European Water 57: 179-185, 2017.

Development of flood and mudflow events for the spatio-temporal risk assessment of networks

J. Hackl[1*], M. Heitzler[2], J.C. Lam[1], B.T. Adey[1] and L. Hurni[2]
[1] *Institute of Construction and Infrastructure Management, Swiss Federal Institute of Technology (ETH), Zürich, Switzerland*
[2] *Institute of Cartography and Geoinformation, Swiss Federal Institute of Technology (ETH), Zürich, Switzerland*
[*] *e-mail: hackl@ibi.baug.ethz.ch*

Abstract: Networks such as transport, water and power are critical lifelines to society. Network managers plan and execute interventions to guarantee their operational state under various circumstances, including after the occurrence of (natural) hazard events. Creating an intervention program demands knowing the probable network-related consequences (i.e., risk) of the various stochastic hazard events that could occur. The way such events are simulated has implications on (i) the overall computational cost of the entire risk assessment, which increases as the complexity of the network of interest increases, (ii) the accuracy of the individual risk estimations, as well as (iii) the quantified uncertainty of resulting risk estimations. To support network managers in their task to assess network-related risks, a method is presented here to develop rainfall-triggered hazard events, namely riverine flood events and mudflow events. The method enables the generation and simulation of hazard events that (i) are of a specific modeller-defined return period, enabling the characterization of the uncertainty of risk estimation for given return periods, and (ii) change over space and time, leading to the spatio-temporal estimation of network-related risk. The method is designed for network managers, and therefore, integrates computationally-efficient models that can be quickly coupled, and require data that is generally available or can be easily obtained or estimated, without impacting the integrity of the results. An example is presented to illustrate the application of the method to develop flood and mudflow events to be used in the assessment of risk for a road network in Switzerland.

Key words: Risk assessment, probabilistic modelling, natural hazards, flood, mudflow

1. INTRODUCTION

Managers of transport, water, power and other networks need methods that support decisions on maintenance, repair, retrofit, renewal and other infrastructure management interventions. Since their networks are spatially distributed and have temporal attributes (e.g., traffic flow, water demand and electricity consumption vary throughout the day), managers understand that independent and dependent disruptive events could occur at one or multiple points within the network, and manifest at different times for various lengths. As a result, each possible scenario will lead to a different set of consequences in terms of restoration costs and loss of level of service. In particular, managers, whose networks are exposed to (natural) hazards, are in need of probabilistic methods that can support the quantification of probable consequences, here referred to as risks, along with their uncertainty, by considering the various stochastic ways hazard events could manifest.

A number of research works has put forward methods, models and support systems in response to these needs. These works cover a wide area of contributions, from those solely concerned with assessing the probable costs of restoration (e.g., Padgett et al. (2010) for the transport sector due to earthquake hazard events) to assessing the probable loss of service (e.g., Hackl et al. (2015) for the transport sector due to flood hazard events). There are also works that have investigated the effects of cascading events (e.g., Kiremidjian et al. (2007) for the transport sector with respect to liquefaction and landslide hazard events due to ground shaking) and a large set of stochastic events (i.e., over 1000; e.g., ERN-AL (2012) for the water sector due to earthquake hazard events). Methods that integrate these various important elements are still needed to support the management of networks. Furthermore, there is a need to expand methods related to the assessment of consequences due to spatio-temporal hazard events such as hydro-meteorological hazards as a large majority of the literature focuses on geological hazards, specifically earthquakes, which are often simulated as sudden events with only spatial characteristics.

The probabilistic method presented here supports the numerical estimation of risk while reducing the computational cost of modelling a complex system, which comprises the continuous, non-linear interaction between a network and its surrounding environment, using peer-reviewed simplified models. As a result, the method supports the simulation of a large set of hazard events and the subsequent quantification of the uncertainty of risk results. The method is solely concerned with rainfall-triggered hazard events, specifically riverine flood events as well as mudflow events, which are modelled as events that change over space and time. The application of the method is illustrated by an example of a road network in Switzerland.

