[37] W. Hazeleger, B.J.J.M. van den Hurk, E. Min, G.J. van Oldenborgh, A.C. Petersen, D.A. Stainforth, E. Vasileiadou, L.A. Smith, Tales of future weather, Nat. Clim. Change 5 (2015) 107–113, https://doi.org/10.1038/nclimate2450.
[38] B. van den Hurk, C. Hewitt, D. Jacob, J. Bessembinder, F. Doblas-Reyes, R. Döscher, The match between climate services demands and Earth System Models supplies, Clim. Serv. 12 (2018) 59–63, https://doi.org/10.1016/j.cliser.2018.11.002.
[39] N. Schaller, J. Sillmann, M. Müller, R. Haarsma, W. Hazeleger, T.J. Hegdahl, T. Kelder, G. van den Oord, A. Weerts, K. Whan, The role of spatial and temporal model resolution in a flood event storyline approach in western Norway, Weather Clim. Extrem. 29 (2020), 100259, https://doi.org/10.1016/j.wace.2020.100259.
[40] Y.L. Everingham, R.C. Muchow, R.C. Stone, N.G. Inman-Bamber, A. Singels, C.N. Bezuidenhout, Enhanced risk management and decision-making capability across the sugarcane industry value chain based on seasonal climate forecasts, Agric. Syst. 74 (2002) 459–477, https://doi.org/10.1016/S0308-521X(02)00050-1.
[41] E.C. McNie, Reconciling the supply of scientific information with user demands: an analysis of the problem and review of the literature, Environ. Sci. Policy. 10 (2007) 17–38, https://doi.org/10.1016/j.envsci.2006.10.004.
[42] National Research Council, Informing Decisions in a Changing Climate, The National Academies Press, Washington, DC, 2009, https://doi.org/10.17226/12626.
[43] C.D. Hewitt, R. Stone, Climate services for managing societal risks and opportunities, Clim. Serv. 23 (2021), 100240, https://doi.org/10.1016/j.cliser.2021.100240.
[44] I. Alam, An exploratory investigation of user involvement in new service development, J. Acad. Mark. Sci. 30 (2002) 250, https://doi.org/10.1177/0092070302303006.
[45] B. Edvardsson, A. Gustafsson, P. Kristensson, L. Witell, Service innovation and customer Co-development, in: P.P. Maglio, C.A. Kieliszewski, J.C. Spohrer (Eds.), Handb. Serv. Sci., Springer US, Boston, MA, 2010, pp. 561–577, https://doi.org/10.1007/978-1-4419-1628-0_24.
[46] G. Felder, J.J. Gómez-Navarro, A.P. Zischg, C.C. Raible, V. Röthlisberger, D. Bozhinova, O. Martius, R. Weingartner, From global circulation to local flood loss: coupling models across the scales, Sci. Total Environ. 635 (2018) 1225–1239, https://doi.org/10.1016/j.scitotenv.2018.04.170.
[47] V. Thompson, N.J. Dunstone, A.A. Scaife, D.M. Smith, J.M. Slingo, S. Brown, S.E. Belcher, High risk of unprecedented UK rainfall in the current climate, Nat. Commun. 8 (2017) 107, https://doi.org/10.1038/s41467-017-00275-3.
[48] ECMWF, Operational Configurations of the ECMWF Integrated Forecasting System (IFS), ECMWF, 2014. https://www.ecmwf.int/en/forecasts/documentation-and-support. (Accessed 26 February 2023).
[49] ECMWF, SEAS5 User Guide, 2021. https://www.ecmwf.int/sites/default/files/medialibrary/2017-10/System5_guide.pdf.
[50] M.A. Ivanov, S. Kotlarski, Assessing distribution-based climate model bias correction methods over an alpine domain: added value and limitations, Int. J. Climatol. 37 (2017) 2633–2653, https://doi.org/10.1002/joc.4870.
[51] D. Maraun, F. Wetterhall, A.M. Ireson, R.E. Chandler, E.J. Kendon, M. Widmann, S. Brienen, H.W. Rust, T. Sauter, M. Themeßl, V.K.C. Venema, K.P. Chun, C. M. Goodess, R.G. Jones, C. Onof, M. Vrac, I. Thiele-Eich, Precipitation downscaling under climate change: recent developments to bridge the gap between dynamical models and the end user, Rev. Geophys. 48 (2010), https://doi.org/10.1029/2009RG000314.
[52] G. Coxon, J. Freer, R. Lane, T. Dunne, W.J.M. Knoben, N.J.K. Howden, N. Quinn, T. Wagener, R. Woods, DECIPHeR v1: dynamic fluxEs and ConnectIvity for predictions of HydRology, Geosci. Model Dev. (GMD) 12 (2019) 2285–2306, https://doi.org/10.5194/gmd-12-2285-2019.
