Monitoring systems for adaptive flood risk management

Inauguraldissertation
der Philosophisch-naturwissenschaftlichen Fakultät
der Universität Bern

vorgelegt von

Nele Barbara Rindsfüser

LeiterIn der Arbeit:
Prof. Dr. Margreth Keiler
Institut für Geographie
Universität Innsbruck

Prof. Dr. Andreas Paul Zischg
Mobiliar Lab für Naturrisiken, Oeschger-Zentrum für Klimaforschung,
Geographisches Institut, Universität Bern

Monitoring systems for adaptive flood risk management

Inauguraldissertation
der Philosophisch-naturwissenschaftlichen Fakultät
der Universität Bern

vorgelegt von
Nele Barbara Rindsfüser

LeiterIn der Arbeit:
Prof. Dr. Margreth Keiler
Institut für Geographie
Universität Innsbruck

Prof. Dr. Andreas Paul Zischg
Mobiliar Lab für Naturrisiken, Oeschger-Zentrum für Klimaforschung,
Geographisches Institut, Universität Bern

Von der Philosophisch-naturwissenschaftlichen Fakultät angenommen.

Bern, 16.Mai 2025

Der Dekan
Prof. Dr. Jean-Louis Reymond

«Was immer du tun kannst oder wovon du träumst – fang damit an.
Mut hat Genie, Kraft und Zauber in sich.»

- Johann Wolfgang von Goethe

Abstract

Flood risk management aims to reduce risks, manage residual risks, and prevent new risks in order to strengthen resilience and contribute to the prevention of increasing flood losses. Climate change, land-use change, human intervention, and socio-economic development lead to dynamics in the main risk components - hazard, exposure, and vulnerability. The spatiotemporal evolution of flood risk poses challenges to flood risk management, necessitating continuous adaptation of risk management strategies. To enable adaptive flood risk management, it is necessary to understand and quantify the evolution of flood risk, and its components hazard, exposure, and vulnerability. A strategy to operationalize adaptive flood risk management is the establishment of a risk monitoring system that systematically identifies critical developments. However, a risk monitoring system (including changes of hazard, exposure, and vulnerability) is currently lacking in both its conceptualization and implementation. This PhD thesis addresses this gap by undertaking the following three objectives: (i) to elaborate principles of flood risk monitoring, (ii) to evaluate the application of flood risk monitoring and (iii) to integrate variations in vulnerability into risk analysis to enhance the knowledge about the impact on flood risk and flood risk monitoring.

The first paper distills the fundamental steps necessary for the elaboration of a flood risk monitoring system. A systematic literature review was conducted to identify and deepen the understanding of local and regional flood risk evolution studies. The synthesis of the literature review delineates the main objectives, key factors and methods that have been selected for the analysis of flood risk evolution and the results of the flood risk analyses. The findings of the review indicate that there is no universally applicable strategy for the monitoring of flood risk. Moreover, the heterogeneity of the approaches hampers comparability of results. Nevertheless, the review enables the formulation of conclusions concerning the monitoring of flood risk and the distillation of the principles of flood risk monitoring. The findings indicate that risk emerges from the interactions between the risk components (hazard, exposure, and vulnerability), thereby indicating that risk itself cannot be directly monitored. The integration of data and proxy data concerning evolving risk factors necessitates the implementation of methodologies such as data mining, data modeling, data analysis, and data combination. The principles of flood risk monitoring, outlined in this paper are as follows: repeated flood risk analyses consisting of the systematic measurement of factors influencing hazard, exposure, and vulnerability; modeling the risk components; and the combination of these components to quantify risk.

The second paper evaluates the implementation of flood risk monitoring through a national case study of Switzerland, encompassing a 10-year data collection period. Data streams of hazard (continuously updated hazard maps), exposure (number of houses in potentially endangered areas), and vulnerability (degree of damage) were collected and analyzed to calculate risk (in terms of potential damage) evolution for each year between 2014 and 2023. The findings indicate that the flood risk in Switzerland has undergone distinct annual changes. These changes are accompanied by spatial variability in the evolution of the flood risk and its components across various administrative units. From 2014 to 2023, the total flood risk in Switzerland increased by 26%, the hazard area expanded by 32%, and the exposure grew by 35%. The disentangling of risk factors facilitates a more profound comprehension of the predominant drivers that increase or decrease risk. The selection of data and methods for the flood risk monitoring concept enabled the systematic quantification of annual flood risk at the national, cantonal, and municipal scale. Consequently, the monitoring of individual risk factors contributes to the observation of risk evolution, thereby validating the efficacy of the flood risk monitoring concept. Nevertheless, challenges persist regarding data availability and consistency, impeding effective flood risk monitoring.

The third paper examines the quantitative knowledge concerning the implementation level and damage-reducing effects of property-level flood risk adaptation (PLFRA) measures. A local case study in the Swiss municipality of Burgdorf was conducted to collect data on PLFRA and incorporate this data into the flood risk analysis, which is based on a comprehensive risk modeling chain. The results demonstrate that neglecting PLFRA measures in the risk analysis leads to an overestimation of flood risk. The incorporation of PLFRA measures and their level of protection in the risk analysis reduced flood risk by 18%. Furthermore, the consideration of all protection levels resulted in a 23% reduction in flood risk.

Additionally, a protection level of 0.5m for each building would reduce the risk by 50%. The results support the notion that adaptive flood risk management requires approaches that consider the spatiotemporal evolution of all risk components (hazard, exposure, and vulnerability).

In conclusion, this doctoral thesis provide a critical perspective on flood risk evolution and introduces principles of flood risk monitoring that enhance the understanding of systemic risks and support the development of a flood risk monitoring concept. Based on these principles, a flood risk monitoring concept is evaluated to identify insights about benefits, challenges, limitations and key lessons to refine the framework and enhance the applicability for long-term flood risk monitoring. Based on the identified gap in the first and second study that vulnerability is often neglected in flood risk evolution analyses, we consider in a third study vulnerability mitigation in flood risk analysis to improve flood risk monitoring.

Keywords: Flood risk dynamic, flood risk evolution, flood risk monitoring, adaptive flood risk management, flood vulnerability analysis, proof of monitoring concept, global change

Contents

1 Introduction: Thesis rationale and scope

River floodplains are popular areas for residential and economic development.[1–4] In recent decades, there has been a significant increase in population and economic assets in flood-prone areas, resulting in increased flood susceptibility and damage.[5,6] Globally, floods represent the most frequent natural hazard, accounting for 31% of economic losses and 16% of fatalities from 1970 to 2019, underscoring their growing severity and impact on societies.[7,8]

Flood risk is commonly defined as the potential adverse consequences of floods in a specified period of time, resulting from dynamic interactions between hazard, exposure, and vulnerability.[9,10] Flood risk management aims to reduce risk, manage residual risk and prevent new risks by analyzing, assessing and evaluating flood risk. An integral part of understanding past, present and/or future risk, and selecting appropriate risk management measures, is a pre-event flood risk analysis. In this analysis, the hazard (frequency and magnitude of floods), exposure (population and assets in flood-prone areas), and vulnerability (susceptibility of the exposed elements) are analyzed to quantify risk.[11]

However, flood risk is subject to change over time.[12–16] The influence of climate change, land-use change, human interventions and socio-economic developments on hazard, exposure and vulnerability has led to and will lead to the evolution of risk.[17–19] Consequently, new strategies in flood risk management are required, moving away from a very static perspective of flood risk towards the integration of changes in flood risk.[20–22] The understanding of flood risk evolution under global change conditions is essential for sustainable decision-making in disaster risk reduction. Adaptive flood risk management can be defined as a strategy for responding to global changes and addressing uncertainties in the planning process.[23–25] It is vital to facilitate adaptive flood risk management and ensure sustainable decision-making in flood risk management. This necessitates a comprehensive understanding, thorough assessment, and continuous monitoring of flood risk evolution.[11,20]

At the international level, the Sendai Framework for Disaster Risk Reduction[26] delineates specific actions for managing disaster risk. Priorities 1 and 2 highlight the significance of enhancing the understanding, assessment, and monitoring of flood risks, while strengthening the mechanisms to achieve these objectives.[26] However, the monitoring tools under Priority 4 primarily focus on observing hazards, disaster losses, and impacts rather than tracking changes over time.[26] In Europe, the EU Floods Directive mandates European Member States[27] to adopt structured methodologies for flood risk management, including periodic reviews and updates every six years to mitigate flood impacts. Nevertheless, these updates are primarily focused on enhancing risk reduction rather than continuously monitoring risk evolution. The comparison of flood risk assessments between successive updates remains challenging due to variations in assessment methodologies.[28–30] Despite this, there is still a lack of guidance and examples for establishing a flood risk monitoring system that supports proactive and adaptive flood risk management.

In recent years, studies analyzing flood risk have increasingly focused on the analysis of the evolution of flood risk, hazard, exposure, and/or vulnerability.[15,31] Within these studies, the understanding of flood risk evolution is deepened by repeating flood risk analyses for selected points in time and spatial scales.[32] However, factors, methods and results vary between studies implying that no "one size fits all applicable risk monitoring strategy" exists.[32] Additionally, most of the studies neglect the evolution of one or more risk components and use different definitions of flood risk.[32,33] The most neglected component is vulnerability. However, risk models that incorporate changes in vulnerability, such as those resulting from property-level flood risk adaptation measures, are crucial for assessing the evolution of flood risk over time. However, the mitigation of vulnerability is rarely considered in flood risk analysis due to a lack of quantitative knowledge about the implementation and damage-reducing effects of PLFRA measures.[34]

In view of the fact that the systematic monitoring of flood risk evolution in flood risk management, incorporating the analysis and quantification of all risk components, is a relatively new research topic, there are several open questions. These include, but are not limited to, data integration, method selection, long-term data consistency, data comparison and the benefits for adaptive flood risk management.

In order to enhance our understanding of flood risk monitoring, the specific objectives of this thesis are as follows:

1. **Review of flood risk evolution studies for the development of flood risk monitoring principles**

   The first objective of this thesis is to provide a synthesis of existing research on flood risk evolution through a systematic review of peer-reviewed literature. A range of approaches to addressing flood risk evolution, the dynamic risk components considered, and the contributions of these studies are analyzed in order to develop principles of flood risk monitoring. The aim is to provide a critical perspective on flood risk evolution and to outline key steps for flood risk monitoring. The objective is to contribute to an iterative framework that enhances the understanding of systemic risk and supports adaptive flood risk management (Chapter 2).

2. **Evaluation of a national flood risk monitoring concept**

   The second objective is to develop a systematic flood risk analysis framework to quantify the evolution of flood risk across administrative units in Switzerland over a specific period. The aim is to gain insights from monitoring annual flood risk evolution, highlighting spatial variations and the dynamics of risk components in order to detect spatiotemporal trends and support adaptive risk management. By developing and evaluating the national flood risk monitoring concept, the study aims to identify challenges and limitations in the implementation of the monitoring approach and to draw key lessons to refine the framework and enhance its applicability for long-term flood risk monitoring (Chapter 3).

3. **Consideration of vulnerability mitigation in flood risk analysis to improve flood risk monitoring**

   The third objective is to analyze the level of implementation of property-level flood risk adaptation (PLFRA) measures and to quantify the effect of PLFRA measures on the overall flood risk in a Swiss municipality. This involves collecting data on PLFRA measures through a field survey, incorporating it into the flood risk analysis, and evaluating their damage-reducing effects. The study aims to demonstrate that neglecting detailed information on all risk components can lead to oversimplified or inaccurate flood risk estimates, highlighting the need to integrate such data into flood risk monitoring for adaptive flood risk management (Chapter 4).

The main findings from Chapters 2 to 4 are synthesized in Chapter 5, with a brief summary of identified limitations and an outlook on further research to advance the concept of flood risk monitoring. Despite the focus on flood risk in this thesis, the scientific basis for flood risk monitoring developed in this thesis can be generalized and is valid for monitoring risk evolution from other natural hazards as well. This research contributes to the broader field of disaster risk reduction by developing, validating, and improving monitoring systems for adaptive flood risk management.

References

1. Alves, P.B.R., Djordjević, S., and Javadi, A.A. (2022). Addressing social and institutional vulnerabilities in the context of flood risk mitigation. J Flood Risk Management *15*, e12839. https://doi.org/10.1111/jfr3.12839.

2. de Moel, H., Aerts, J.C.J.H., and Koomen, E. (2011). Development of flood exposure in the Netherlands during the 20th and 21st century. Global Environmental Change *21*, 620–627. https://doi.org/10.1016/j.gloenvcha.2010.12.005.

3. Kreibich, H., Bubeck, P., Van Vliet, M., and De Moel, H. (2015). A review of damage-reducing measures to manage fluvial flood risks in a changing climate. Mitig Adapt Strateg Glob Change *20*, 967–989. https://doi.org/10.1007/s11027-014-9629-5.

4. Zischg, A.P., and Bermúdez, M. (2020). Mapping the Sensitivity of Population Exposure to Changes in Flood Magnitude: Prospective Application From Local to Global Scale. Front. Earth Sci. *8*, 390. https://doi.org/10.3389/feart.2020.534735.

5. Früh-Müller, A., Wegmann, M., and Koellner, T. (2015). Flood exposure and settlement expansion since pre-industrial times in 1850 until 2011 in north Bavaria, Germany. Regional Environmental Change *15*, 183–193. https://doi.org/10.1007/s10113-014-0633-9.

6. Han, Y., Huang, Q., He, C., Fang, Y., Wen, J., Gao, J., and Du, S. (2020). The growth mode of built-up land in floodplains and its impacts on flood vulnerability. Science of The Total Environment *700*, 134462. https://doi.org/10.1016/j.scitotenv.2019.134462.

7. World Meteorological Association (2021). WMO Atlas of Mortality and economic losses from weather, climate and water extremes (1970-2019) (Technical Report).

8. Swiss Re (2023). Floods: Natural catastrophes in focus. https://www.swissre.com/risk-knowledge/mitigating-climate-risk/floods.html.

9. Reisinger, A., Howden, M., and Vera, C. (2020). The Concept of Risk in the IPCC Sxth Assessment Report: A summary of Cross-Working Group Discussions (Intergovernmental Panel on Climate Change).

10. UNDRR [United Nations Office for Disaster Risk Reduction] (2017). The Sendai Framework Terminology on Disaster Risk Reduction. “Disaster Risk”. https://www.undrr.org/terminology/disaster-risk.

11. UNDRR [United Nations Office for Disaster Risk Reduction] (2022). Global Assessment Report on Disaster Risk Reduction 2022: Our World at Risk: Transforming Governance for a Resilient Future.

12. Domeneghetti, A., Carisi, F., Castellarin, A., and Brath, A. (2015). Evolution of flood risk over large areas: Quantitative assessment for the Po river. Journal of Hydrology *527*, 809–823. https://doi.org/10.1016/j.jhydrol.2015.05.043.

13. Elmer, F., Hoymann, J., Düthmann, D., Vorogushyn, S., and Kreibich, H. (2012). Drivers of flood risk change in residential areas. Nat. Hazards Earth Syst. Sci. *12*, 1641–1657. https://doi.org/10.5194/nhess-12-1641-2012.

14. Mazzorana, B., Levaggi, L., Keiler, M., and Fuchs, S. (2012). Towards dynamics in flood risk assessment. Nat. Hazards Earth Syst. Sci. *12*, 3571–3587. https://doi.org/10.5194/nhess-12-3571-2012.

15. Merz, B., Hall, J., Disse, M., and Schumann, A. (2010). Fluvial flood risk management in a changing world. Nat. Hazards Earth Syst. Sci. *10*, 509–527. https://doi.org/10.5194/nhess-10-509-2010.

16. Zischg, A.P., Hofer, P., Mosimann, M., Röthlisberger, V., Ramirez, J.A., Keiler, M., and Weingartner, R. (2018). Flood risk (d)evolution: Disentangling key drivers of flood risk change with a retro-model experiment. Science of The Total Environment *639*, 195–207. https://doi.org/10.1016/j.scitotenv.2018.05.056.

17. Kundzewicz, Z.W., Su, B., Wang, Y., Wang, G., Wang, G., Huang, J., and Jiang, T. (2019). Flood risk in a range of spatial perspectives - From global to local scales. Natural Hazards and Earth System Sciences *19*, 1319–1328. https://doi.org/10.5194/nhess-19-1319-2019.

18. Hemmati, M., Ellingwood, B.R., and Mahmoud, H.N. (2020). The Role of Urban Growth in Resilience of Communities Under Flood Risk. Earth's Future *8*. https://doi.org/10.1029/2019EF001382.

19. Mazzoleni, M., Mård, J., Rusca, M., Odongo, V., Lindersson, S., and Di Baldassarre, G. (2021). Floodplains in the Anthropocene: A Global Analysis of the Interplay Between Human Population, Built Environment, and Flood Severity. Water Res. *57*. https://doi.org/10.1029/2020WR027744.

20. Zischg, A. (2023). Flood risk change: a complexity perspective (Elsevier).

21. Schanze, J., and Maleska, V. (2019). Towards a more systemic understanding of flood risks. J Flood Risk Management *12*. https://doi.org/10.1111/jfr3.12569.