2. PROBABILISTIC METHOD

The presented probabilistic method was constructed using the iterative process described in Adey et al. (2016). The detailed quantitative and computer-supported models used to estimate network-related risk are described in Hackl et al. (2016) and Heitzler et al. (2016). In this paper, the focus lies on the *hazard module* (i.e., the modelling of the different rainfall-triggered events and their interactions over space and time).

The environmental conditions, whose data is generally available (e.g., terrain, hydrological network, gauge station data), can be approximated (e.g., precipitation fields Sigrist et al. (2012)), or can be collected through inventory (e.g., geological features), and hazard events, which could possibly impact the network, are defined through the hazard module that is illustrated in Figure 1 using Business Process Model and Notation (BPMN). Each specific event, which should be considered in the risk assessment, is described by a so-called *model*, which is in this context a peer-reviewed model (i.e., understood to be accurate given the assumptions and limitations of each of those models) with unambiguously-defined input and output interfaces. Inputs are either provided via external input (e.g., user inputs, geo data, historical data) or via internal input (i.e., by using outputs of other models generating compatible datasets). Hence, each model interacts with other models by receiving and delivering information (i.e., processed data). This dynamic interaction is also shown in Figure 1.

Most network managers are mainly interested in the additional loads impacting their critical structures, and therefore, need to have the capability to select hazard events based on the periodicity of the manifested site-specific loads, as opposed to being primarily concerned with the preceding source rainfall events leading to those loads. The presented probabilistic method accounts for this particular need by enabling the selection of the hazard events based on the return period of interest related to loads at a specific site. This selection is achieved through a calibration process (Figure 1). In this process, a random rainfall event is produced, and the corresponding discharge values are computed. Should the obtained discharge value at a location of interest be in the 50-percentile of the discharge values calculated for that specific location using gauge data and for the desired return period, the simulation continues; otherwise, the rainfall event gets calibrated, and the evaluation process starts again.

In order to provide a computationally-efficient and accurate estimation of risk, the structures of the models and of the modelling environment in which the models are embedded have to be adapted to the specific context and needs of a network manager. For example, the hazard module illustrated in Figure 1 describes two hazard events: riverine flood events and mudflow events. Both hazards are triggered by a rainfall event, which causes additional discharge in the rivers and an increase in surface-water flow.

Once the models and data are assembled appropriately, the modelling environment can be used to perform simulations. The inputs for the simulation may be defined by the network manager or potentially automated when performing multiple runs (e.g., by sampling a certain distribution using

Monte Carlo methods). The results of a simulation represents the outcome of a so-called *scenario*, which is one possible sequence of events based on a set of initial conditions.