[53] A. Zischg, Modelling spatiotemporal dynamics of flood risk change, in: Flood Risk Change Complex. Perspect., Elsevier, Amsterdam, Netherlands, 2023, 187–171.
[54] D. Vetsch, A. Siviglia, D. Ehrbar, M. Facchini, M. Gerber, S. Kammerer, S. Peter, L. Vonwiler, C. Volz, D. Farshi, R. Mueller, P. Rousselot, R. Veprek, R. Faeh, BASEMENT - Basic Simulation Environment for Computation of Environmental Flow and Natural Hazard Simulation, 2017. Version 2.8.
[55] AWN, Digitales Terrainmodell LIDAR 50cm, Amt für Wald und Naturgefahren des Kantons Bern, 2015. https://www.geo.apps.be.ch/de/geodaten/geoproduktedownload/listing.html?type=geoproduct&code=LDTM50CM.
[56] Kanton Zürich, Digitales Terrainmodell (DTM) (2014).
[57] Kanton Zug, Höhenmodell der amtlichen Vermessung 2013 auf Basis "Lidar", 2013.
[58] Kanton Solothurn, Digitales Terrainmodell (DTM) (2014).
[59] Kanton Luzern, Digitales Terrainmodell (DTM) (2012).
[60] Kanton Aargau, DTM 0.5-Meter Raster, 2014.
[61] Canton de Vaud, Modèles altimétriques LiDAR (2004).
[62] Swisstopo, SwissALTI3D (2013). https://www.swisstopo.admin.ch/de/geodata/height/alti3d.html. (Accessed 26 February 2023).
[63] RPF, Hydraulische berechnungen hochrhein, Regierungspräsidium Freiburg (RPF) (2015).
[64] D. Vetsch, M. Bürgler, S. Kammerer, L. Seidelmann, D. Vanzo, C. Volz, L. Vonwiler, BASEmesh-v2, 2021. https://basement.ethz.ch/download/tools/basemesh.html.
[65] A.P. Zischg, G. Felder, M. Mosimann, V. Röthlisberger, R. Weingartner, Extending coupled hydrological-hydraulic model chains with a surrogate model for the estimation of flood losses, Environ. Model. Softw. 108 (2018) 174–185, https://doi.org/10.1016/j.envsoft.2018.08.009.
[66] A.P. Zischg, M. Mosimann, D.B. Bernet, V. Röthlisberger, Validation of 2D flood models with insurance claims, J. Hydrol. 557 (2018) 350–361, https://doi.org/10.1016/j.jhydrol.2017.12.042.
[67] V. Röthlisberger, A.P. Zischg, M. Keiler, A comparison of building value models for flood risk analysis, Nat. Hazards Earth Syst. Sci. 18 (2018) 2431–2453, https://doi.org/10.5194/nhess-18-2431-2018.
[68] Swisstopo, swissTLM3D, Fed. Off. Topogr. Swisstopo, 2019. https://www.swisstopo.admin.ch/de/geodata/landscape/tlm3d.html. (Accessed 26 February 2023).
[69] Bundesamt für Gesundheit (BAG), Kennzahlen, 2022. https://www.bag.admin.ch/bag/de/home/zahlen-und-statistiken/zahlen-fakten-zu-pflegeheimen/kennzahlen.html. (Accessed 26 February 2023).
[70] Swisstopo, swissTLM3D, Fed. Off. Topogr. Swisstopo. (2022). https://www.swisstopo.admin.ch/en/geodata/landscape/tlm3d.html. (Accessed 26 February 2023).
[71] FSO, Structural Business Statistics STATENT 2014 Provisional, Federal Statistical Office (FSO), 2016. https://www.bfs.admin.ch/news/en/2016-0435. (Accessed 26 February 2023).
[72] FSO, Buildings and Dwellings Statistic (Since 2009), Federal Statistical Office (FSO), 2016. https://www.bfs.admin.ch/bfs/en/home/statistiken/bau-wohnungswesen/erhebungen/gws2009.html. (Accessed 26 February 2023).
[73] M. Bermúdez, A.P. Zischg, Sensitivity of flood loss estimates to building representation and flow depth attribution methods in micro-scale flood modelling, Nat. Hazards 92 (2018) 1633–1648, https://doi.org/10.1007/s11069-018-3270-7.
[74] A.P. Zischg, V. Röthlisberger, M. Mosimann, R. Profico-Kaltenrieder, D.N. Bresch, S. Fuchs, M. Kauzlaric, M. Keiler, Evaluating targeted heuristics for vulnerability assessment in flood impact model chains, J. Flood Risk Manag. 5 (2021) 171, https://doi.org/10.1111/jfr3.12736.
[75] KOHS, Freibord bei Hochwasserschutzprojekten und Gefahrenbeurteilungen, Wasser, Energ. Luft 105 (2013) 43–53.