22. Wassénius, E., and Crona, B.I. (2022). Adapting risk assessments for a complex future. One Earth *5*, 35–43. https://doi.org/10.1016/j.oneear.2021.12.004.

23. Klijn, F., Kreibich, H., de Moel, H., and Penning-Rowsell, E. (2015). Adaptive flood risk management planning based on a comprehensive flood risk conceptualisation. Mitig Adapt Strateg Glob Change *20*, 845–864. https://doi.org/10.1007/s11027-015-9638-z.

24. Emami, K. (2020). Adaptive Flood Risk Management. Irrig. and Drain. *69*, 230–242. https://doi.org/10.1002/ird.2411.

25. Haasnoot, M., Kwakkel, J.H., Walker, W.E., and ter Maat, J. (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. Global Environmental Change *23*, 485–498. https://doi.org/10.1016/j.gloenvcha.2012.12.006.

26. UNDRR [United Nations Office for Disaster Risk Reduction] (2015). Sendai Framework for Disaster Risk Reduction 2015-2030.

27. European Commission (2007). Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks (Text with EEA relevance).

28. Priest, S.J., Suykens, C., Van Rijswick, H.F.M.W., Schellenberger, T., Goytia, S., Kundzewicz, Z.W., van Doorn-Hoekveld, W.J., Beyers, J.-C., and Homewood, S. (2016). The European Union approach to flood risk management and improving societal resilience: lessons from the implementation of the Floods Directive in six European countries. ECOLOGY AND SOCIETY *21*. https://doi.org/10.5751/ES-08913-210450.

29. European Commission and Directorate-General for Environment (2021). Current practice in flood risk management in the European Union: September 2021 (Publications Office of the European Union).

30. Rauter, M., Thaler, T., Attems, M.-S., and Fuchs, S. (2019). Obligation or Innovation: Can the EU Floods Directive Be Seen as a Tipping Point Towards More Resilient Flood Risk Management? A Case Study from Vorarlberg, Austria. Sustainability *11*, 5505. https://doi.org/10.3390/su11195505.

31. Mishra, A., Mukherjee, S., Merz, B., Singh, V.P., Wright, D.B., Villarini, G., Paul, S., Kumar, D.N., Khedun, C.P., Niyogi, D., et al. (2022). An Overview of Flood Concepts, Challenges, and Future Directions. Journal of Hydrologic Engineering *27*. https://doi.org/10.1061/(ASCE)HE.1943-5584.0002164.

32. Rindsfüser, N., Zischg, A.P., and Keiler, M. (2024). Monitoring Flood Risk Evolution: a systematic review. iScience *0*. https://doi.org/10.1016/j.isci.2024.110653.

33. Metin, A.D., Dung, N.V., Schroeter, K., Guse, B., Apel, H., Kreibich, H., Vorogushyn, S., and Merz, B. (2018). How do changes along the risk chain affect flood risk? NATURAL HAZARDS AND EARTH SYSTEM SCIENCES *18*, 3089–3108. https://doi.org/10.5194/nhess-18-3089-2018.

34. Sairam, N., Schröter, K., Lüdtke, S., Merz, B., and Kreibich, H. (2019). Quantifying Flood Vulnerability Reduction via Private Precaution. Earth's Future *7*, 235–249. https://doi.org/10.1029/2018EF000994.

2 Monitoring flood risk evolution: a systematic review

Nele Rindsfüser[1,2], Andreas P. Zischg[1,2] and Margreth Keiler[3,4]

[1] *Oeschger Centre for Climate Change Research, Mobiliar Lab for Natural Risks, University of Bern, Bern, Switzerland*
[2] *Institute of Geography, University of Bern, Bern, Switzerland*
[3] *Department of Geography, University of Innsbruck, Innsbruck, Austria*
[4] *Institute for Interdisciplinary Mountain Research, Austrian Academy of Sciences, Innsbruck, Austria*

Published in: iScience 27, September 2024, 110653
https://doi.org/10.1016/j.isci.2024.110653

Abstract

Land-use change, climate change, human interventions, and socio-economic developments influence the evolution of the risk components hazard, exposure, and vulnerability, and consequently of flood risk. Adaptive flood risk management is a way to cope with evolving risks, but it requires measuring the evolution of risks. To develop principles of flood risk monitoring, we systematically reviewed scientific literature on flood risk evolution analyses. The reviewed publications indicate a wide spread in increase or decrease of flood risk evolution over decades. Furthermore, the publications show a high diversity in factors and methods for flood risk evolution analyses and indicate the main challenges for developing flood risk monitoring. Flood risk monitoring needs the systematic detection of flood risk evolution by periodically (re)evaluate the factors that influence the risk components - hazard, exposure and vulnerability - modeling those risk components and combining them to quantify flood risk.

Keywords: Flood risk dynamics, complex systems, flood risk management, adaptive management, adaptation, natural hazards, exposure, vulnerability, climate change, global change

2.1 Introduction

On a global level, floods have caused the most reported disasters or loss events related to weather, climate and water hazards (44%), led to the second highest economic losses (31%) and the third highest number of deaths (16%) from 1970-2019.[1] In a general context, flood risk can be expressed in different dimensions, e.g. as the potential future losses due to floods or as the probability of an adverse outcome that arises from the combination of a natural hazard and vulnerable elements within a community.[2] The analysis and assessment of flood risk is an interdisciplinary approach and may differ depending on the foci and discipline.[3]

Following the general concept of the Intergovernmental Panel on Climate Change IPCC[4] and the United Nations Office for Disaster Risk Reduction UNDRR,[5] disaster risk is defined as "the likelihood over a specified time period of severe alterations in the normal functioning of a community or a society due to hazardous physical events interacting with vulnerable social conditions, leading to widespread adverse human, material, economic or environmental effects that require immediate emergency response to satisfy critical human needs and that may require external support for recovery".[4] From natural and technical sciences perspective, risk can be quantified by a deterministic risk equation (2-1).[6]

$$R_{i,j} = f(p_j, p_{i,j}, A_i, v_{i,j}) \qquad (2\text{-}1)$$

Where $R_{i,j}$ is the risk dependent on object i and scenario j, p_j is the probability of defined scenario j, $p_{i,j}$ is the probability of exposure of object i to scenario j, A_i is the value of object i (the value at risk affected by scenario j), and $v_{i,j}$ is the vulnerability of object i in dependence on scenario j. An overview on differences of flood risk assessment considering different spatial scales is provided by de Moel et al.[3]

The flood risk analysis provides an important part for an overall risk governance (see Klinke and Renn[7] for a broad overview including also sociopolitical perspectives) and especially for risk management. The aim of flood risk management is to reduce risk to an acceptable level for the relevant society via prevention, mitigation, preparedness, and response measures. It also includes managing residual risks and preventing new or increasing risk.[5] The basis for understanding past, current and/or future risk in a flooding system and for selecting appropriate risk management measures is a pre-event risk assessment that considers the characteristics of the hazard, the exposure of elements at risk, and the vulnerability. Herein, the flooding system is defined as physical and human systems that "influence or are influenced by flooding".[8]

However, flood risk is not static but changes over time.[6,9–13] Flood events and risk are strongly related to climate change and this will raise further challenges for the global community.[14] Moreover, land-use change, human interventions, and socio-economic developments all influence exposure and vulnerability, thus changes of all risk components have led and will lead to the evolution of flood risk.[15–17] Consequently, the evolution of flood risk can be highly dynamic and complex.[18–20] The complex properties lead to the emergence of systemic risks, which are characterized by interactions and transboundary effects in the scope of consequences,[21,22] and need to be better understood and addressed in whole systems approaches.[5,23,24] Approaches of risk analysis that address the evolution of risk in a comprehensive way and also take into account the interactions and feedback between hazards and the more societal risk components are scarce.[25,26] Moreover, the future dynamics of drivers influencing hazard, exposure, and vulnerability, and consequently flood risk evolution is fraught with a high degree of uncertainty.

Understanding flood risk and the evolution of flood risk under global change conditions is therefore essential for sustainable decision-making in disaster risk reduction. This was already addressed in the Sendai Framework Priorities and targets by "focusing on monitoring, assessing and understanding disaster risk" (Priority 1), as well as for "strengthening the mechanisms for monitoring and assessment of disaster risks" in the context of risk governance (Priority 2).[27] However, monitoring tools mainly observe hazard and provide information on early warning as part of Priority 4 (Enhancing disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation and reconstruction)[27] but not changing risk.

Additionally, monitoring tools address the need for developing national and international platforms to monitor trends and patterns of disaster losses and impacts to properly capture any progress towards reducing losses.[5,28] Other monitoring tools in relation to risk and risk reduction integrated in the Sendai Monitor (loss data and impacts, strategies for risk reduction) show little progress.[29]

Moreover, new assessment tools are needed to enable adaptive flood risk management to address the changing and systemic risks.[30] However, focusing on understanding disaster risk and the implementation of adaptive flood risk management requires a flood risk monitoring that screens critical developments of hazard, exposure, and vulnerability in a comprehensive way and warns the decision makers when a critical point in flood risk evolution will be approached. In the context of reducing flood impacts on European societies, the EU Floods Directive 2007/60/EC[31] provides guidelines to European Member States on flood risk assessment and management. The Flood Directive (FD) comprises three planning steps, i) the preliminary assessment of flood risk and the identification of Areas of Potential Significant Flood Risk (APSFR), ii) the establishment of flood hazard maps and flood risk maps, and iii) the flood risk management plans to reduce the risks. These steps are to be repeated, reviewed, and, if necessary updated every six years. In 2022, most member states started the third cycle (2022-2027).[32] However, the focus of the FD is not on the monitoring of risks – despite acknowledging the aspects of dynamic risk by the repeated assessment – but to assess risk to find adequate risk reduction measures. Moreover, the member states implemented very different approaches to address the FD[33–35] and updated and changed the applied approaches from the first to third cycle which limits to observe the risk evolution. Yet, a scientific basis for risk monitoring serving for a proactive adaptive flood risk management is still missing.

Based on the highlighted challenges of the analysis and evolution of flood risk and the still existing limitation to address risk monitoring for an adaptive flood risk management, this study provides in a first step a review of local and regional flood risk evolution studies and in a second step an outline for a flood risk monitoring approach. We focus on pluvial and fluvial floods.

In the review part, we aim to present a synthesis of research on the evolution of flood risk through a systematic review of peer-reviewed articles to deepen the understanding of flood risk evolution. We analyzed the different approaches for addressing flood risk evolution, the dynamical risk components considered and the contribution of these publications on risk evolution for developing principles of flood risk monitoring. In the second part, we provide a critical perspective on flood risk evolution and distil the basic steps towards risk monitoring. We understand risk monitoring in this study as the systematic detection of risk evolution by periodically measuring the factors that influence the risk components hazard, exposure and vulnerability, modeling the risk components and combining them to quantify risk. We aim to contribute with the iterative framework to support a better understanding of systemic risk and adaptive flood risk management.[21]

2.2 Systematic Review: Flood risk evolution

The following chapter includes the method description, an overview and classification of the selected publications, and the results and synthesis of the systematic review. The results and syntheses of publications are organized into sections according to whether they analyzed an evolution in all three risk components (*H, E, V),* in two risk components *(H, E or H, V or E,V),* or in one risk component *(H or E or V)*. The sections are sub-divided into publications analyzing an evolution in the past, future, or a comparison of past and future. Each sub-section answers the questions (a) what were the main objectives of the studies, (b) with which methods and factors was flood risk evolution and important drivers analyzed and (c) what are the main conclusions regarding flood risk evolution and drivers.

2.2.1 Method

In order to elaborate principles of flood risk monitoring, we conducted a systematic search, review, and synthesis of peer-reviewed literature about flood risk evolution. This systematic review follows formal methodological steps outlined in Berrang-Ford et al.,[36] Khan et al.,[37] and Liberati[38] to add transparency and reproducibility to the review process. The literature was searched with Scopus and Web of Science (last update: 19.04.2024) by using a search string (**Figure 2-1**) generated in an iterative process. Literature related to the research questions was screened to receive a set of search terms. After selecting search terms, various combinations were tested to obtain a search string that returned literature that met the eligibility criteria. Various Boolean operators were used to broaden and narrow the results. We searched within the article title, abstract and keywords fields in the Scopus database and in the topic field in Web of Science database. Additional search criteria were the language (English) and document type (article, review). The time of publication was limited to the period from 2000 until the date of the last search in Scopus and Web of Science (19.04.2024). After the removal of duplicates, 846 papers remained for the first selection. The retrieved titles and abstracts were screened according to pre-defined inclusion and exclusion criteria (Table 2-1). The second selection was done by reading the whole paper and screening according to pre-defined inclusion and exclusion criteria (Table 2-1). At the end, 111 papers were classified as relevant for the content analysis and synthesis. Undoubtedly, relevant publications may be missing in our literature search due to the varying use of terms in their titles, keywords or abstracts. Nevertheless, our results are robust in terms of flood risk evolution studies revealed.

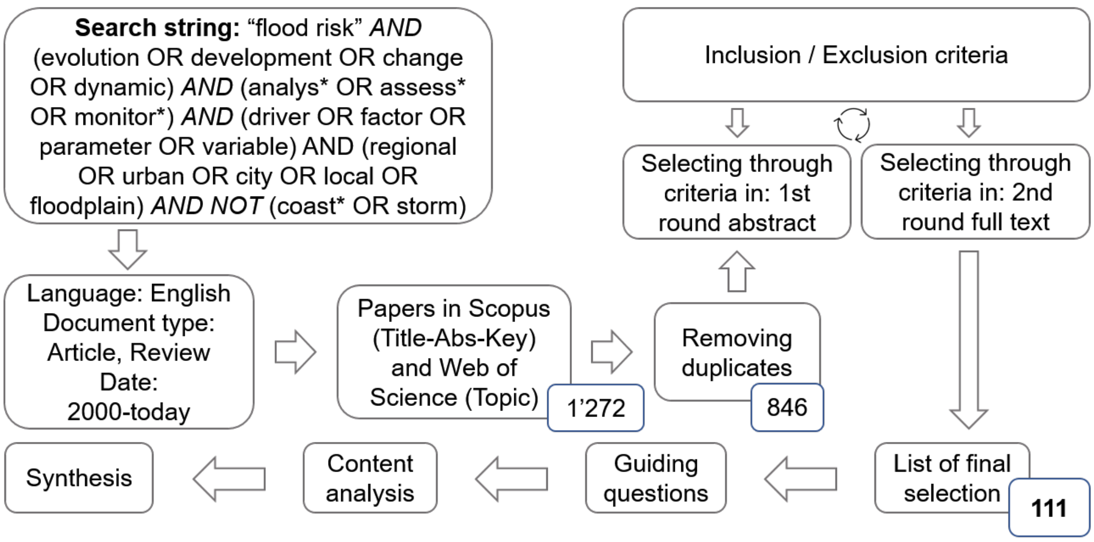


Figure 2-1. Experimental procedure systematic review

Table 2-1. Inclusion- and exclusion criteria systematic review	
Inclusion criteria	**Exclusion criteria**
Flood risk evolution analysis (Hazard, Exposure, Vulnerability, single or in combination) (past, present, future)	Model performance or uncertainty analysis
Identification or analysis of drivers of changing flood risk	Susceptibility-, hazard-, inundation-, risk mapping
Interaction and feedback between drivers	Resilience/ Adaptation
Spatiotemporal dynamics	Evaluation of mitigation strategies/ recovery / event management
	Evaluation of water pollution, quality/ quantity
	Event/ precipitation monitoring

After the final selection, we analyzed the literature (n=111) following a set of guiding questions:

- How is flood risk conceptualized in the studies?
- What is the geographical region of the case studies?
- What is the temporal scale of risk analysis?
- Which factors are used for risk evolution analysis?
- Which methods are used to analyze flood risk evolution?
- What are the main outcomes from analyzing flood risk evolution?

The coding and content analysis of the studies was conducted in MAXQDA, a software for qualitative data and text analysis, following the guiding questions. After coding and content analysis, the studies were grouped according to the risk component(s) in which they analyzed an evolution and in what timespan they analyzed an evolution of flood risk. Finally, the grouped literature was integrated in an Excel-Sheet to assemble the results of the content analysis and to synthesize the results. The selection, coding and content analysis of the literature was assessed by the first author of the manuscript in an iterative process with consultations and crosschecking of the co-authors.

2.2.2 General overview and classification of analyzed publications

From total 111 papers selected for the review, 101 were research articles and ten were review articles. The earliest paper was published in 2003 and most of the articles were published in 2023. Case studies were realized around the world, with most located in Asia and Europe. In Table 2-2, the studies included for the systematic review (without review articles) are categorized by the applied risk definition (colored background), the risk components used to analyze an evolution (rows) and the time referred to by the risk analysis (columns). The studies analyzed the flood risk evolution under different risk conceptualizations, but how risk was defined and conceptualized was not always clearly presented in the studies. Moreover, 65% of the studies lacked a clear definition of risk (blue background in Table 2-2). For those studies we categorized the definition of risk according to their implicit descriptions of risk conceptualization. Although all studies mentioned flood risk, only 36% of the studies included all three risk components in their analysis. Flood risk, hazard, exposure, or vulnerability evolution was analyzed for either past or future or as a comparison of past, present and future periods (columns). Most of the studies analyzed risk evolution in the past (52%) (first column of Table 2-2). 55% of the studies analyzed the evolution of one risk component. By combining more than one risk component, evolution was not always included in every risk component. 22 papers combined the evolution of all three risk components in the risk analysis.