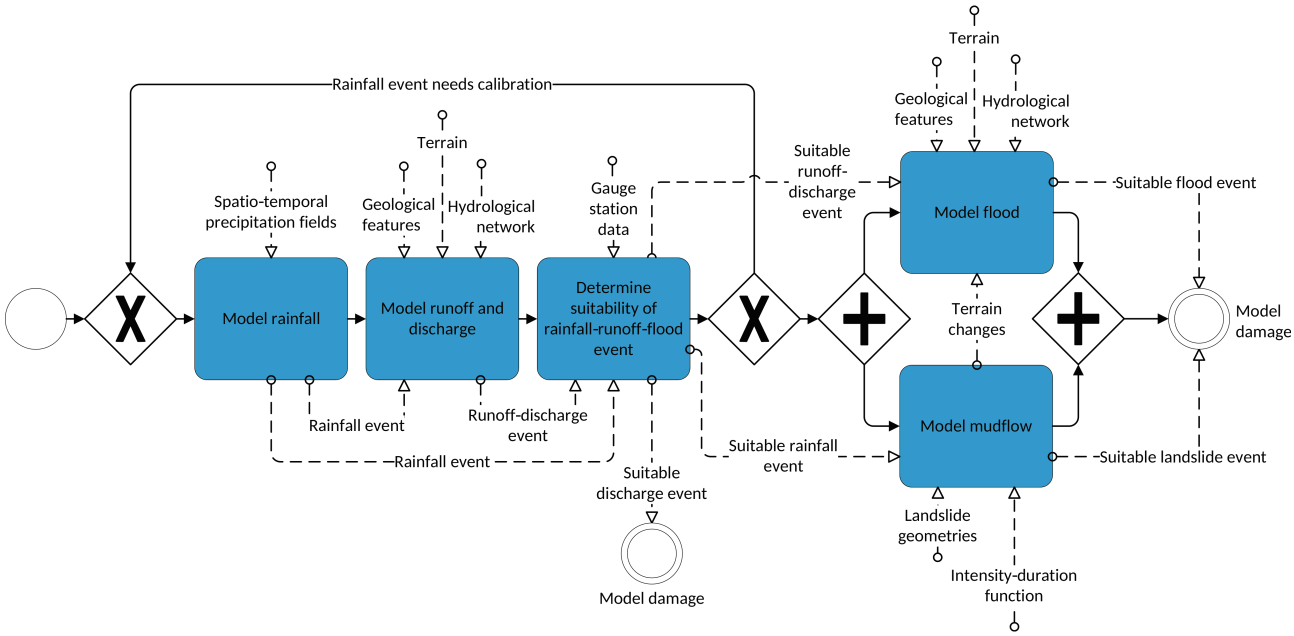

Figure 1. Hazard module for rainfall-triggered events.

The use of stochastic inputs allows to express the uncertainties related to the environmental conditions. For example, the use of a random spatio-temporal precipitation field allows to consider uncertainties related to the rainfall event. These uncertainties propagate through the entire hazard module and will be passed on to succeeding models (i.e., damage model and consequence models for costs of restoration and loss of level of service), influencing the estimated risks. Instead of single risk values for a specific return period, a distribution of risk can be obtained.

3. EXAMPLE

3.1 Introduction

An example is included here to illustrate the application of the method described to determine the probable environmental conditions surrounding road networks and the resulting riverine flood events and mudflow events, for the Rhine Valley area around Chur, Switzerland in the Canton of Grisons (Figure 3.B) This area was suspected to have an unacceptable level of road network-related risk due to riverine floods as well as mudflows. Historical records and previous studies suggested that the heavy rainfalls in this area have the potential to result in the listed hazard events. The road network in the area of study, which is considered to play an important role in the economy of the eastern part of Switzerland, consists of 32 km of high speed roads, 559 km of local roads, and 92 bridges, with many of these objects exposed to the hazards of interest. A detailed description of the area in the context of the example can be found in Hackl et al. (2016).

3.2 Application of method

To describe the environmental conditions and hydro-meteorological hazard events, the model shown in Figure 1 was utilized. This model included five defined sets of activities:

1. The rainfall events were generated based on the spatio-temporal precipitation fields of the RdisaggH-Dataset (Wüest et al., 2010). This dataset was reduced to the extent of the target

area and regridded to conform to the target extent and resolution. Based on a predetermined start date and duration, the corresponding subset from the spatio-temporal precipitation catalogue was extracted. The fields of this catalogue subset were then normalized according to the maximum rainfall amount over the considered time period. Afterwards, each normalized value was multiplied by a randomized precipitation volume. Once a precipitation volume was assigned to each dataset, the datasets themselves were normalized. By multiplying the assigned precipitation volume for a given time step to that precipitation field, the actual amounts of rainfall were determined.