[76] S. Bremer, S. Meisch, Co-production in climate change research: reviewing different perspectives, WIREs Clim. Change. 8 (2017) e482, https://doi.org/10.1002/wcc.482.

[77] R. Longhurst, Semi-structured interviews and focus groups, in: Key Methods Geogr., third ed., SAGE Publications, Los Angeles, 2016, pp. 143–156.

[78] D.B. Bernet, V. Prasuhn, R. Weingartner, Surface water floods in Switzerland: what insurance claim records tell us about the damage in space and time, Nat. Hazards Earth Syst. Sci. 17 (2017) 1659–1682, https://doi.org/10.5194/nhess-17-1659-2017.

[79] P. Costabile, C. Costanzo, G. De Lorenzo, R. De Santis, N. Penna, F. Macchione, Terrestrial and airborne laser scanning and 2-D modelling for 3-D flood hazard maps in urban areas: new opportunities and perspectives, Environ. Model. Softw. 135 (2021), 104889, https://doi.org/10.1016/j.envsoft.2020.104889.

[80] M. Pregnolato, A. Ford, S.M. Wilkinson, R.J. Dawson, The impact of flooding on road transport: a depth-disruption function, Transp. Res. Part Transp. Environ. 55 (2017) 67–81, https://doi.org/10.1016/j.trd.2017.06.020.

[81] C. Arrighi, M. Pregnolato, R.J. Dawson, F. Castelli, Preparedness against mobility disruption by floods, Sci. Total Environ. 654 (2019) 1010–1022, https://doi.org/10.1016/j.scitotenv.2018.11.191.

[82] Staatsarchiv Kanton Bern, Die Broye tritt über die Ufer, 1944. https://www.query.sta.be.ch/detail.aspx?ID=427834. (Accessed 26 February 2023).

[83] W. Schmid, Schötz Hochwasser, zerstörte Brücke über die Wigger zum Weiler Bifig, ETH-Bibliothek Zürich, Bildarchiv, 1972, https://doi.org/10.3932/ETHZ-A-000899610.

[84] G.R. Bezzola, C. Hegg, Ereignisanalyse Hochwasser 2005, Teil 1 – Prozesse, Schäden und erste Einordnung., Bundesamt für Umwelt BAFU and Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft (WSL), Bern and Birmensdorf, 2007. https://www.bafu.admin.ch/bafu/de/home/themen/naturgefahren/publikationen-studien/publikationen/ereignisanalyse-hochwasser-2005-prozesse-schaeden-und-erste-einordnungen.html. (Accessed 26 February 2023).

[85] WMO, WMO Guidelines on Multi-Hazard Impact-Based Forecast and Warning Services, World Meteorological Organization (WMO), Geneva, 2015. https://library.wmo.int/index.php?lvl=notice_display&id=17257. (Accessed 26 February 2023).

[86] M. Siegrist, H. Gutscher, Flooding risks: a comparison of lay people's perceptions and expert's assessments in Switzerland, Risk Anal. 26 (2006) 971–979, https://doi.org/10.1111/j.1539-6924.2006.00792.x.

[87] I. Dallo, M. Marti, Why should I use a multi-hazard app? Assessing the public's information needs and app feature preferences in a participatory process, Int. J. Disaster Risk Reduc. 57 (2021), 102197, https://doi.org/10.1016/j.ijdrr.2021.102197.

[88] S. Potter, S. Harrison, P. Kreft, The benefits and challenges of implementing impact-based severe weather warning systems: perspectives of weather, flood, and emergency management personnel, Weather Clim. Soc. 13 (2021) 303–314, https://doi.org/10.1175/WCAS-D-20-0110.1.

[89] T.J. Hegdahl, K. Engeland, M. Müller, J. Sillmann, An event-based approach to explore selected present and future atmospheric river–induced floods in western Norway, J. Hydrometeorol. 21 (2020) 2003–2021, https://doi.org/10.1175/JHM-D-19-0071.1.