Table 2-2. Categorization of reviewed studies. The studies were categorized according to three criteria: a) the period for which the risk evolution was analyzed (past, future, past-future), b) the integration of evolving risk components (H, E, V) and c) the applied risk definition visualized by the colored background. The background color shows: blue = no risk definition, red = H x E x V, green = H x V, yellow = other. The italic letters in brackets indicate studies that hold one or two of the three risk components (H, E, V) constant over the analyzed period and considered the others as dynamically changing.

	Past	**Future**	**Past - Future**
Hazard, Exposure, Vulnerability	• Akdim et al.[39] • Galligari et al.[40] • Wang et al.[41]	• Liu et al.[42] • Liu et al.[43] • Sauer et al.[44] • Steinhausen et al.[45] • Zuo et al.[46]	• Feng et al.[47] • Nguyen et al.[48]
	• Chen et al.[49] • Guoyi et al.[50] • Lazzarin et al.[51] • Peng et al.[52] • Seemuangngam & Lin[53]	• Chyon et al.[54] • Tesselaar et al.[55]	• Poussin et al.[56]
	• Chen et al.[57] • Ciullo et al.[58] • Wongboontham et al.[59]		• Elmer et al.[10]
Hazard, Exposure	• Abass et al.[60] • Akhter et al.[61] • Andrade & Scarpati[62] • Cortès et al.[63] • Faccini et al.[64] • Flores et al.[65] • Franci et al.[66] • Zischg et al.[13] (*V* const.)	• Clark et al.[67] • Eder et al.[68] (*V* const.) • Januriyadi et al.[69] (*V* const.) • Kefi et al.[70] (*V* const.) • Murnane et al.[71]	• Khan et al.[72] (*V* const.)
	• Domeneghetti et al.[9] (*V* const.)	• Beckers et al.[73] (*V* const.) • Sharma et al.[74]	
	• Waghwala & Agnihotri[75]		
Hazard, Vulnerability	• Chandole et al.[76]	• Chen et al.[77] • Kittikhun et al.[78]	• Kim et al.[79]
	• Pan et al.[80]		
Exposure, Vulnerability	• Naba et al.[81] (H const.)		

Hazard	• Aich et al.[82] • Asinya & Alam[83] • Dixon et al.[84] • Du et al.[85] • Grandry et al.[86] • Hung et al.[87] • Janicka et al.[88] • Mei et al.[89] (E, V const.) • Rončák et al.[90] • Schober et al.[91] (E const.) • Slater & Villarini[92] • Sofia & Nikolopoulos[93] • Sokolova et al.[94] • Tang et al.[95] • Wilby & Quinn[96] • Yan et al.[97] • Zhang et al.[98]	• Amiri et al.[99] • Burton et al.[100] • De Oliveira et al.[101] • Du et al.[102] • Kay & Jones[103] • Li et al.[104] • Liu et al.[105] • Lu et al.[106] • Meresa et al.[107] • Nigussie & Altunkaynak[108] • Nyaupane[109] • Ryu & Kim[110] • Sayers et al.[111] (E, V const.) • Smith et al.[112] • Tam et al.[113] • Wang et al.[114] • Wu[115] • Yosri et al.[116] (E, V const.)	• Tripathi et al.[117]
	• Angra & Sapountzaki[118] • Attaran et al.[119]		• Smits et al.[120] (E, V const.) • Yu & Jung[121] (E, V const.)
	• Dutal [122]	• Park et al.[123]	• Radojevic et al.[124]
Exposure	• Ramiaramana & Teller[125] • Abdelkareem et al.[126] (H, V const.)	• Hemmati et al.[127] (H, V const.)	
	• Früh-Müller et al.[128]	• Chen et al.[129] (H, V const.)	
Vulnerability	• Lv et al.[130] • Wang et al.[131]	• Gultom et al.[132] (H const.)	
	• Yang et al.[133]		
	• Boudou et al.[134] • Liu & Shi[135] • Mao et al.[136]		

The selection of factors or the choice of model to analyze flood risk evolution varies across the analyzed studies depending on the risk conceptualization, research questions of the study, spatiotemporal scale of analyses and data availability. Consequently, the comparison and synthesis between individual studies is quite limited. In the following sections, we present the summarized outcomes of the content analysis with a focus on the main objectives, and diversity of methods, key factors and results of flood risk evolution analyses.

2.2.3 Hazard, Exposure, Vulnerability evolution

22 of 111 studies analyzed flood risk evolution with evolving factors describing the hazard, exposure, and vulnerability component.

2.2.3.1 Evolution in the past

Studies that integrated an evolution of all three risk components into the risk analyses had varying research foci. The most common denominator is the evaluation and analysis of past conditions of the flooding system to learn about the evolution of this system. The gained knowledge is key to a flood risk evolution analysis to compare different risk situations. The main objectives were to learn from past risk evolution for future decisions in flood risk management,[39] to compare risk evolution in different regions to detect hotspots[41,57] and flood management performance,[52] to compare various risk situations with flood loss[49,58] or to consider the impact of urbanization and settlement dynamics on risk evolution.[40,50,51,53,59]

The approaches selected for the analyses of flood risk under historic conditions were qualitative and quantitative data-, index- and/or model-based analyses. After the collection of data for the state-describing variables for different periods, they were used to analyze inherent evolutions, to compare different states with occurred flood events or other evolutions of state-describing variables,[39] or they were modified so that they can be used as input for index- or model-based evaluations.[40,41,49–53,57–59]

Index-based analyses described the risk components through several indicators (see for a general overview[137]). Data for hazard evolution analyses were mainly precipitation time series (as proxy) and catchment characteristics. The amount of flood season precipitation,[57] the amount of monthly precipitation, monthly maximum precipitation,[49] the average annual precipitation[50] or maximum 3-day continuous precipitation[52] were used as indicators for precipitation time series. As catchment characteristics, for example, changes in wetlands or vegetation cover rate[49], changes in normalized difference vegetation index (NDVI)[52] or distance to river[50] were selected as indicators. The indicators used for exposure analyses were, for example, population density, road density, economic density, built-up area and/or the amount of gross regional or domestic product.[49,50,52,57] Indicators for social vulnerability were, for example, the age of the population, the proportion of rural residents to the overall population,[49,52] and/or coping capacities (e.g. municipal flood control investment per unit area).[57] Indicators to assess the economic vulnerability were built-up density and proportion of farmland.[52] Indicators were chosen a priori or selected via statistical analyses from a set of indicators to estimate their relevance. Finally, the identified indicators were aggregated in a risk index through weighting or statistical models. Risk evolution was detected by comparison of the resulting flood risk of several periods.

The model-based analyses integrated several descriptive variables of risk components into one stylized model[58] or coupled data analyses with a hydraulic model.[40,51] The selection of data for hazard evolution analyses depended on whether the study relies on flood-related variables (e.g. flood magnitudes, flooded area, high-water levels) or starts with the analysis of source variables of a flood event (e.g. precipitation or flood discharge) to model the flood-related variables with hydraulic models. Data for exposure evolution analyses were gross domestic product and population density[58] or data for buildings.[40,51] Data for vulnerability evolution analyses were proxies for flood protection levels, social memory of floods and relation between flood water levels and relative damage[58] or structural characteristics of buildings.[40] Lazzarin et al.[51] integrated the vulnerability of residential buildings by using vulnerability functions. Ciullo et al.[58] integrated time-invariant parameters and time-varying variables describing the three risk components into the dynamic model to detect risk evolution. Galligari et al.[40] conducted several individual analyses of risk components and combined the knowledge gained to make statements about the risk evolution. Lazzarin et al.[51] coupled a damage model to the hydrodynamic model to analyze the flood risk evolution.

Almost all analyzed studies came to the same result: the main reason for flood risk evolution was exposure evolution. Within each of the studies, the risk evolution in regions was compared and varying rising/decreasing flood risk detected. The study of Galligari et al.[40] showed that built-up area and/or the number of buildings expanded but building density decreased. Regarding the vulnerability evolution, an increase in rooftop improvements was detected as adaptation strategy. Thus, related variables had an amplifying or dampening effect on the overall flood risk evolution. For example, the increase in building re-enforcement protected against heavy rainfall but not in case of increased runoff and water table rise.[40] On the one hand, building consolidation decreased vulnerability of buildings against heavy rainfall, but, on the other, it increased vulnerability against a flood event. The study of Peng et al.[52] showed a trend in first increasing and then decreasing risk for Beijing and an overall decreasing trend for Munich from 2000 to 2020. They stated that the reason for the differences lies in the urbanization process and the situation for flood risk mitigation.[52] Lazzarin et al.[51] showed in their case study an increase of 85% in expected damage from 1983 to 2021. Akdim et al.[39] and Chen et al.[57] stated that the relations in human-natural systems and factors describing flood risk evolution are multiple and complex.

2.2.3.2 Evolution in the future

Seven studies[42–46,54,55] analyzed the expected future evolution of risk. The main objective of these studies was to analyze the impacts of climate-, socio-economic-, and land-use change on flood risk for different spatiotemporal scales. The evolution of risk was analyzed by a combination of data selection-, statistical-, index-, and/or model-based approaches. In contrast to the studies that analyzed evolution in the past, scenario-based simulations and statistical techniques were used to project and predict future changes in flood risk related factors.

Future hazard related factors were selected from available datasets,[46] modified through modeled land-use change scenarios[42,43] and/or modeled with a hydrodynamic model while integrating climate change and/or flood protection scenarios.[45,54,55] Data for index-based hazard evolution analysis were, for example, precipitation time series (maximum three-day precipitation and number of days with daily rainfall above 50mm) and catchment characteristics (digital elevation model, slope, topographic wetness index, distance to river and runoff coefficient).[42,43] In these examples, the runoff coefficient as indicator for hazard evolution was modified according to the new land-use types. Outputs from hydrological-, and hydraulic modeling (e.g. flood duration, flood depth, flood extent) were modified as indicators (e.g. in Chyon[54]) or used to calculate statistics (e.g. changes in flood frequency and magnitude)[45] and impacts (e.g. expected annual damage).[45,55] Indicators for exposure and vulnerability evolution analysis were, for example, the total population per unit area and total general budget revenue per unit area. In this example[42], the changes in population and general budget revenue per unit area were spatialized with a multiple regression model. The results were combined with a weighted average method to work out flood risk maps for each year under each scenario (e.g. Liu et al.[42]). Steinhausen et al.[45] used several methods to calculate population, GDP and wealth-to-income ratio for exposure evolution analysis. Vulnerability evolution was integrated by private precautionary measures, previous flood experience, building footprint area and building type.[45] Tesselaar et al.[55] utilized population growth as input for exposure evolution analysis and depth-damage curves for vulnerability analysis.

The results showed an increase or decrease in flood risk depending on the time, region, and selected scenarios. Overall, future climate change will lead to an increase in flood risk but the dominant driver is socioeconomic change (e.g. Steinhausen et al.[45]). For example, Liu et al.[42] stated that an increase comes mainly with removed vegetative surface, raw lands replaced by impervious area, and increased exposure with urban growth. Zuo et al.[46] detected as well an increase in size and proportion of high flood risk areas, with population density and gross domestic product density as the most important drivers. Another driver of increasing flood risk, analyzed by Tesselaar et al.[55], is the offset of dis-amenities of floods by insurances.

A stabilized flood risk was detected through a balance between socio-economic development and ecological protection measures.[42,43] Additionally, Steinhausen et al.[45] stated that improved private precautionary measures would reduce flood risk on average by 15%. Without these measures, fluvial flood risk can increase seven-, to ten-fold until the end of the century.[45]

2.2.3.3 Evolution from past to future

The studies analyzing risk under past and future conditions compared different periods to identify and estimate risk evolution. The focus was on quantifying risk in terms of expected annual damage to buildings and/or attributing risk changes to single drivers (climate change, land-use change, change in building values).[10,47,48,56]

The approach selected for the analyses of flood risk evolution under historic and future conditions was a combination of data selection, model-, index-, and scenario-based analyses. Climate, hydrological, and hydraulic models were used to estimate damage and risk. For the quantification of flood hazard, discharge measurements and discharge projections provided the input for inundation modeling. Hazard probabilities were calculated with extreme value statistics of observed and predicted discharge data. To analyze the impact of climate change on hazard, climate change scenarios based on the IPCC emissions scenarios were used.[14] Nguyen et al.[48] calculated a flood hazard index by integrating flood depth, velocity and susceptibility from a machine learning and hydrodynamic model to create a flood hazard map. Exposure was quantified by analyzing land-use data from satellite images,[10] land-use maps,[48,56] and land parcel information.[47] Future projections of land-use change were analyzed with the Land Use Scanner model and based on the IPCC emissions scenario.[10,56] Additionally, Nguyen et al.[48] integrated population density, poverty level, number of women, number of schools, and agricultural area as indicators from statistical offices for the analysis of exposure and vulnerability evolution. Future changes in population density and vulnerability indicators were collected from planning reports.[48] In the other studies, structural vulnerability is represented by stage-damage functions[10,56] or depth-damage fragility curves[47] as relation between inundation height, land-use and building values. Changes in building values were considered by using time-adjusted reconstruction costs[10] and published price indices.[47] Additionally, Poussin et al.[56] integrated risk mitigation factors into the stage-damage functions to analyze the effects of adaptation strategies on the damage and risk. Finally, different scenarios with related damage calculations were compared to detect the most relevant drivers of flood risk change. Nguyen et al.[48] combined flood hazard, exposure, and vulnerability indicators with GIS methodologies to construct flood risk maps and evaluate changes in flood risk areas.

The results showed that climate change, land-use change, and asset value developments affect flood risk in varying degrees. Almost all studies concluded that climate variations have an important impact on changes in flood risk but they were not the dominant driver, at least for the time period under study.[10,47,56] Exposure evolution in form of land-use change was increasing under several scenarios and stated as the dominant driver.[10,47,56] The asset value developments appeared to be a minor driver of flood risk evolution.[10] The results of the overall risk estimations showed varying increasing/decreasing rates of the flood risk (represented by the expected annual damage) depending on the analyzed years (intervals) and scenarios. For example, Elmer et al.[10] analyzed in their maximum land-use scenario a decrease of 30% in risk from 1990-2020 while considering effective building values. Whereas Feng et al.[47] stated that the risk raised by 30% from 2001-2011 due to a combination of socioeconomic developments and climate conditions. Poussin et al.[56] suggested that land-use and climate changes might increase annual flood risk by up to 185% by 2030 compared with 2000. With a focus on assessing and comparing flood risk areas, Nguyen et al.[48] concluded that areas with high and very high flood hazard, exposure, vulnerability, and risk increased, while areas of low risk decreased due to a combination of climate change, land use change, population growth, and socio-economic growth.

2.2.4 Hazard, Exposure evolution

A large proportion of studies (18 of 111) analyzed flood risk evolution only with evolving factors describing the hazard and exposure component. Nevertheless, in some studies, the vulnerability component was integrated as a constant variable over time to calculate flood risk.

2.2.4.1 Evolution in the past

As stated in the previous chapter, the most common denominator of studies analyzing past risk evolution was the identification of past conditions of the flooding system to learn about the evolution and compare different risk situations. Even though this chapter deals with studies that do not considered an evolution in vulnerability, they had the same common denominator. The detailed objectives were not the same, as the studies had varying research foci. In detail, they examined factors that play an important role in flood dynamics[60,62,64,75] and detected changes in factors describing the hazard and exposure component.[66] Further, one study aimed to analyze and link changes in floodplain population dynamics with flood-related variables.[61] Four studies focused on studying the evolution in flood risk, including hazard, exposure, and vulnerability (constant), how it has been affected by different changes and on detecting the main drivers of flood risk evolution.[9,13,63,65]

The approaches selected to analyze historic conditions of factors to determine past risk evolution were qualitative and/or quantitative data analyses, as well as index-based-, and/or model-based analyses. A comparison with observed flood events and/or discharge data served to evaluate which precipitation events caused a flood event and whether they showed a statistically significant change.[62–64] Further, with this analysis, it was analyzed whether flood events were explainable through changes in climate or if other reasons were responsible for changed impacts of flood events. Land-use/ cover analysis was used to examine changes in land surface and correlated change in runoff processes.[63] In addition, the studies looked at the historical evolution of land-use in terms of urban area to detect changes in exposure due to urban sprawl.[64,66] A more detailed study of exposure evolution in form of dynamics in floodplain population was conducted by Akhter et al.[61] By analyzing floodplain population growth rate and the proportion of floodplain population compared with flood-related variables, they analyzed the impact of floods on dynamics in floodplain population.[61]

The index-based study[75] calculated an urbanization and flood risk index to evaluate the impact of urbanization on two flood events. Data for hazard analysis were the inundation area, flood depth and discharge of these flood events. Data for exposure analysis was the urban area. The urbanization index was calculated as percentage of the urban area from the total study area. Finally, flood risk was analyzed with an average flood depth index and an urban submergence index.