2. The runoff volume was computed from the volume of rainfall that was considered to be intercepted, infiltrated, stored, evaporated, or transpired. Therefore, the ModClark model (Kull and Feldman, 1998) was used to estimate the discharge during the rainfall event. This model explicitly accounts for translation and storage, where the storage was determined through a linear reservoir model. Translation was accounted for through a grid-based travel-time model. The grid was superimposed on the watershed. For each cell of the grid representation of the watershed, the distance to the watershed outlet was specified. Translation time to the outlet was computed. The area of each cell was specified, and from this, the volume of inflow to the linear reservoir for each time interval was computed as the product of area and rainfall excess. This excess was computed for each cell using the watershed data extracted from the GIS model. Each cell's excess was then lagged to the basin outlet according to the cell's travel time. Next, individual lagged cell outflows were routed through a linear reservoir, with a lag time due to natural storage effects. The lagged and routed outflows were then summed, base flow was added, and the watershed's outlet hydrograph was produced.
3. The rainfall and the runoff model were used together to determining whether the resulting discharge scenario corresponded to the discharge value of a desired return period, which was estimated based on available gauge data. If the desired return period was not achieved, the rainfall event was calibrated (i.e., up-scale, down-scale of predetermined spatio-temporal precipitation fields), and the analysis was performed again.
4. A simple 1D model was used and justified by the relatively large size of the investigated area (approximately 20 km) and the need of a model that would require relatively little computation time to run simulations. In particular, a steady and gradually varied flow in open channels was considered. The required discharge and stage data were acquired by the hydrological model, described above, using rainfall data as an input, rather than being measured by gauge stations. The outputs of interests were the velocity, shear stress, and water depth in each cross-section of the rivers, which could be used for estimating the effects on network objects such as bridges, ramps, and dams.
5. Also due to computational constraints, the design of the mudflow model was kept simple, considering only predetermined areas of potential landslides (Losey and Wehrli, 2013). In total, 54 potential mudflows were considered for the target area. Because the duration of landslides to occur usually is in the range of seconds to minutes while the time step of the simulation was one hour, the dynamic process itself was not modelled. For each time step, an iteration was performed over all triggering locations. For each location, the respective values were extracted from the precipitation field and used as input for the intensity-duration function (Rickenmann, 1999): $T=32\cdot D^{-0.72}$, where T was the threshold that caused the mudflow to be potentially triggered when exceeded, and D was the duration of the rainfall event in the triggering location. The output of this model for each time step was a digital elevation map (DEM), whose elevation values were updated according to the heights of the triggered landslides at a given time step.

The major source of randomness was introduced by the directionality of the spatio-temporal precipitation fields and the scaling of these. In the considered scenarios, the initial condition that the network manager could freely chose was limited to the return period(s) of the flood. This feature was of particular importance to support scenario selection for infrastructure management applications (e.g., assess the performance of a network with respect to a given return period) and the quantification of the uncertainty of probable consequences for a desired return period.

In total, 1,180 simulations were conducted: 20 simulations for each of the return periods between 1 and including 9 years as well as 100 simulations for each of the return periods of 10, 25, 50, 100, 250, 500, 1,000, 2,500, 5,000 and 10,000 years - such selection enables the generation of a loss exceedance curves (i.e., functional representations of cost of restoration or monetized loss of level of service over return periods). Depending on the return period, rainfall patterns with different durations were calculated. For return periods smaller than 100 years, the rainfall patterns had a duration of 7 to 13 hours, for periods between 100 and 1,000 years. Patterns had a duration between 10 and 16 hours, and for patterns greater than 1,000, they had a duration between 13 and 19 hours. The durations of the resulting flood events varied greatly and were in the range of 20 to 30 hours.

3.3 Software and hardware

The code used in the determination of the risk was programmed in Python. Since most network managers use geographic information systems (GIS), a GIS interface was developed to facilitate the import and export of data. Furthermore, the program code was optimized for massively parallel computing in order to reduce the computational time of the optimization process (i.e., each simulation ran on a designated CPU, and therefore, an increase in the amount of CPUs, increases the number of simulations). The computation of the scenarios was conducted on a 4x10 Core Intel Xenon E5-2690v2 3.0Ghz, 384GB DDR2 server running on Ubuntu 14.04 64bit operating system. Overall, the real-time computational time for all hazard events amounted to approximately 2 days.

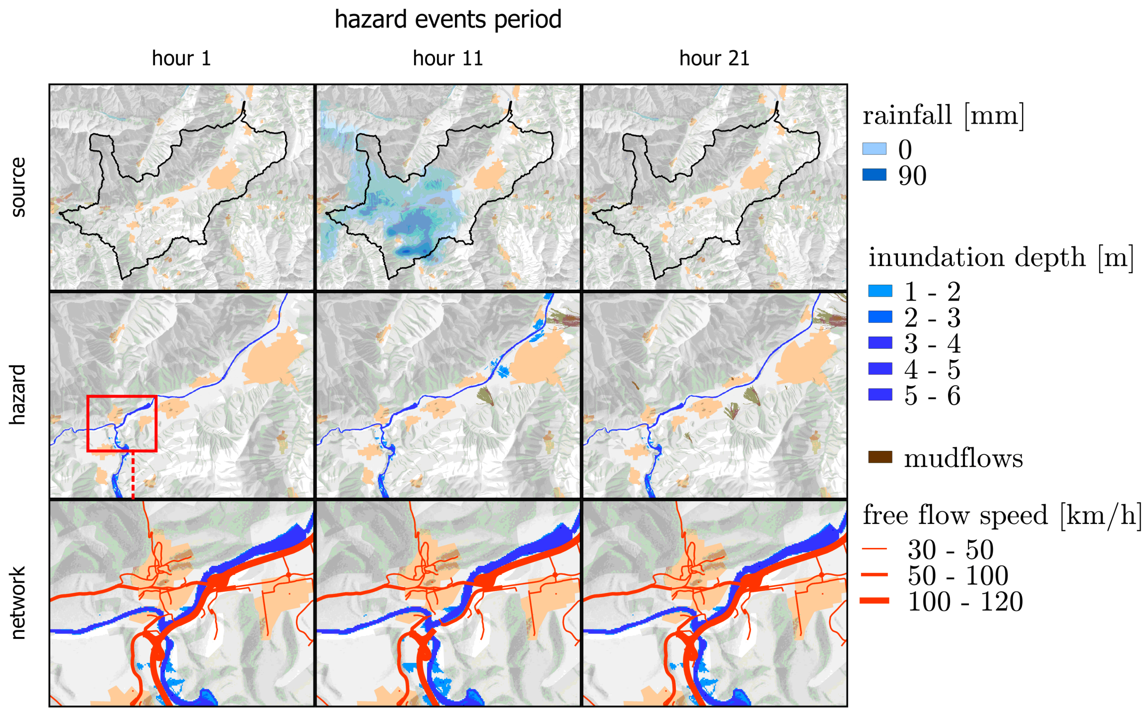

Figure 2. Changes over time for a specific simulation run.

3.4 Results

Figure 2 shows how the rainfall, the flood and the mudflow events, and the consequences of the road network change over time for one specific simulation run. While the beginning of the simulation (hour 1) corresponds to a period before the hazard events occur, hours 11 and 21 correspond to periods during and at the end of the hazard events, respectively. In addition to the evolution of the flood event over time, the triggering of different mudflow events can be observed, which can be used in a later processing step to estimate the probable consequences on the network, which in this case are changes of free flow speed on the inundated and damaged road network.