Modeling studies analyzed the evolution in single risk components and then combined the results into a risk analysis. Data for hazard analysis were precipitation data as input for rainfall-runoff modeling to calculate various flood-related variables (discharge, water level)[65], observed discharge data to statistically analyze trends[9] and derived hydrographs to simulate floods.[13] The hydrographs were scaled to various peak discharges and delineated to a certain occurrence probability.[13] Further, flood-related variables (inundation extents and flow depths) were modeled with a hydrodynamic model.[13] Data for exposure analysis were land-use maps to evaluate the expansion of urban and residential area in a flood-prone area.[9] Further, population data were an important element for exposure analysis to analyze the number of people living in flood-prone areas.[9] In a more general study of exposure, changes in land-use categories were analyzed through satellite image classification and overlaid with a certain flood extent.[65] Finally, hazard and exposure analyses were combined into a risk evolution calculation to gain basic information for flood risk management and to determine which drivers were responsible for flood risk evolution.[9,13]

Factors describing climate-, land-use-, and population dynamics were the most important to analyze risk evolution. Nevertheless, the results of the studies showed that the evolution of these factors was highly variable depending on the selected location (e.g. Po river (Italy), Lujan river (Buenos Aires), metropolitan area of Barcelona (Spain), rural central Gonja district (Ghana)). For example, Abass et al.,[60] Cortès et al.,[63] Domeneghetti et al.[9] and Flores et al.[65] stated that they found no evidence that past floods were climate change-induced because of a lack of significant changes in precipitation or discharge time series. Andrade & Scarpati[62] and Faccini et al.,[64] however, stated that risk increased due to changes in precipitation patterns. The effects of changes in land-use and population growth on flood risk evolution also varied between studies. Domeneghetti et al.[9] showed that flood risk (expected damage) doubled since 1954, mainly due to settlement growth.

The review of the papers revealed that the dynamics in the flooding system cannot just be ascribed to the evolution of one single driving factor. For example, Akhter et al.[61] stated that even if they detected a correlation between population dynamics and the influence of structural and non-structural measures, these dynamics cannot only be attributed to mitigation measures. Zischg et al.[13] showed moreover that the construction of levees, and the effect of unintended river incision, decreased flood risk whereas settlement growth increased flood risk.

2.2.4.2 Evolution in the future

Studies analyzing future flood risk evolution focused on the analysis of impacts from climate change, urban development and/or management strategies on hazard and/or exposure evolution.[71,74] Some studies quantified risk evolution in terms of calculating damage resulting from changes in the flooding system.[68–70,73] Therefore, the main objective of these studies was to analyze changes in the hazard and exposure component under future scenarios and combine these evolutions into a risk evolution analysis.

The approach selected for analyses of future risk evolution due to changes in climate, socio-economic development and risk management strategies was scenario-based modeling. Hazard evolution was analyzed with climate, hydrological and hydraulic models. The impact of climate change on hazard evolution was integrated in the analyses either through a change in precipitation depending on global climate models (GCMs) and representative concentration pathways (RCP) scenarios,[69–71,74] an increase in peak discharge of 30%[73] or a 10% addition to the flood hydrographs.[68] In addition, one study analyzed the impact of land-use change and land subsidence on flood hazard evolution using a combined RCP and shared socio-economic pathway (SSP) scenario[69] and one study analyzed the impact of planned flood protection measures on flood hazard.[68] Finally, changes in flooded areas and water depths were modeled for the hazard evolution analyses. For example, future exposure maps (settlement areas) were generated in terms of future demand in land-use (population forecast and household size trend) and the location of new settlement areas under a current trend and a dense urban development scenario.[73] Eder et al.[68] based the projections of settlement development areas on information from policy documents and land-use plans. Another approach to predict future land-use change was the analysis of two previous land-use maps as input for a transition model to predict future land-use.[70] On a coarser level, the SSP scenarios were used to develop future exposure data (e.g. GDP and population).[71] The vulnerability component of risk was integrated as a constant variable for risk calculations. Finally, the risk evolution was calculated with the combination of inundation depths from the hazard evolution analyses, exposure from the exposure evolution analyses and related stage-, or depth-damage functions.

Results showed that hazard and exposure parameters will increase or decrease[68,73] depending on the selected scenarios and combination of scenarios. For example, Beckers et al.[73] stated that in a wet climate scenario the peak discharge would increase by 30% for the time horizon 2071-2100 while a dry climate scenario will lead to a slight decrease in the peak discharge. The degree to which climate change and land-use change will influence the risk evolution depends also on the selected scenarios.[73] For example, Kefi et al.[70] found that the potential damage will increase in one catchment due to climate change and in another the main driver of change in potential damage is the change in built-up areas.

Overall, depending on the region, the analysis of direct damage under future scenarios showed an increase by 80% and 212%, respectively.[70] Beckers et al.[73] calculated for a wet climate scenario a relative increase in flood damage of 630% in 2100 with a 3-8 times higher influence of climate than the effect of land use change. Januriyadi et al.,[69] in turn, found that future climate change and urban development will lead to an increase in flood risk (expected annual damage costs) by 322% to 402% by 2050. In contrast, Eder et al.[68] showed that the potential damage to buildings and land could decrease by up to 75% under future scenarios (flood protection measures, settlement development, and climate change).

2.2.4.3 Evolution from past to future

Only one study compared past and future conditions of a flooding system to analyze flood risk evolution. The objective of this study was to analyze the damage of a past flood event under a future urban development scenario.[72]

The approach selected for this analysis was a combination of observed data collection from an occurred flood event in past, a hydraulic model to reconstruct the flood event, a stochastic land-use/ cover change model to project urban development scenarios and a damage assessment model. Data for hazard analysis were precipitation inputs, hydrological inflows, drainage control structures, cross sections of channels and a digital elevation model. The future urban development scenario was used as input in the hydraulic model (affecting the hazard evolution) as well as in the damage assessment model (affecting the exposure evolution). Vulnerability, as structural vulnerability, was integrated as constant variable with associated depth-damage curves for residential and commercial properties.

They concluded that flood damage can increase significantly due to urban growth (up to 800%), with an impact on the hazard as well as the exposure component of risk.[72] This is an example of a driver of change that influences two risk components, namely hazard and exposure.

2.2.5 Hazard, Vulnerability evolution

A very-small proportion of studies (5 of 111) analyzed flood risk evolution with evolving factors only describing the hazard and vulnerability component.

2.2.5.1 Evolution in the past

Past evolution of flood risk with changes in factors describing the hazard and vulnerability components was examined by two studies.[76,80] The aim of these studies was to analyze spatiotemporal flood risk evolution and investigate drivers of flood risk evolution.

The studies used an index-based approach. Pan et al.[80] used indicators describing the four influencing variables of hazard-causing factors (e.g. flood frequency), community vulnerability (e.g. proportion of population aged), protection works (e.g. plant cover), and systemic governance (e.g. proactive prevention). In contrast, Chandole et al.[76] used spatially explicit criteria to calculate flood hazard (e.g. average annual rainfall, NDVI, distance from river, elevation) and flood vulnerability indicator (e.g. agricultural production, land use/ land cover).

Pan et al.[80] revealed that hazard related indicators had the largest weight and influence on flood risk. Chandole et al.[76] stated that the high and very high risk areas increased, and the very low and moderate risk areas decreased from the Base scenario (before 2002) to the Advance scenario (after 2002).

2.2.5.2 Evolution in the future

Future evolution of risk with changes in factors describing the hazard and vulnerability components was examined by two studies.[77,78] The aim of these studies was to analyze the impacts of urbanization, socio-economic development, land-use-, and/or climate change on future flood risk.

Future flood risk was analyzed through scenario-based modeling and index-based analyses. Chen et al.[77] selected indices for the hazard and vulnerability component and modified a selection of indices with modeled scenarios. For the hazard component these were maximum 1-day rainfall amount, number of heavy rainfall days above 25mm, areas in low-lying area, type of slope, runoff depth and distance to river.[77] The digital elevation model, slope, and distance to river were kept as constant variables. Therefore, hazard evolution was analyzed by modifying precipitation data with regional climate models (RCMs) under selected RCP scenarios and by modifying the runoff depth under future urbanization scenarios from an urban growth model.[77] Indices selected for the vulnerability component were the gross domestic product density and the population density.[77] Vulnerability evolution was analyzed by modifying these two indices according to selected SSP scenarios.[77] Finally, the hazard and vulnerability indicators were aggregated in a risk index through weighting and displayed as flood risk on maps.[77] In contrast, Kittikhun et al.[78] analyzed hazard evolution with modeled land-use change according to actual and planned land-use and integrating these changes into a rainfall-runoff model to model flood hydrographs and inundation areas. The vulnerability evolution was analyzed with the flood risk index composed of sub-indices describing exposure, susceptibility and resilience and modified with results from the modeled land-use changes.[78] Finally, both results were combined to compare the flood risk index results under actual and planned land-use.[78]

The results showed that flood risk will increase in most parts of the studied area with differences between the selected climate/development scenarios.[77] Kittikhun et al.[78] concluded that flood risk will increase if no land-use planning aimed at risk reduction is applied.

2.2.5.3 Evolution from past to future

One study analyzed the comparison of past and future flood risk with evolving hazard and vulnerability component. It aimed at analyzing the risk situation before and after the completion of four major river restoration projects.[79]

The risk in the past and the future was analyzed by using an index-based approach. The index combined eight indicators describing the hazard component and ten indicators describing the socioeconomic vulnerability component.[79] Past hazard was described with historical precipitation data and future hazard was analyzed with future climate change simulation data.[79] The evolution of socio-economic vulnerability was analyzed with changes to six indicators.[79] In addition, an expert-based weighting of indicators was applied.[79]

The results showed that the risk index increased after the river restoration project and would increase due to climate change.[79] The study concluded that the risk reduction due to river restoration will be leveled off where floods are expected to increase due to climate changes.[79]

2.2.6 Exposure, Vulnerability evolution

One study analyzed flood risk evolution with evolving factors describing the exposure and vulnerability component. The hazard component was integrated as a constant variable over time.

2.2.6.1 Evolution in the past

The objective of this study was to quantify potentially exposed populations and investigate the relationship between poverty and flood exposure.[81]

They used Geographical Information System (GIS) tools and remote sensing data to map populations affected by floods (exposure) and calculated a poverty index (vulnerability). While taking population and poverty values of different years, they assessed the evolution in exposure and vulnerability.

The results showed an increase in exposed people on a national scale but a decrease on a regional scale. The poverty index decreased over the years. Further, the results confirmed the relationship between floods, exposure and poverty.

2.2.7 Hazard evolution

A large proportion of studies (43 of 111) analyzed evolving factors describing the hazard component. In some studies, the exposure and/or vulnerability component was integrated as a constant variable over time to calculate flood risk.

2.2.7.1 Evolution in the past

Hazard evolution in the past is mainly analyzed out of an interest in reasons for changed hazard-related factors (flood magnitude, flood extent, water depth, etc.). The main objectives were to detect changes in the flooding system to examine their impacts on hazard-related factors and processes. The main drivers were climate trends, land-use change and morphological changes. In comparison to the studies presented earlier, the level of detail is higher in the studies analyzing only the evolution in one of three risk components.

The approaches selected to detect changes in hazard-related factors from changes in the flooding system were the same as in the risk analyses studies and consisted of (statistical) data analyses, modeling and/or index analyses. (Statistical) data analyses were used to detect trends in observed and/or modeled precipitation, temperature, discharge and/or flood data and make them clearly visible.[82,84,86,93,97,118] Yan et al.[97] used a variety of environmental proxy reconstructions to examine how climatic and land-use changes affected floods. The main drivers of changes in hazard-related factors[92] and their correlations[93] were assessed by statistical models.

In addition, statistical approaches were used to predict the evolution of magnitude and frequency of flood events.[83,85,90,91,96] Flood-related variables with different settings were simulated with modeling approaches to evaluate the impact of climate-, land-use-, or morphological change on hazard evolution. To this end, observed or experimental climate, land-use/cover and morphological data were integrated into the models and several model runs were conducted under various settings to analyze the impact on flood-related variables.[82–84,88,90,91,95,119] Information about land-use/cover change was integrated into the simulation models by means of land-use maps for representing different time periods.[77,82,98] The analyzed land-use/cover categories vary across studies. For example, Aich et al.[82] analyzed the changes in crop, pasture, savannah, water and rock land-use cover. Dixon et al.[84] and Sokolova et al.[94] analyzed the impact of changes in forests, and Slater & Villarini[92] used the harvested acreage of corn and soybean to represent agricultural practices. Rončák et al.[90] used an experimental approach to analyze the impact of land-use/cover change on flood hazard. To do this, they created land-use scenarios and integrated these scenarios in a rainfall-runoff model.[90]

Channel or catchment morphological changes were also integrated in the hazard evolution analyses. For example, Asinya & Alam[83] modeled and analyzed the effect of various synthetic channel morphological conditions (river width, bed elevation, etc.) on flood-related variables (flood inundation, flood frequency). Dixon et al.[84] analyzed the effect of engineered logjams on channel morphology and thus flood-related variables (flood discharge). A detailed analysis of connections between longitudinal variability in river conveyance, flows, sediment connectivity and flood changes was conducted by Sofia & Nikolopoulos.[93] Mei et al.[89] used an index-based approach with constant exposure and vulnerability indices. Therefore, the change in flood risk was obtained only with changing hazard indices (changing rainfall regimes).[89] Dutal et al.[122] used an index-based approach to identify flood hazard zones in two different years. With the overlay of flood hazard maps and two land-use maps, they revealed the effects of urbanization on flood hazard zones.[122] Hung et al.[87] applied a machine learning and remote sensing approach to assess continuous inundation susceptibility and the effects of climate change.

The results showed that climate-, land-use/cover-, river channel morphology change and river restoration projects were important drivers. Nevertheless, the drivers of detected changes were a mix of factors and the determination of causes of changes is highly complex due to the interaction between factors intervening in flood processes.[86,93]

2.2.7.2 Evolution in the future

The main objective of future hazard evolution analyses was to examine the impact of climate change scenarios on flood-related variables and processes, as well as analyzing uncertainties. Yet three studies analyzed the impact of future land-use change scenarios on hazard evolution.

The relevant approaches were (statistical) data analyses, scenario-based modeling and/or index-based analysis. The focus of these studies was on using future climate projections from global and RCMs under RCPs as input for hydrological and hydraulic modeling. The generated flow time series were used to analyze changes. For example, Kay & Jones[103], Lu et al.[106], Meresa et al.[107] and Wang et al.[114] extracted the annual maxima from the flow time series to detect changes in flood frequency. In addition, they built land-use change and urban development scenarios based on past observations as well as future plans from municipalities and/or assumptions of socio-economic developments and then integrated them in hydrological and hydraulic modeling.[100,101,104,108] Sayers et al.[111] generated flood events under climate change and used a statistical empirical copula to generate a large number of unseen events to calculate future fluvial flood risk. Park et al.[123] used four indicators (precipitation data) to analyze the impact of climate change on flood hazard without hydrological or hydraulic modeling. Du et al.[102] analyzed the trend in future extreme precipitation events under climate change with intensity-area-duration methodology. Yosri et al.[116] used a deep learning approach to predict future flood risk under climate change.

Results showed that future climate change will contribute to an increase in flood-related variables and proxies (e.g. extreme runoff, flood magnitude, inundation extent).[104,106,107,109–112,115,123] Nevertheless, as stated by Kay & Jones[103], Liu et al.[105], Ryu & Kim[110], and Wang et al.[114], changes in discharge and flood frequency and magnitude varied in spatial distribution and statistical significance depending on catchment and selected RCMs. Additionally, Kay & Jones[103] and Liu et al.[105] stated that the results are associated with several uncertainties and hydrological changes are often non-linear. While analyzing urban growth, land-use and climate change scenarios, and integrating these scenarios in hydrological and hydraulic models, drivers of change in flood-related variables were tested.[100,101,104] Results showed that determining and modeling future changes and analyzing their impacts on hazard evolution provides useful information for flood risk management.[100,104] The analysis of the impact of urbanization under three land-use policy scenarios on flood inundation indicated that unrestricted urbanization will lead to an increase in inundated land.[108]

2.2.7.3 Evolution from past to future

Hazard evolution analysis in past and future was conducted by four studies. They aimed to analyze the impact of land-use change and/or climate change on hazard evolution. Radojevic et al.[124], Smits et al.[120] and Yu and Jung[121] analyzed flood risk evolution in the past and future with changes in the hazard component and constant exposure and/or vulnerability. Tripathi et al.[117] analyzed and compared the impact of future climate change and urban development on a past flood event.

The hazard evolution was analyzed with statistical methods and hydrological/hydraulic modeling or index-based analysis. Statistical tests were used to analyze the evolution of flood frequency and severity in the past.[124] Changes in flood regimes were analyzed by integrating land-use data from different periods into the models.[124] Tripathi et al.[117] integrated climate change (increase in precipitation) and urban development (increase in impervious surface) into a hydrological model to analyze the impact on the peak flow of a past flood event. Smits et al.[120] and Yu and Jung[121] utilized modified precipitation indicators under different climate change scenarios to assess flood hazard evolution.

Results indicated that land-use change from peri-urban development had a different effect on flood regimes depending on the selected spatial scale of analysis.[124] By comparing the outcomes of a past flood event with future conditions, Tripathi et al.[117] detected that an increase in urban areas will lead to a higher impact of the flooding. In addition, the longer inundation time and higher peak flow will lead to higher damage.[117] Results of the index-based analyses showed different increasing and decreasing hazard (risk) areas with a high spatial variability.[120,121] They concluded that the analyses of risk areas and cause analysis of flood risks served a useful tool for decision makers to find strategies for climate change adaptation.[120,121]

2.2.8 Exposure evolution

A very-small proportion of studies (5 of 111) analyzed evolving factors describing the exposure component of flood risk. In some studies, the hazard and/or vulnerability component was integrated as a constant variable over time to calculate flood risk.

2.2.8.1 Evolution in the past

The main objectives of these studies was to analyze the long-term historic development of settlements and population in terms of flood exposure.[125,126,128]

Exposure evolution was examined by (statistical) data analysis. The spatial data of settlement areas were overlapped with measures such as distance to flooding zones, extent of floodplain and topographic variables to analyze exposure evolution.[128] In addition to settlement data for exposure analysis, Ramiaramanana & Teller[125] used demographic data to analyze the evolution in number of inhabitants. Combining the percentage of population and built-up areas in flood prone areas served to detect socio-economic drivers and challenges.[125] Abdelkareem and Mansour[126] used Remote Sensing analysis to detect changes in vegetation and infrastructure.

The results showed that exposure strongly increased in the past. Früh-Müller et al.[128] stated that the total built-up area within the flooding zone of the studied area increased almost fivefold. Ramiaramanana & Teller[125] also found that over the selected time period the built-up area increased yearly by 6.1%.

2.2.8.2 Evolution in the future

Exposure evolution in future was analyzed by Hemmati et al.[127] and Chen et al.[129] The aim of Hemmati et al.[127]was to analyze the interaction between urbanization and flood risk to enhance the knowledge about non-structural mitigation measures. The main objective of Chen et al.[129] was to analyze the effect of economic change on flash flood risk.

An urban growth-, hazard-, risk analysis- and policy implementation model was used to examine flood risk under various urban development scenarios.[127] While keeping the hazard and vulnerability component constant, the exposure component in terms of urban growth evolved over time under several policy scenarios. Chen et al.[129] used a hydrological/ hydrodynamic model for hazard assessment, asset value spatialization for exposure analysis and a flash flood damage model for risk assessment. Five economic scenarios from the shared socioeconomic pathways (SSPs) were used to calculate exposure evolution.

Results showed that exposed people and assets might increase under current urban development plans, but that considering non-structural strategies can mitigate the consequences of floods.[127] Chen et al.[129] stated that the flash flood risk under economic change will increase by the end of the century by around 90% depending on the scenario selection.

2.2.9 Vulnerability evolution

A very-small proportion of studies (7 of 111) analyzed evolving factors describing the vulnerability component of flood risk.

2.2.9.1 Evolution in the past

Vulnerability evolution analysis varied between studies depending on the selected conceptualization. The studies assigned to this category mainly aim for a quantitative analysis of impacts of land-use change, socioeconomic evolution and/or disaster risk management on the vulnerability evolution.

Vulnerability evolution was mostly analyzed by evaluating the exposure (elements at risk) and the susceptibility of the elements at risk. Therefore, data of exposure and susceptibility were evaluated and combined with data-, index-, and model-based analysis to examine vulnerability evolution. Data and indices selected to analyze vulnerability evolution are built-up area, building-use type, population living per building, population density, regional GDP and land-use type/categories in comparison with historical flood data.

Past vulnerability evolution is uncertain and complex.[134] The results showed an increasing or decreasing trend depending on local characteristics and the assessed periods.[131,133,134,136] For example, Yang et al.[133] concluded in their case study that human and economic vulnerability was steadily declining from 2000 to 2020. Lv et al.[130] stated that reasons for changing vulnerability in the past were an increase in building land, inflation and mismatch between urban growth and mitigation measures.

2.2.9.2 Evolution in the future

The aim of Gultom et al.[132] was to analyze vulnerability in present and future to determine the evolution of vulnerability or resilience.

To this aim, they analyzed the evacuation route efficiency by using space syntax methods and sheltering capacity determined by data and simple equations. The calculation was repeated with projected population data to predict future changes.

The analysis and comparison of flood vulnerability showed an increase in resilience due to the implementation of a ring road having a positive effect on the evacuation routes.

2.3 From flood risk evolution to flood risk monitoring

The analyzed studies presented great variety and diversity in the approaches. This hampers comparability, but the review allows drawing conclusions on flood risk monitoring and distilling the principles of risk monitoring.

As seen from the previous chapters, flood risk evolves through a combination of dynamically changing factors in the flooding system. These factors, represented by data or proxy data that change over time, quantify the evolution of the risk components, hazard, exposure, and vulnerability analyses. The combination of the changing risk components in a risk analysis allows analyzing flood risk evolution.

The presented publications analyzed flood risk evolution by repeating flood risk analysis in regular (e.g. 1- or 10-year) periods[10,57] or for selected years of interest.[42,47] In general, all spatial scales are represented, from very small-scale studies,[73] to catchment-wide,[9] and national[61] studies. The selection of periods and spatial scales depends on the risk factors assumed as changing dynamically over space and time, on the availability and resolution of data, and on methodology.

Flood risk evolution analyses, integrating the evolution of hazard, exposure and vulnerability, use comparative (statistical) data-, index-, model-, and scenario-based analysis approaches. These approaches are used either as stand-alone risk calculation methods or in combination. Comparative (statistical) data analyses are useful to detect the diversity of changing factors in a flooding system.[39] Nevertheless, changing variables can only be analyzed for the past and the quality is determined by the amount of data that is available at comparable levels of accuracy over a long period. The quantification of flood risk according to the narrow definition of this term is missing in data-and index-based approaches. Index-based analyses are useful to compare risk between spatial units and to identify risk-hotspots.[49,57] Repeated surveys of the risk index can prove the effectiveness of risk management strategies.[49] Nevertheless, although the parameter selection is flexible, the results are method-dependent and not transferable to other regions. Hence, comparability of flood risk evolution over several regions is limited. Furthermore, risk is quantified on an aggregated level of a region and detailed statements about local impacts of flood hazards on exposure and vulnerability are not possible with index-based approaches. With model-based analyses, flood hazard evolution can be quantified, and exposure and vulnerability can be derived from the simulations and geospatial overlay analyses. The outcomes of model-based risk evolution studies are comparable across regions. Model-based analyses allow analyzing the effects of change in an individual risk factor (e.g., settlement growth) on the overall risk evolution, as well as analyzing the combined effects of all changing risk factors. The studies that consider the change of more than one risk component show that the evolution of the risk factors can have self-reinforcing (cumulative) effects on overall risk evolution or even cancel each other out and keep overall risk nearly constant. Only a model-based approach allows for disentangling the individual effects of changing risk factors on the overall risk evolution and thus to identify the most relevant driver of change in a flooding system. A disadvantage of model-based analyses are the amount and resolution of data and computational power needed. Scenario-based analyses can enhance risk evolution analyses by integrating possible influences of climate and socio-economic changes.

The repeated analyses of risk in the past allow the detection of flood risk evolution (**Figure 2-2**). Further, they enable the detection of drivers of change and the system dynamics leading to an increase or decrease of risk. In addition, the analyses of past risk evolution enable the detection of events and management strategies that had or will have (delayed) effects on the risk system. While analyzing past evolution, it is possible to ascertain past developments leading to limitations for future evolutions (legacy effect). Nevertheless, to evaluate risk evolution in the past, difficulties arise with data availability, data completeness, data accuracy, and scales over periods. Consequently, the comparability of the risk analysis outcomes over multiple periods is not always given and the availability bias must be taken into account. In addition, the risk analyses are prone to uncertainties from the climatic/hydrological/hydraulic analyses as well as from exposure and vulnerability analyses.[138]

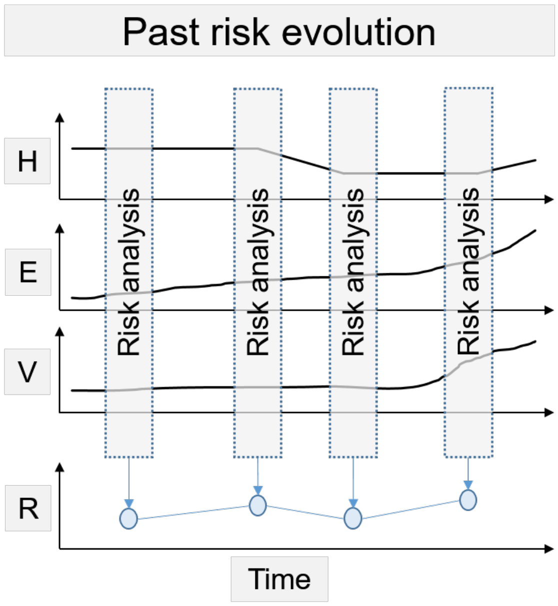


Figure 2-2. Illustration of past risk evolution. The risk analysis combines the three risk components (*H=Hazard, E=Exposure, V=Vulnerability*). Each component (*H,E,V*) has its own evolution over time. The repeated risk analysis over several time steps detects an increase or decrease of risk in past, and therefore risk evolution.

The analyses of future risk evolution allow identifying possible drivers of change and pathways of risk evolution (**Figure 2-3**). Future risk prediction enables the detection of critical thresholds that are important for adaptive flood risk management. However, future estimations of hazard, exposure and vulnerability are based on scenarios and are therefore prone to uncertainties.[139] It is therefore crucial to monitor, which of the underlying scenarios are becoming effective. Depending on the spatiotemporal scale of the case study, the risk increases or decreases due to different explanations. For example, Elmer et al.[10] detected a decrease in risk for residential buildings from the years 1990-2000 that can be attributed to changes in flood hazard, and an increase in risk for residential buildings from the years 2000-2020 due to changes in exposure (urban sprawl).

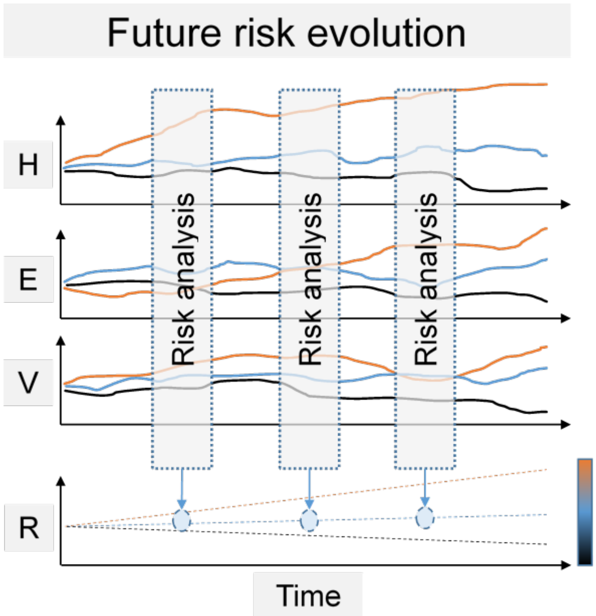


Figure 2-3. Illustration of future risk evolution. The evolution of all three risk components (*H=Hazard, E=Exposure, V=Vulnerability*) in the future can be analyzed using several future scenarios. As in the past, the possible risk evolution can be projected while analyzing risk for several time steps. Comparing the periods reveals trends in risk evolution.

2.4 Flood risk monitoring

Although the review focused on flood risk evolution, the conclusions can be generalized and are valid for monitoring risk evolution from other natural hazards as well. The use and interpretation of the term monitoring varies between disciplines. The IPCC defines monitoring as "systematically identifying, characterizing and assessing progress over time".[4] However, monitoring tools mainly observe the hazard and provide information on early warning[27] or observe global and national patterns of disaster losses and impacts.[5] The monitoring approaches listed above capture only parts of the overall risk. However, risk results from the interactions between the risk components (H, E, V), consequently, risk itself cannot be monitored directly. Additionally, risk monitoring cannot be done by just monitoring a single data stream; it requires the combination of data and proxy data of the evolving risk factors and thus methods such as data mining, data modeling, data analyses, and data combination.

In conclusion, we define the term "risk monitoring" as the systematic detection of risk evolution by periodically (re)evaluating the factors influencing the risk components hazard, exposure and vulnerability, modeling the risk components and combining them to quantify risk.

The most important component of a monitoring is the risk analysis framework (**Figure 2-4**). It describes how risk is quantified and how the risk factors describing the three risk components hazard, exposure, and vulnerability are determined. These factors need to be integrated in a model framework to calculate the three risk components. Modeling the risk factors is needed if the evolution of risk factors must be derived from proxy data that can be monitored quantitatively. After modeling and combination of data that represent the risk factors, risk can be analyzed and evaluated.

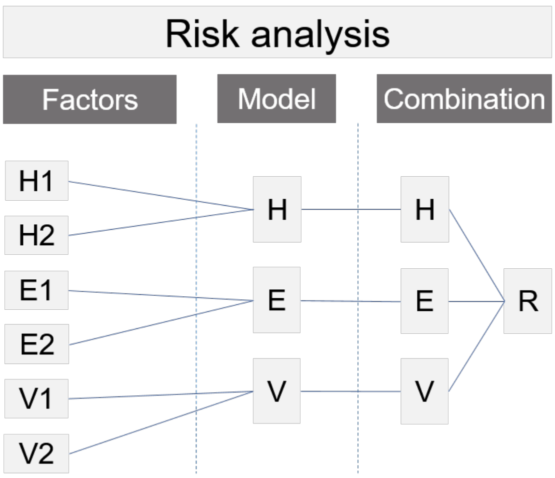


Figure 2-4. Principles of risk analysis. Several monitored factors are used to model each of the risk components (*H=Hazard, E=Exposure, V=Vulnerability*). The risk components are combined to quantify risk (*R*).

By repeated risk analysis, risk values can be compared over time and trends detected (**Figure 2-5**). After at least two repeated quantitative risk analyses, a risk monitoring reveals an additional dimension in risk analysis. It shows if risks in a certain place are increasing or decreasing. The trend can be quantified in a rate of change. This in turn allows estimating the period in which a certain risk threshold will be reached and when risk will not be societally acceptable anymore and risk mitigation measures are required. This informs decision-making in adaptive risk management in addition to knowing the current state of risks. Risk monitoring is a monitoring approach independent of the selected time step length between different time steps (e.g. every year or every ten years). This contrasts with other monitoring setups where selected state-describing variables are being monitored continuously (e.g. discharge). While risk monitoring is made on discrete time steps, monitoring changes in the risk components can in principle be a continuous monitoring of data streams.

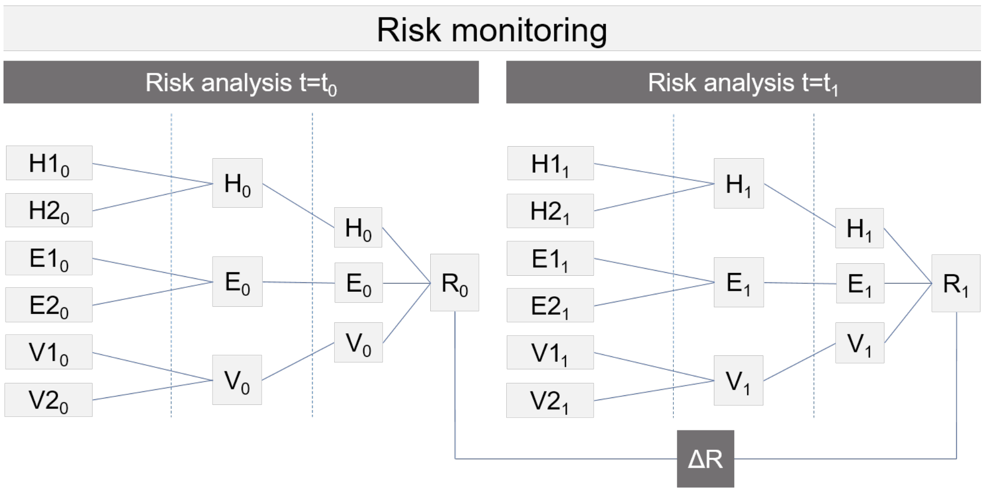


Figure 2-5. Principles of risk monitoring. Systematic detection of risk evolution (*ΔR*) by periodically ($t=t_0$, $t=t_1$) measuring the factors influencing the risk components hazard (*H*), exposure (*E*) and vulnerability (*V*), modeling the risk components and combining them to quantify risk.

2.4.1 Opportunities and Challenges

To elaborate flood risk monitoring, it is necessary to determine what risk monitoring can or should be used for. Essential objectives of flood risk monitoring are (a) to gain a better understanding of flood risk evolution, (b) to identify spatiotemporal variations of flood risk evolution, (c) to maintain the safety level of flood risk management, and d) to detect possible drivers that lead to an increase or decrease in flood risk. This allows detecting legacy effects, rebound effects, time delays, and the effects of the implementation of flood risk management strategies. Following on from the target setting, it must be defined which actors will use the results for which target group and for which kind of decision-making. It must be defined in the beginning whether the risk is analyzed qualitatively, semi-quantitatively, or quantitatively. A strict quantification of risk evolution is possible only with model-based approaches. The objective and purpose of risk monitoring also determine the selection of data or factors to be examined.