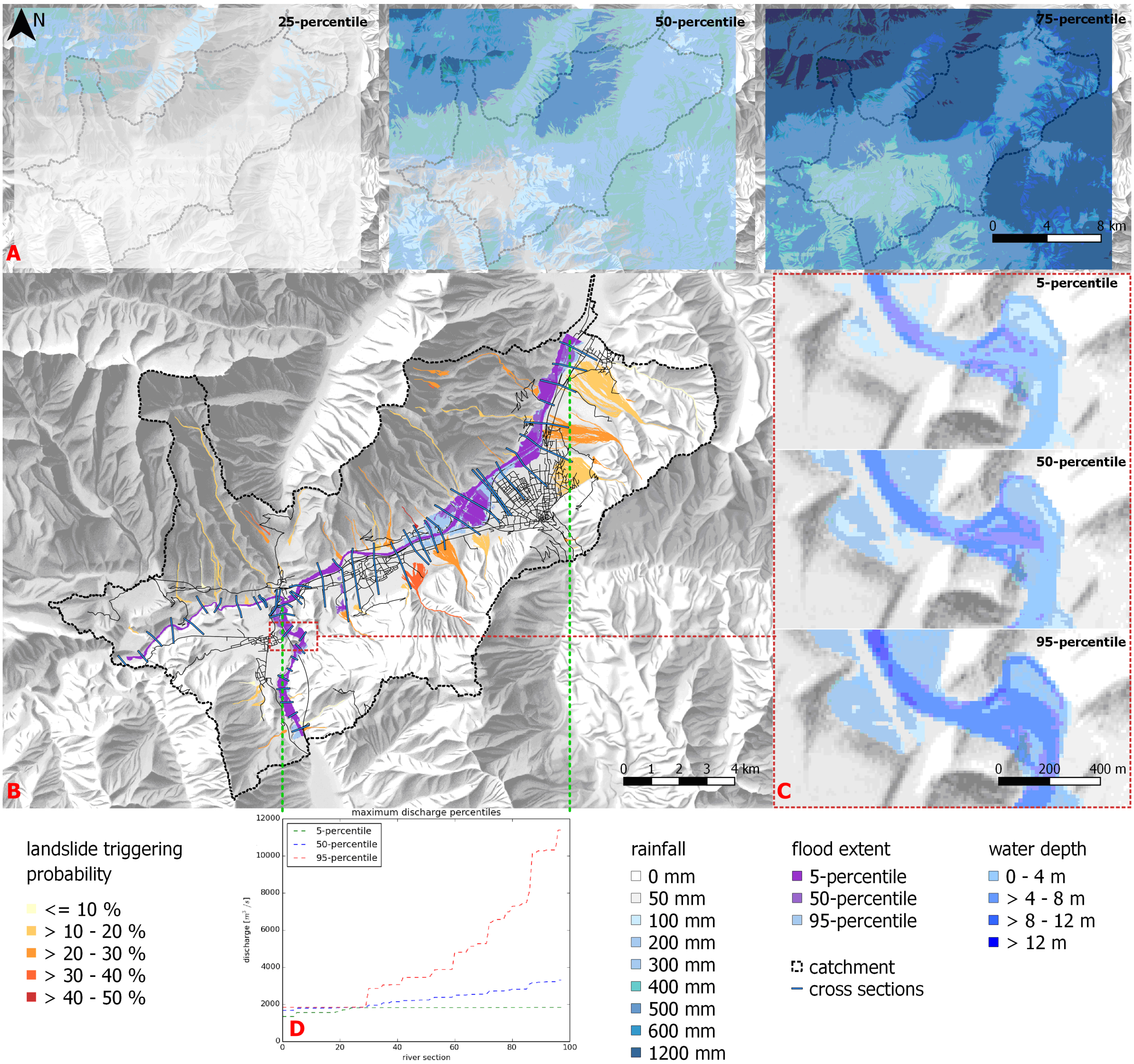

Figure 3. Aggregated simulation for a return period of 500 years.

The aggregated simulation results for a scenario with a return period of 500 years are illustrated in Figure 3. Figure 3.A shows the 25, 50 and 75-percentile of precipitation fields, where darker areas indicate more intense rainfall. An overview of the area is given in Figure 3.B. In this figure, the hazard events of interest are also presented, specifically the 5, 50 and 95-percentile of possible inundation depths and the location of possible mudflows color-coded according to their probability of occurrence. Figure 3.C zooms into a particular area. The expected discharge along the river is illustrated in Figure 3.D. It can be observed that the, 5, 50 and 95-percentile values are approximately 1,800 m^3/s at section 30, because in the chosen scenario this value corresponds to the targeted discharge value of the 500 year flood event at a predefined gauging station located in that section.

4. CONCLUSIONS

The probabilistic method introduced here supports the modelling of the environmental conditions and hazard events impacting networks. As defined here, hydro-meteorological hazards such as riverine flood events and mudflow events change over space and time. With the decomposition into peer-reviewed models, this complexity was reduced, which resulted in a decrease of the overall computational cost of the entire risk assessment and allowed to quantify the uncertainty of resulting risk estimations. Therefore, network manager rely on computationally-efficient models that can be quickly coupled and require data that is generally available or can be easily obtained or estimated, without impacting the integrity of the results. When an increased level of detail is required of any model, this could be achieved at a computational cost.