This review summarizes the data and factors that change and can be monitored to analyze the evolution of risk. Hence, the review points out examples for the variability of potential risk monitoring setups and provides a starting point for the selection of methods and factors to be considered in the design of a risk monitoring concept.

The comparability of data over a long time period is one of the most important challenges. Once a risk monitoring concept is drafted, it must be guaranteed that the necessary data for periodically repeated risk analysis are continuously updated and expected to be available for the next decades. In addition, several sources of uncertainty exist in the risk analyses in general and, consequently, in risk monitoring as well. Examples are the definition of hazard scenarios, the process of modeling (input data, calibration etc.), the data quality, as well as uncertainties in the vulnerability analysis. The data availability is closely linked with the objectives of the risk monitoring. Given the diverse approaches to analyzing risk, the combination of approaches can serve to evaluate the spatiotemporal evolution of risk. Depending on the objective, varying levels of detail are necessary and useful. Another important aspect is the spatial delineation of the system. Different spatial reference systems must be used and combined, such as political units, hydrological catchments, or raster cells. While the risk components hazard and exposure are mostly used in a similar meaning across the reviewed publications, we found great diversity in the use and definition of the term "vulnerability". How the evolution of this risk component is implemented in a risk monitoring concept must be carefully evaluated.

2.5 Conclusion

In this study, flood risk evolution analysis studies were systematically reviewed. The review shows that there is no one size fits all applicable risk monitoring strategy. However, there is a variety of studies which analyzed flood risk evolution in the past and for the future and which served as a basis to elaborate principles of a flood risk monitoring. Further, the results of the review can help further researchers to find appropriate methodology and factors to analyze flood risk evolution and/or set up a national/regional or local flood risk monitoring concept.

The detailed monitoring of factors describing the risk components allows disentangling important changes in risk components that lead to an increase or decrease in risk. This disentangling means that management measures can be implemented specifically to address the main drivers of change.

Further research is needed in holistic risk analyses, including dynamics in hazard, exposure and vulnerability. The focus should be on a complex systems perspective to analyze non-linearity, interactions between and co-evolution in risk components, and feedback mechanisms.[19] In addition, further research and implementation of monitoring studies is necessary for enabling adaptive flood risk management. The focus should be on data mining, validation, warranty of consistency and modeling frameworks.

References

1. World Meteorological Association (2021). WMO Atlas of Mortality and economic losses from weather, climate and water extremes (1970-2019) (Technical Report).

2. Birkmann, J., Cardona, O.D., Carreño, M.L., Barbat, A.H., Pelling, M., Schneiderbauer, S., Kienberger, S., Keiler, M., Alexander, D., Zeil, P., et al. (2013). Framing vulnerability, risk and societal responses: the MOVE framework. Nat Hazards *67*, 193–211. https://doi.org/10.1007/s11069-013-0558-5.

3. De Moel, H., Jongman, B., Kreibich, H., Merz, B., Penning-Rowsell, E., and Ward, P.J. (2015). Flood risk assessments at different spatial scales. Mitig Adapt Strateg Glob Change *20*, 865–890. https://doi.org/10.1007/s11027-015-9654-z.

4. IPCC (2022). Annex II: Glossary. In Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, V. Möller, J. B. R. Matthews, R. van Diemen, C. Méndez, S. Semenov, J. S. Fuglestvedt, and A. Reisinger, eds. (Cambridge University Press), pp. 2897–2930. https://doi.org/10.1017/9781009325844.029.

5. UNDRR [United Nations Office for Disaster Risk Reduction] (2022). Global Assessment Report on Disaster Risk Reduction 2022: Our World at Risk: Transforming Governance for a Resilient Future.

6. Fuchs, S., Keiler, M., Sokratov, S., and Shnyparkov, A. (2013). Spatiotemporal dynamics: the need for an innovative approach in mountain hazard risk management. Nat Hazards *68*, 1217–1241. https://doi.org/10.1007/s11069-012-0508-7.

7. Klinke, A., and Renn, O. (2021). The Coming of Age of Risk Governance. Risk Analysis *41*, 544–557. https://doi.org/10.1111/risa.13383.

8. Hall, J. (2003). Quantified scenarios analysis of drivers and impacts of changing flood risk in England and Wales: 2030-2100. Global Environmental Change Part B: Environmental Hazards *5*, 51–65. https://doi.org/10.1016/j.hazards.2004.04.002.

9. Domeneghetti, A., Carisi, F., Castellarin, A., and Brath, A. (2015). Evolution of flood risk over large areas: Quantitative assessment for the Po river. Journal of Hydrology *527*, 809–823. https://doi.org/10.1016/j.jhydrol.2015.05.043.

10. Elmer, F., Hoymann, J., Düthmann, D., Vorogushyn, S., and Kreibich, H. (2012). Drivers of flood risk change in residential areas. Nat. Hazards Earth Syst. Sci. *12*, 1641–1657. https://doi.org/10.5194/nhess-12-1641-2012.

11. Mazzorana, B., Levaggi, L., Keiler, M., and Fuchs, S. (2012). Towards dynamics in flood risk assessment. Nat. Hazards Earth Syst. Sci. *12*, 3571–3587. https://doi.org/10.5194/nhess-12-3571-2012.

12. Merz, B., Hall, J., Disse, M., and Schumann, A. (2010). Fluvial flood risk management in a changing world. Nat. Hazards Earth Syst. Sci. *10*, 509–527. https://doi.org/10.5194/nhess-10-509-2010.

13. Zischg, A.P., Hofer, P., Mosimann, M., Röthlisberger, V., Ramirez, J.A., Keiler, M., and Weingartner, R. (2018). Flood risk (d)evolution: Disentangling key drivers of flood risk change with a retro-model experiment. Science of The Total Environment *639*, 195–207. https://doi.org/10.1016/j.scitotenv.2018.05.056.

14. IPCC (2022). Summary for Policymakers. Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

15. Hemmati, M., Ellingwood, B.R., and Mahmoud, H.N. (2020). The Role of Urban Growth in Resilience of Communities Under Flood Risk. Earth's Future *8*. https://doi.org/10.1029/2019EF001382.

16. Kundzewicz, Z.W., Su, B., Wang, Y., Wang, G., Wang, G., Huang, J., and Jiang, T. (2019). Flood risk in a range of spatial perspectives - From global to local scales. Natural Hazards and Earth System Sciences *19*, 1319–1328. https://doi.org/10.5194/nhess-19-1319-2019.

17. Mazzoleni, M., Mård, J., Rusca, M., Odongo, V., Lindersson, S., and Di Baldassarre, G. (2021). Floodplains in the Anthropocene: A Global Analysis of the Interplay Between Human Population, Built Environment, and Flood Severity. Water Res. *57*. https://doi.org/10.1029/2020WR027744.

18. de Ruiter, M.C., and van Loon, A.F. (2022). The challenges of dynamic vulnerability and how to assess it. iScience *25*, 104720. https://doi.org/10.1016/j.isci.2022.104720.

19. Mishra, A., Mukherjee, S., Merz, B., Singh, V.P., Wright, D.B., Villarini, G., Paul, S., Kumar, D.N., Khedun, C.P., Niyogi, D., et al. (2022). An Overview of Flood Concepts, Challenges, and Future Directions. Journal of Hydrologic Engineering *27*. https://doi.org/10.1061/(ASCE)HE.1943-5584.0002164.

20. Naylor, A., Ford, J., Pearce, T., and Van Alstine, J. (2020). Conceptualizing Climate Vulnerability in Complex Adaptive Systems. One Earth *2*, 444–454. https://doi.org/10.1016/j.oneear.2020.04.011.

21. Hochrainer-Stigler, S. (2020). Extreme and Systemic Risk Analysis: A Loss Distribution Approach (Springer Singapore) https://doi.org/10.1007/978-981-15-2689-3.

22. Renn, O. (2021). New challenges for risk analysis: systemic risks. Journal of Risk Research *24*, 127–133. https://doi.org/10.1080/13669877.2020.1779787.

23. Renn, O., Laubichler, M., Lucas, K., Kröger, W., Schanze, J., Scholz, R.W., and Schweizer, P. (2022). Systemic Risks from Different Perspectives. Risk Analysis *42*, 1902–1920. https://doi.org/10.1111/risa.13657.

24. Schanze, J., and Maleska, V. (2019). Towards a more systemic understanding of flood risks. J Flood Risk Management *12*. https://doi.org/10.1111/jfr3.12569.

25. Hossain, M.S., Ramirez, J.A., Haisch, T., Speranza, C.I., Martius, O., Mayer, H., and Keiler, M. (2020). A coupled human and landscape conceptual model of risk and resilience in Swiss Alpine communities. Science of The Total Environment *730*, 138322. https://doi.org/10.1016/j.scitotenv.2020.138322.

26. Zischg, A. (2023). Flood risk change: a complexity perspective (Elsevier).

27. UNDRR [United Nations Office for Disaster Risk Reduction] (2015). Sendai Framework for Disaster Risk Reduction 2015-2030.

28. Cutter, S.L., and Gall, M. (2015). Sendai targets at risk. Nature Clim Change *5*, 707–709. https://doi.org/10.1038/nclimate2718.

29. UNDRR [United Nations Office for Disaster Risk Reduction] (2023). Measuring Implementation of the Sendai Framework. Sendaimonitor. https://sendaimonitor.undrr.org/.

30. Wassénius, E., and Crona, B.I. (2022). Adapting risk assessments for a complex future. One Earth *5*, 35–43. https://doi.org/10.1016/j.oneear.2021.12.004.

31. European Commission (2007). Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks (Text with EEA relevance).

32. European Commission (2024). Floods - European Commission. https://environment.ec.europa.eu/topics/water/floods_en.

33. Priest, S.J., Suykens, C., Van Rijswick, H.F.M.W., Schellenberger, T., Goytia, S., Kundzewicz, Z.W., van Doorn-Hoekveld, W.J., Beyers, J.-C., and Homewood, S. (2016). The European Union approach to flood risk management and improving societal resilience: lessons from the implementation of the Floods Directive in six European countries. ECOLOGY AND SOCIETY *21*. https://doi.org/10.5751/ES-08913-210450.

34. Rauter, M., Thaler, T., Attems, M.-S., and Fuchs, S. (2019). Obligation or Innovation: Can the EU Floods Directive Be Seen as a Tipping Point Towards More Resilient Flood Risk Management? A Case Study from Vorarlberg, Austria. Sustainability *11*, 5505. https://doi.org/10.3390/su11195505.

35. European Commission and Directorate-General for Environment (2021). Current practice in flood risk management in the European Union: September 2021 (Publications Office of the European Union).

36. Berrang-Ford, L., Pearce, T., and Ford, J.D. (2015). Systematic review approaches for climate change adaptation research. Reg Environ Change *15*, 755–769. https://doi.org/10.1007/s10113-014-0708-7.

37. Khan, K.S., Kunz, R., Kleijnen, J., and Antes, G. (2003). Five Steps to Conducting a Systematic Review. J R Soc Med *96*, 118–121. https://doi.org/10.1177/014107680309600304.

38. Liberati, A. (2009). The PRISMA Statement for Reporting Systematic Reviews and Meta-Analyses of Studies That Evaluate Health Care Interventions: Explanation and Elaboration. Ann Intern Med *151*, W. https://doi.org/10.7326/0003-4819-151-4-200908180-00136.

39. Akdim, B., Gartet, A., Laaouane, M., and Amyay, M. (2013). Flood risk and mitigation strategies in the southeastern suburbs of Fez City (Morocco). Estudios Geograficos *74*, 379–408. https://doi.org/10.3989/estgeogr.201314.

40. Galligari, A., Tonolo, F.G., and Massazza, G. (2020). Floodplain settlement dynamics in the Maouri Dallol at Guéchémé, Niger: A multidisciplinary approach. Sustainability (Switzerland) *12*. https://doi.org/10.3390/su12145632.

41. Wang, C., Wang, K., Liu, D., Zhang, L., Li, M., Imran Khan, M., Li, T., and Cui, S. (2024). Development and application of a comprehensive assessment method of regional flood disaster risk based on a refined random forest model using beluga whale optimization. Journal of Hydrology *633*. https://doi.org/10.1016/j.jhydrol.2024.130963.

42. Liu, J., Wang, J., Xiong, J., Cheng, W., Cui, X., He, W., He, Y., Duan, Y., Yang, G., and Wang, N. (2021). Dynamic Assessment of the Flood Risk at Basin Scale under Simulation of Land-Use Scenarios and Spatialization Technology of Factor. WATER *13*. https://doi.org/10.3390/w13223239.

43. Liu, J., Xiong, J., Chen, Y., Sun, H., Zhao, X., Tu, F., and Gu, Y. (2023). An integrated model chain for future flood risk prediction under land-use changes. Journal of Environmental Management *342*. https://doi.org/10.1016/j.jenvman.2023.118125.

44. Sauer, J., Pallathadka, A., Ajibade, I., Berbés-Blázquez, M., Chang, H., Cook, E.M., Grimm, N.B., Iwaniec, D.M., Lloyd, R., and Post, G.C. (2023). Relating social, ecological, and technological vulnerability to future flood exposure at two spatial scales in four U.S. cities. Sustainable Cities and Society *99*. https://doi.org/10.1016/j.scs.2023.104880.

45. Steinhausen, M., Paprotny, D., Dottori, F., Sairam, N., Mentaschi, L., Alfieri, L., Lüdtke, S., Kreibich, H., and Schröter, K. (2022). Drivers of future fluvial flood risk change for residential buildings in Europe. Global Environmental Change *76*. https://doi.org/10.1016/j.gloenvcha.2022.102559.

46. Zuo, D., Wu, C., Zheng, Y., Chen, X., and Wang, L. (2023). Climate change and human activity impacts on future flood risk in the Pearl River Delta based on the MaxEnt model. Frontiers in Earth Science *10*. https://doi.org/10.3389/feart.2022.1053829.

47. Feng, Y., Rakowski, C.L., McPherson, T.N., and Judi, D.R. (2019). A partition of the combined impacts of socioeconomic development and climate variation on economic risks of riverine floods. Journal of Flood Risk Management *12*. https://doi.org/10.1111/jfr3.12508.

48. Nguyen, H.D., Nguyen, Q.-H., Dang, D.K., Van, C.P., Truong, Q.H., Pham, S.D., Bui, Q.-T., and Petrisor, A.-I. (2024). A novel flood risk management approach based on future climate and land use change scenarios. Science of the Total Environment *921*. https://doi.org/10.1016/j.scitotenv.2024.171204.

49. Chen, Y., Li, J., and Chen, A. (2021). Does high risk mean high loss: Evidence from flood disaster in southern China. Science of the Total Environment *785*. https://doi.org/10.1016/j.scitotenv.2021.147127.

50. Guoyi, L., Liu, J., and Shao, W. (2023). Urban flood risk assessment under rapid urbanization in Zhengzhou City, China. Regional Sustainability *4*, 332–348. https://doi.org/10.1016/j.regsus.2023.08.004.

51. Lazzarin, T., Defina, A., and Viero, D.P. (2023). Assessing 40 Years of Flood Risk Evolution at the Micro-Scale Using an Innovative Modeling Approach: The Effects of Urbanization and Land Planning. GEOSCIENCES *13*. https://doi.org/10.3390/geosciences13040112.

52. Peng, L., Wang, Y., Yang, L., Garchagen, M., and Deng, X. (2024). A comparative analysis on flood risk assessment and management performances between Beijing and Munich. Environmental Impact Assessment Review *104*. https://doi.org/10.1016/j.eiar.2023.107319.

53. Seemuangngam, A., and Lin, H.-L. (2024). The impact of urbanization on urban flood risk of Nakhon Ratchasima, Thailand. Applied Geography *162*. https://doi.org/10.1016/j.apgeog.2023.103152.

54. Chyon, M.S.A., Biswas, S., Mondal, M.S., Roy, B., and Rahman, A. (2023). Integrated assessment of flood risk in Arial Khan floodplain of Bangladesh under changing climate and socioeconomic conditions. Journal of Flood Risk Management *16*. https://doi.org/10.1111/jfr3.12876.

55. Tesselaar, M., Botzen, W.J.W., Tiggeloven, T., and Aerts, J.C.J.H. (2023). Flood insurance is a driver of population growth in European floodplains. Nature Communications *14*. https://doi.org/10.1038/s41467-023-43229-8.

56. Poussin, J.K., Bubeck, P., H. Aerts, J.C.J., and Ward, P.J. (2012). Potential of semi-structural and non-structural adaptation strategies to reduce future flood risk: Case study for the Meuse. Natural Hazards and Earth System Sciences *12*, 3455–3471. https://doi.org/10.5194/nhess-12-3455-2012.

57. Chen, J., Li, Q., Wang, H., and Deng, M. (2020). A machine learning ensemble approach based on random forest and radial basis function neural network for risk evaluation of regional flood disaster: A case study of the yangtze river delta, China. International Journal of Environmental Research and Public Health *17*. https://doi.org/10.3390/ijerph17010049.

58. Ciullo, A., Viglione, A., Castellarin, A., Crisci, M., and Di Baldassarre, G. (2017). Socio-hydrological modelling of flood-risk dynamics: comparing the resilience of green and technological systems. Hydrological Sciences Journal *62*, 880–891. https://doi.org/10.1080/02626667.2016.1273527.