The method was implemented in the context of an example that aimed at stochastically simulating spatio-temporal rainfall events that caused flood and mudflow events. The results of this application are of significance to risk assessments for networks. For example, besides temporary inundation, flood events can cause scour to selected bridges that play a key role in communicating two sides of a city. Also, mudflow events can cause permanent damage to road sections that are critical due to lack of redundancy (e.g., alternative routes). Despite the virtues of the probabilistic method presented here, there is still work to be done in the development of flood and mudflow events to support network managers in calculating network related risk. Future work may focus on enhancing the hazard module described in the example to output refined results. This may include improving the determination of the time periods for the rainfall events and the intensity-duration function that triggers the mudflow events. Furthermore, given the need to determine the uncertainties related to the results, it is necessary to further explore the adequate distribution of the inputs and initial conditions. Further work could also consider an enhancement to account for the uncertain calculated discharge values in the calibration process.

REFERENCES

Adey, B. T., J. Hackl, J. C. Lam, P. van Gelder, P. Prak, N. van Erp, M. Heitzler, I. Iosifescu-Enescu, and L. Hurni (2016). Ensuring acceptable levels of infrastructure related risks due to natural hazards with emphasis on conducting stress tests. In K. Kobayashi (Ed.), 1st International Symposium on Infrastructure Asset Management (SIAM2016), Kyoto, Japan, pp.19–29.

Consorcio Evaluación de Riesgos Naturales América Latina, E.-A. (2012). Tomo i: Perfil de riesgo catastrófico, medidas de mitigacin y proteccin financiera. caso sedapal y emapica. Report, Programa de Agua y Saneamiento del Banco Mundial.

Hackl, J., B. T. Adey, M. Heitzler, and I. Iosifescu-Enescu (2015). An overarching risk assessment process to evaluate the risks associated with infrastructure networks due to natural hazards. Special Issue of International Journal of Performability Engineering on Transport System Safety, Risk and Asset Management 11(2).

Hackl, J., M. Heitzler, J. C. Lam, B. T. Adey, and L. Hurni (2016). Final model, methodology and information exchange. Deliverable 4.2, Novel indicators for identifying critical, INFRAstructure at RISK from Natural Hazards (INFRARISK). grant agreement No. 603960, 224p.

Heitzler, M., J. C. Lam, J. Hackl, B. T. Adey, and L. Hurni (2016). Improved visualization of risk related to network infrastructure. 9th International Forum on Engineering Decision Making (IFED), Stoos, Switzerland.

Kiremidjian, A., J. E. Moore, Y. Fan, O. Yazlali, N. Basoz, and M. Williams (2007). Seismic risk assessment of transportation network systems.

Kull, D. and A. Feldman (1998). Evolution of clark's unit graph method to spatially distributed runoff. Journal of Hydrologic engineering 3(1), 9–19.

Losey, S. and A. Wehrli (2013). Schutzwald in der schweiz: Vom projekt silvaprotect-ch zum harmonisierten schutzwald. Final report, Bundesamt für Umwelt (BAFU), Bern, Switzerland.

Padgett, J. E., R. DesRoches, and E. Nilsson (2010). Regional seismic risk assessment of bridge network in charleston, south carolina. Journal of Earthquake Engineering 14(6), 918–933.

Rickenmann, D. (1999). Empirical relationships for debris flows. Natural Hazards 19(1), 47–77.

Sigrist, F., H. R. Künsch, and W. A. Stahel (2012). A dynamic nonstationary spatio-temporal model for short term prediction of precipitation. The Annals of Applied Statistics 6(4), 1452–1477.

Wüest, M., C. Frei, A. Altenhoff, M. Hagen, M. Litschi, and C. Schär (2010). A gridded hourly precipitation dataset for Switzerland using rain-gauge analysis and radar-based disaggregation. International Journal of Climatology 30(12), 1764–1775.