59. Wongboontham, T., Nitivattananon, V., Pal, I., and Nguyen, T.P.L. (2023). Enhancing Urban Flood Resilience: The Role and Influence of Socio-Economics in the Chao Phraya River Basin, Thailand. International Journal of Sustainable Development and Planning *18*, 3061–3076. https://doi.org/10.18280/ijsdp.181009.

60. Abass, K., Dumedah, G., and Frempong, F. (2019). Understanding the physical and human contexts of fluvial floods in rural Ghana. International Journal of River Basin Management. https://doi.org/10.1080/15715124.2019.1653310.

61. Akhter, F., Mazzoleni, M., and Brandimarte, L. (2021). Analysis of 220 years of floodplain population dynamics in the us at different spatial scales. Water (Switzerland) *13*. https://doi.org/10.3390/w13020141.

62. Andrade, M.I., and Scarpati, O.E. (2007). Recent changes in flood risk in the Gran La Plata, Buenos Aires province, Argentina: Causes and management strategy. GeoJournal *70*, 245–250. https://doi.org/10.1007/s10708-008-9137-9.

63. Cortès, M., Llasat, M.C., Gilabert, J., Llasat-Botija, M., Turco, M., Marcos, R., Martín Vide, J.P., and Falcón, L. (2018). Towards a better understanding of the evolution of the flood risk in Mediterranean urban areas: the case of Barcelona. Natural Hazards *93*, 39–60. https://doi.org/10.1007/s11069-017-3014-0.

64. Faccini, F., Luino, F., Paliaga, G., Sacchini, A., Turconi, L., and de Jong, C. (2018). Role of rainfall intensity and urban sprawl in the 2014 flash flood in Genoa City, Bisagno catchment (Liguria, Italy). Applied Geography *98*, 224–241. https://doi.org/10.1016/j.apgeog.2018.07.022.

65. Flores, A.P., Giordano, L., and Ruggerio, C.A. (2020). A basin-level analysis of flood risk in urban and periurban areas: A case study in the metropolitan region of Buenos Aires, Argentina. HELIYON *6*. https://doi.org/10.1016/j.heliyon.2020.e04517.

66. Franci, F., Mandanici, E., and Bitelli, G. (2015). Remote sensing analysis for flood risk management in urban sprawl contexts. Geomatics, Natural Hazards and Risk *6*, 583–599. https://doi.org/10.1080/19475705.2014.913695.

67. Clark, S., Sharma, A., and Sisson, S.A. (2018). Patterns and comparisons of human-induced changes in river flood impacts in cities. Hydrology and Earth System Sciences *22*, 1793–1810. https://doi.org/10.5194/hess-22-1793-2018.

68. Eder, M., Löschner, L., Herrnegger, M., Hogl, K., Nordbeck, R., Scherhaufer, P., Schober, B., Seher, W., Wesemann, J., Zahnt, N., et al. (2022). RegioFEM — Applying a floodplain evaluation method to support a future-oriented flood risk management (Part II). Journal of Flood Risk Management *15*. https://doi.org/10.1111/jfr3.12758.

69. Januriyadi, N.F., Kazama, S., Moe, I.R., and Kure, S. (2018). Evaluation of future flood risk in asian megacities: A case study of Jakarta. Hydrological Research Letters *12*, 14–22. https://doi.org/10.3178/hrl.12.14.

70. Kefi, M., Mishra, B.K., Masago, Y., and Fukushi, K. (2020). Analysis of flood damage and influencing factors in urban catchments: case studies in Manila, Philippines, and Jakarta, Indonesia. Natural Hazards *104*, 2461–2487. https://doi.org/10.1007/s11069-020-04281-5.

71. Murnane, R.J., Daniell, J.E., Schäfer, A.M., Ward, P.J., Winsemius, H.C., Simpson, A., Tijssen, A., and Toro, J. (2017). Future scenarios for earthquake and flood risk in Eastern Europe and Central Asia. Earth's Future *5*, 693–714. https://doi.org/10.1002/2016EF000481.

72. Khan, D.M., Veerbeek, W., Chen, A.S., Hammond, M.J., Islam, F., Pervin, I., Djordjevic, S., and Butler, D. (2018). Back to the future: assessing the damage of 2004 Dhaka flood in the 2050 urban environment. JOURNAL OF FLOOD RISK MANAGEMENT *11*, S43–S54. https://doi.org/10.1111/jfr3.12220.

73. Beckers, A., Dewals, B., Erpicum, S., Dujardin, S., Detrembleur, S., Teller, J., Pirotton, M., and Archambeau, P. (2013). Contribution of land use changes to future flood damage along the river

Meuse in the Walloon region. Natural Hazards and Earth System Sciences *13*, 2301–2318. https://doi.org/10.5194/nhess-13-2301-2013.

74. Sharma, S., Gomez, M., Keller, K., Nicholas, R., and Mejia, A. (2021). Regional Flood Risk Projections under Climate Change. JOURNAL OF HYDROMETEOROLOGY *22*, 2259–2274. https://doi.org/10.1175/JHM-D-20-0238.1.

75. Waghwala, R.K., and Agnihotri, P.G. (2021). Impact assessment of urbanization on flood risk and integrated flood management approach: a case study of Surat city and its surrounding region. ISH Journal of Hydraulic Engineering *27*, 577–587. https://doi.org/10.1080/09715010.2019.1658548.

76. Chandole, V., Joshi, G.S., and Srivastava, V.K. (2024). Flood risk mapping under changing climate in Lower Tapi river basin, India. STOCHASTIC ENVIRONMENTAL RESEARCH AND RISK ASSESSMENT. https://doi.org/10.1007/s00477-024-02677-4.

77. Chen, X., Zhang, H., Chen, W., and Huang, G. (2021). Urbanization and climate change impacts on future flood risk in the Pearl River Delta under shared socioeconomic pathways. Science of the Total Environment *762*. https://doi.org/10.1016/j.scitotenv.2020.143144.

78. Kittikhun, C., Pilailar, S., Chittaladakorn, S., and Jhonpadit, E. (2020). Flood Risk Index for Land-Use Changes: Case Study of Pakpanang River Basin. ENGINEERING JOURNAL-THAILAND *24*, 25–40. https://doi.org/10.4186/ej.2020.24.5.25.

79. Kim, J.-S., Moon, Y.-I., Yoon, S.-K., and Choi, M. (2015). A case study of regional risk assessment of river restoration projects: Nakdong River Basin, South Korea. Journal of Water and Climate Change *6*, 628–637. https://doi.org/10.2166/wcc.2015.113.

80. Pan, W., Yan, M., Zhao, Z., and Gulzar, M.A. (2023). Flood Risk Assessment and Management in Urban Communities: The Case of Communities in Wuhan. LAND *12*. https://doi.org/10.3390/land12010112.

81. Naba, C., Ishidaira, H., Magome, J., and Souma, K. (2023). ANALYSIS OF FLOOD-POVERTY RELATIONSHIP IN BURKINA FASO USING REMOTELY SENSED NIGHTTIME LIGHT. Journal of Japan Society of Civil Engineers *11*, 1–9. https://doi.org/10.2208/JOURNALOFJSCE.23-27035.

82. Aich, V., Liersch, S., Vetter, T., Andersson, J.C.M., Müller, E.N., and Hattermann, F.F. (2015). Climate or land use? - Attribution of changes in river flooding in the Sahel zone. Water (Switzerland) *7*, 2796–2820. https://doi.org/10.3390/w7062796.

83. Asinya, E.A., and Alam, M.J.B. (2021). Flood Risk in Rivers: Climate Driven or Morphological Adjustment. Earth Systems and Environment *5*, 861–871. https://doi.org/10.1007/s41748-021-00257-y.

84. Dixon, S.J., Sear, D.A., Odoni, N.A., Sykes, T., and Lane, S.N. (2016). The effects of river restoration on catchment scale flood risk and flood hydrology. Earth Surface Processes and Landforms *41*, 997–1008. https://doi.org/10.1002/esp.3919.

85. Du, H., Xia, J., Zeng, S., and Tu, Y. (2024). Climate Change and Multi-Reservoirs Impacts on Extreme Flood: Nonstationary Regional Frequency Analysis and Uncertainty Estimation. Water Resources Management *38*, 951–965. https://doi.org/10.1007/s11269-023-03703-w.

86. Grandry, M., Gailliez, S., Brostaux, Y., and Degré, A. (2020). Looking at trends in high flows at a local scale: The case study of Wallonia (Belgium). Journal of Hydrology: Regional Studies *31*. https://doi.org/10.1016/j.ejrh.2020.100729.

87. Hung, P.M., Nguyen, H.D., and Van, C.P. (2023). ASSESSMENT OF INUNDATION SUSCEPTIBILITY IN THE CONTEXT OF CLIMATE CHANGE, BASED ON MACHINE

LEARNING AND REMOTE SENSING: CASE STUDY IN VINH PHUC PROVINCE OF VIETNAM. Geographia Technica *18*, 93–112. https://doi.org/10.21163/GT_2023.182.07.

88. Janicka, E., Kanclerz, J., Agaj, T., and Gizinska, K. (2023). Comparison of Two Hydrological Models, the HEC-HMS and Nash Models, for Runoff Estimation in Michalowka River. SUSTAINABILITY *15*. https://doi.org/10.3390/su15107959.

89. Mei, C., Liu, J., Wang, H., Shao, W., Yang, Z., Huang, Z., Li, Z., and Li, M. (2021). Flood risk related to changing rainfall regimes in arterial traffic systems of the Yangtze River Delta. Anthropocene *35*. https://doi.org/10.1016/j.ancene.2021.100306.

90. Rončák, P., Lisovszki, E., Szolgay, J., Hlavčová, K., Kohnová, S., Csoma, R., and Poórová, J. (2017). The potential for land use change to reduce flood risk in mid-sized catchments in the Myjava region of Slovakia. Contributions to Geophysics and Geodesy *47*, 95–112. https://doi.org/10.1515/congeo-2017-0007.

91. Schober, B., Hauer, C., and Habersack, H. (2020). Floodplain losses and increasing flood risk in the context of recent historic land use changes and settlement developments: Austrian case studies. Journal of Flood Risk Management *13*. https://doi.org/10.1111/jfr3.12610.

92. Slater, L.J., and Villarini, G. (2017). Evaluating the drivers of seasonal streamflow in the U.S. Midwest. Water (Switzerland) *9*. https://doi.org/10.3390/w9090695.

93. Sofia, G., and Nikolopoulos, E.I. (2020). Floods and rivers: a circular causality perspective. Scientific Reports *10*. https://doi.org/10.1038/s41598-020-61533-x.

94. Sokolova, G.V., Verkhoturov, A.L., and Korolev, S.P. (2019). Impact of deforestation on streamflow in the amur river basin. Geosciences (Switzerland) *9*. https://doi.org/10.3390/geosciences9060262.

95. Tang, Z., Wang, P., Li, Y., Sheng, Y., Wang, B., Popovych, N., and Hu, T. (2024). Contributions of climate change and urbanization to urban flood hazard changes in China's 293 major cities since 1980. Journal of Environmental Management *353*. https://doi.org/10.1016/j.jenvman.2024.120113.

96. Wilby, R.L., and Quinn, N.W. (2013). Reconstructing multi-decadal variations in fluvial flood risk using atmospheric circulation patterns. Journal of Hydrology *487*, 109–121. https://doi.org/10.1016/j.jhydrol.2013.02.038.

97. Yan, X., Liu, J., Rühland, K.M., Dong, H., He, J., and Smol, J.P. (2022). Human deforestation outweighed climate as factors affecting Yellow River floods and erosion on the Chinese Loess Plateau since the 10th century. Quaternary Science Reviews *295*. https://doi.org/10.1016/j.quascirev.2022.107796.

98. Zhang, H., Ma, W.-C., and Wang, X.-R. (2008). Rapid urbanization and implications for flood risk management in hinterland of the Pearl River Delta, China: The Foshan study. Sensors *8*, 2223–2239. https://doi.org/10.3390/s8042223.

99. Amiri, A., Soltani, K., Ebtehaj, I., and Bonakdari, H. (2024). A novel machine learning tool for current and future flood susceptibility mapping by integrating remote sensing and geographic information systems. Journal of Hydrology *632*. https://doi.org/10.1016/j.jhydrol.2024.130936.

100. Burton, A.J.R., Shepard, M.A., and Riddell, K.J. (2003). Land use and flood risk through catchment flood-management plans. Water and Environment Journal *17*, 220–225. https://doi.org/10.1111/j.1747-6593.2003.tb00472.x.

101. de Oliveira, A.K.B., Carneiro Alves, L.M., Carvalho, C.L., Haddad, A.N., de Magalhães, P.C., and Miguez, M.G. (2023). A framework for assessing flood risk responses of a densely urbanized watershed, to support urban planning decisions. Sustainable and Resilient Infrastructure *8*, 400–418. https://doi.org/10.1080/23789689.2023.2175139.

102. Du, S., Wu, R., Sun, H., Yan, D., Xue, J., Liao, W., Tuo, Y., and Zhang, W. (2022). Projection of Precipitation Extremes and Flood Risk in the China-Pakistan Economic Corridor. FRONTIERS IN ENVIRONMENTAL SCIENCE *10*. https://doi.org/10.3389/fenvs.2022.887323.

103. Kay, A.L., and Jones, D.A. (2012). Transient changes in flood frequency and timing in Britain under potential projections of climate change. International Journal of Climatology *32*, 489–502. https://doi.org/10.1002/joc.2288.

104. Li, L., Yang, J., and Wu, J. (2020). Future Flood Risk Assessment under the Effects of Land Use and Climate Change in the Tiaoxi Basin. SENSORS *20*. https://doi.org/10.3390/s20216079.

105. Liu, W., Zhang, A., Wang, L., Fu, G., Chen, D., Liu, C., and Cai, T. (2014). Projecting streamflow in the Tangwang River basin (China) using a rainfall generator and two hydrological models. Climate Research *62*, 79–97. https://doi.org/10.3354/cr01261.

106. Lu, Y., Qin, X.S., and Xie, Y.J. (2016). An integrated statistical and data-driven framework for supporting flood risk analysis under climate change. Journal of Hydrology *533*, 28–39. https://doi.org/10.1016/j.jhydrol.2015.11.041.

107. Meresa, H., Zhang, Y., Tian, J., and Faiz, M.A. (2022). Disentangling aggregated uncertainty sources in peak flow projections under different climate scenarios. Journal of Hydrology *613*. https://doi.org/10.1016/j.jhydrol.2022.128426.

108. Nigussie, T.A., and Altunkaynak, A. (2019). Modeling the effect of urbanization on flood risk in Ayamama Watershed, Istanbul, Turkey, using the MIKE 21 FM model. Natural Hazards *99*, 1031–1047. https://doi.org/10.1007/s11069-019-03794-y.

109. Nyaupane, N., Thakur, B., Kalra, A., and Ahmad, S. (2018). Evaluating future flood scenarios using CMIP5 climate projections. Water (Switzerland) *10*. https://doi.org/10.3390/w10121866.

110. Ryu, J.H., and Kim, J. (2019). A Study on Climate-Driven Flash Flood Risks in the Boise River Watershed, Idaho. WATER *11*. https://doi.org/10.3390/w11051039.

111. Sayers, P., Griffin, A., Lowe, J., Bernie, D., Carr, S., Kay, A., and Stewart, L. (2024). Beyond the local climate change uplift – The importance of changes in spatial structure on future fluvial flood risk in Great Britain. Natural Hazards *120*, 3773–3798. https://doi.org/10.1007/s11069-023-06350-x.

112. Smith, A., Freer, J., Bates, P., and Sampson, C. (2014). Comparing ensemble projections of flooding against flood estimation by continuous simulation. JOURNAL OF HYDROLOGY *511*, 205–219. https://doi.org/10.1016/j.jhydrol.2014.01.045.

113. Tam, T.H., Abdul Rahman, M.Z., Harun, S., Shahid, S., Try, S., Jamal, M.H., Ismail, Z., Razak, K.A., Ghani, M.K., and Abdul Wahab, Y.F. (2023). Flood hazard assessment using design rainfall under climate change scenarios in the Kelantan River Basin, Malaysia. International Journal of Disaster Resilience in the Built Environment. https://doi.org/10.1108/IJDRBE-05-2022-0048.

114. Wang, S., Zhang, L., She, D., Wang, G., and Zhang, Q. (2021). Future projections of flooding characteristics in the Lancang-Mekong River Basin under climate change. Journal of Hydrology *602*. https://doi.org/10.1016/j.jhydrol.2021.126778.

115. Wu, S.-Y. (2010). Potential impact of climate change on flooding in the Upper Great Miami River Watershed, Ohio, USA: A simulation-based approach [Impact potentiel du changement climatique sur les inondations dans le bassin supérieur de la Rivière Great Miami, Ohio, Etats-Unis: Une approche basée sur la simulation]. Hydrological Sciences Journal *55*, 1251–1263. https://doi.org/10.1080/02626667.2010.529814.

116. Yosri, A., Ghaith, M., and El-Dakhakhni, W. (2024). Deep learning rapid flood risk predictions for climate resilience planning. Journal of Hydrology *631*. https://doi.org/10.1016/j.jhydrol.2024.130817.

117. Tripathi, R., Sengupta, S.K., Patra, A., Chang, H., and Jung, I.W. (2014). Climate change, urban development, and community perception ofanextreme flood: A case study of Vernonia, Oregon, USA. Applied Geography *46*, 137–146. https://doi.org/10.1016/j.apgeog.2013.11.007.

118. Angra, D., and Sapountzaki, K. (2022). Climate Change Affecting Forest Fire and Flood Risk—Facts, Predictions, and Perceptions in Central and South Greece. Sustainability (Switzerland) *14*. https://doi.org/10.3390/su142013395.

119. Attaran, S., Mosaedi, A., Sojasi Qeidari, H., and Farrokhi Derakhshandeh, J. (2024). Co-evolution of human and hydrological system: Presenting a socio-hydrological approach to flood adaptation in Kalat city, Iran. International Journal of Disaster Risk Reduction *102*. https://doi.org/10.1016/j.ijdrr.2024.104292.

120. Smits, W.K., Attoh, E.M.N.A.N., and Ludwig, F. (2024). Flood risk assessment and adaptation under changing climate for the agricultural system in the Ghanaian White Volta Basin. Climatic Change *177*. https://doi.org/10.1007/s10584-024-03694-6.

121. Yu, I., and Jung, H. (2022). Flood Risk Assessment to Enable Improved Decision-Making for Climate Change Adaptation Strategies by Central and Local Governments. Sustainability (Switzerland) *14*. https://doi.org/10.3390/su142114335.

122. Dutal, H. (2023). Determining the effect of urbanization on flood hazard zones in Kahramanmaras, Turkey, using flood hazard index and multi-criteria decision analysis. Environmental Monitoring and Assessment *195*. https://doi.org/10.1007/s10661-022-10693-6.

123. Park, J., Kang, M.S., Song, I., Song, J.-H., and Jun, S.M. (2016). Probabilistic Risk Assessment of Flood Disaster in South Korea Under The Impact Of Climate Change. Irrigation and Drainage *65*, 16–25. https://doi.org/10.1002/ird.2049.

124. Radojevic, B., Breil, P., and Chocat, B. (2013). Are periurban areas key places to mitigate urban inundations? Journal of Flood Risk Management *6*, 124–134. https://doi.org/10.1111/j.1753-318X.2012.01166.x.

125. Ramiaramanana, F.N., and Teller, J. (2021). Urbanization and floods in sub-saharan africa: Spatiotemporal study and analysis of vulnerability factors—case of antananarivo agglomeration (Madagascar). Water (Switzerland) *13*. https://doi.org/10.3390/w13020149.

126. Abdelkareem, M., and Mansour, A.M. (2023). Risk assessment and management of vulnerable areas to flash flood hazards in arid regions using remote sensing and GIS-based knowledge-driven techniques. Natural Hazards *117*, 2269–2295. https://doi.org/10.1007/s11069-023-05942-x.

127. Hemmati, M., Mahmoud, H.N., Ellingwood, B.R., and Crooks, A.T. (2021). Shaping urbanization to achieve communities resilient to floods. Environmental Research Letters *16*. https://doi.org/10.1088/1748-9326/ac1e3c.

128. Früh-Müller, A., Wegmann, M., and Koellner, T. (2015). Flood exposure and settlement expansion since pre-industrial times in 1850 until 2011 in north Bavaria, Germany. Regional Environmental Change *15*, 183–193. https://doi.org/10.1007/s10113-014-0633-9.

129. Chen, L., Li, Q., and Xu, Y. (2023). Flash Flood Risk Assessment in the Context of Economic Change Scenarios. Weather, Climate, and Society *15*, 3–16. https://doi.org/10.1175/WCAS-D-21-0141.1.

130. Lv, H., Guan, X., and Meng, Y. (2020). Comprehensive evaluation of urban flood-bearing risks based on combined compound fuzzy matter-element and entropy weight model. Natural Hazards *103*, 1823–1841. https://doi.org/10.1007/s11069-020-04056-y.

131. Wang, G., Hu, Z., Liu, Y., Zhang, G., Liu, J., Lyu, Y., Gu, Y., Huang, X., Zhang, Q., Tong, Z., et al. (2020). Impact of expansion pattern of built-up land in floodplains on flood vulnerability: A case study in the North China plain area. Remote Sensing *12*, 1–29. https://doi.org/10.3390/rs12193172.

132. Gultom, B.J., Andi, Zaneta, J., and Javiera, E. (2022). Flood risk of today and tomorrow Spatial analysis of flood vulnerability in Pontianak City. International Review for Spatial Planning and Sustainable Development *10*, 170–187. https://doi.org/10.14246/irspsd.10.3_170.

133. Yang, X., Xu, L., Zhang, X., and Ding, S. (2023). Spatiotemporal evolutionary patterns and driving factors of vulnerability to natural disasters in China from 2000 to 2020. INTERNATIONAL JOURNAL OF DISASTER RISK REDUCTION *95*. https://doi.org/10.1016/j.ijdrr.2023.103890.

134. Boudou, M., Danière, B., and Lang, M. (2016). Assessing changes in urban flood vulnerability through mapping land use from historical information. Hydrology and Earth System Sciences *20*, 161–173. https://doi.org/10.5194/hess-20-161-2016.

135. Liu, J., and Shi, Z.-W. (2017). Quantifying land-use change impacts on the dynamic evolution of flood vulnerability. Land Use Policy *65*, 198–210. https://doi.org/10.1016/j.landusepol.2017.04.012.

136. Mao, D., Fu, X., Wang, J., and Guo, R. (2019). Assessment of Flood Vulnerability of the Dongting Lake Area in China with Regard to Land Use/Cover Change. JOURNAL OF COASTAL RESEARCH, 388–396. https://doi.org/10.2112/SI93-051.1.

137. Sahani, J., Kumar, P., Debele, S., Spyrou, C., Loupis, M., Aragão, L., Porcù, F., Shah, M.A.R., and Di Sabatino, S. (2019). Hydro-meteorological risk assessment methods and management by nature-based solutions. Science of The Total Environment *696*, 133936. https://doi.org/10.1016/j.scitotenv.2019.133936.

138. Salman, A.M., and Li, Y. (2018). Flood Risk Assessment, Future Trend Modeling, and Risk Communication: A Review of Ongoing Research. Natural Hazards Review *19*. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000294.

139. Kundzewicz, Z.W., Hirabayashi, Y., and Kanae, S. (2010). River Floods in the Changing Climate-Observations and Projections. Water Resources Management *24*, 2633–2646. https://doi.org/10.1007/s11269-009-9571-6.

3 Flood risk monitoring in Switzerland: proof of concept

Nele Rindsfüser[1,2*], Markus Mosimann[1,2], Margreth Keiler[3,4] and Andreas Paul Zischg[1,2]

[1] *Oeschger Centre for Climate Change Research, Mobiliar Lab for Natural Risks, University of Bern, Bern, Switzerland*
[2] *Institute of Geography, University of Bern, Bern, Switzerland*
[3] *Department of Geography, University of Innsbruck, Innsbruck, Austria*
[4] *Institute for Interdisciplinary Mountain Research, Austrian Academy of Sciences, Innsbruck, Austria*

Published in: International Journal of Disaster Risk Reduction, Volume 119, March 2025, 105337
https://doi.org/10.1016/j.ijdrr.2025.105337

Abstract

The spatiotemporal evolution of flood risk is a challenge for flood risk management. Climate change, land-use change, human intervention, and socio-economic development lead to dynamics in the main risk components - hazard, exposure, and vulnerability. These dynamics require continuous adaptation of risk management strategies to ensure the safety level of humans and their assets in the long term. To enable adaptive flood risk management, it is necessary to monitor the risk evolution. Risk monitoring provides a better understanding of the risk evolution, identifies spatiotemporal differences, and detects location-specific drivers of change. However, flood risk monitoring concepts and their application are lacking. In this study, we evaluate the application of flood risk monitoring using a national case study (Switzerland) with data collected over a time period of 10 years. The continuously updated hazard maps, the number of houses in potentially endangered areas and the degree of damage are used to quantify the evolution of flood risk in terms of potential damage to buildings. The results show varying annual evolution of the flood risk in Switzerland and in different administrative units, the spatial variability of the flood risk evolution, and the variability in the evolution of the flood risk components. Between 2014 and 2023, the total flood risk in Switzerland increased by 26%, the hazard area increased by 32% and the exposure by 35%. The disentangling of risk factors allows a better understanding of important drivers that increase or decrease risk. However, data availability and consistency are challenges for flood risk monitoring.

Keywords: Flood risk evolution, flood risk management, global change adaptation, natural hazards, exposure, vulnerability, systematic risk analysis, quantitative risk analysis

3.1 Introduction

Floods are the most frequently occurring natural hazards, having an increasing impact on societies around the globe.[1] From 2013 to 2022, insured flood losses increased around 30% compared to the previous decade.[1] Flood risk management is an important factor and contributes to the prevention of an ever-increasing trend of flood losses. A comprehensive flood risk management aims to reduce risk, manage residual risk and prevent new risks.[2] Flood risk is defined as "a function of the probability of a flood event or scenario and its related extent of damage".[3] Therefore, an integral part of flood risk management is the analysis of hazard (frequency and magnitude of floods), exposure (population and assets in flood-prone areas), and vulnerability (susceptibility of the exposed elements) to quantify risk.[2,4–6] However, with climate change, land-use change, human interventions and socio-economic developments, flood risk and its components change or evolve in space and time.[7–10] Thus, flood risk management is confronted with an ever-changing system, uncertainties in the evolution of risk and increased complexity.[10–13] These challenges call for new strategies in flood risk management, moving away from a very static perspective of flood risk to one that takes into account changes in flood risk.[3,14,15] Adaptive flood risk management is a strategy for global change adaptation and for confronting uncertainties in the planning process.[4,16,17] To enable adaptive flood risk management and to meet the objective of sustainable decision-making in flood risk management, the sound understanding, assessment and monitoring of flood risk evolution is essential.[2,3]

At the global level, the Sendai Framework for Disaster Risk Reduction[18] provides concrete actions for disaster risk management. The need to better understand, assess and monitor flood risk and to strengthen the mechanisms to achieve these objectives is addressed in Priorities 1 and 2.[18] However, monitoring tools developed in accordance with Priority 4 of the Sendai Framework address mainly the observation of hazard or disaster losses and impacts but not changing risks.[18] In Europe, the EU Floods Directive (FD) for European Member states[19] provides planning steps for flood risk management that have to be repeated, reviewed, and, if necessary, updated every six years to reduce the impact of floods. However, updating the flood risk assessment according to the FD aims to improve risk reduction and not to monitor risk evolution. The comparability of flood risk related to the sequence updates is difficult due to changes in the methodologies for assessing flood risk.[20–22] Recommendations and examples to set up a flood risk monitoring concept serving a proactive and adaptive flood risk management are still missing.

In the last decades, flood risk analysis studies focused increasingly on the analysis of the evolution of flood risk, hazard, exposure, and/or vulnerability for either past or future or as a comparison of past, present and future periods.[11,23] Rindsfüser et al.[24] showed in their review that studies analyzing pluvial and fluvial flood risk at local or regional scales deepen the understanding of flood risk evolution by repeating flood risk analyses for selected points in time and spatial scales. For example, Chen et al.[25] analyzed the risk evolution for southern China in the past with an index-based approach. They selected several indicators describing the hazard, exposure, and vulnerability component of risk and applied the combination of entropy weight and TOPSIS to assess flood risk evolution.[25] The results demonstrate intra-annual variation and temporal-spatial distribution of flood risk.[25] In contrast, Elmer et al.[26] analyzed the risk evolution for the lower part of the Mulde River basin from past to future with a flood risk chain from climate influence on meteorology over hydrological and hydraulic modelling to damage and risk estimations. They analyzed the development of potential damage over time and transferred this damage to risk estimates. Additionally, Elmer et al.[26] were able to analyze the drivers that cause the change of flood risk and quantify the contributions of these drivers. These two examples show that the selected methodologies and results vary between studies depending on the objectives of the study and availability of data.[24] Thus, flood risk evolution studies give a basis to elaborate principles for a monitoring but a "one size fits all applicable risk monitoring strategy" does not exist.[24] The principles for monitoring flood risk evolution outlined in Rindsfüser et al.[24] are the repeated flood risk analyses consisting of the systematically measuring of factors influencing hazard, exposure, and vulnerability, modelling the risk components and combining them to quantify risk. Thus, the main components of flood risk monitoring are data mining, data modelling, data combination, and data analyses.[24]

Considering the current and upcoming challenges due to global change for adaptive flood risk management and the limited scientific fundamentals for risk evolution and risk monitoring, this study aims to proof a flood risk monitoring concept in Switzerland and deduce new insights to further develop risk evolution analysis and monitoring for adaptive risk management. The flood risk monitoring concept follows the main principles of flood risk monitoring outlined in Rindsfüser et al.[24] and consists of data mining, data modelling, data combination and data analyses. Several studies (summarized in Zischg[3]) developed model experiments to analyze flood risk change in Switzerland and serve as a basis for the flood risk monitoring concept. For example, Röthlisberger et al.[27] selected (proxy-) data on risk components and developed models on a national scale to quantify building values for flood risk analysis. Röthlisberger et al.[28] analyzed spatiotemporal aspects of flood exposure in Switzerland. The flood risk monitoring concept is applied in a retrospective analysis for the ten-year period between 2014 and 2023. Therefore, we focus on the following research questions:

- How can flood risk analysis be set up to systematically quantify flood risk in administrative units across Switzerland over a specific period to detect flood risk evolution and enable effective flood risk monitoring?
- Which insights can be deduced for risk management from a systematic analysis of the annual flood risk evolution in Switzerland, including spatially differentiated flood risk evolution and the variability in the evolution of flood risk components?
- What are the challenges and limitations in applying the monitoring concept, and what are the key lessons learnt for the further development of risk monitoring for adaptive flood risk management?

3.2 Data and Methods

The flood risk monitoring concept consists of 1) the selection of factors and data for the risk analysis that is available in the past and in the future, 2) the determination of the methodology to calculate and analyze each risk component, 3) the determination of the methodology to combine the data to calculate and analyze risk, 4) the repetition of the analysis steps for each year and 5) the comparison of the annual data to analyze hazard, exposure and potential damage evolution (**Figure 3-1**).

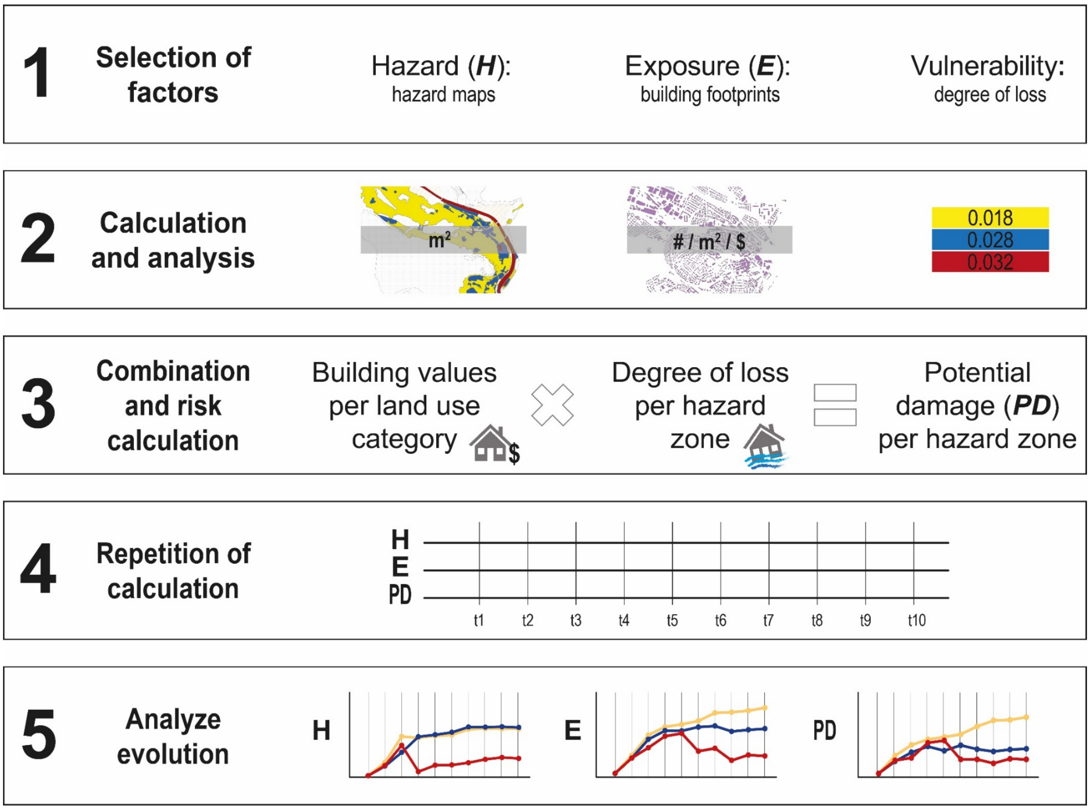


Figure 3-1. Flood risk monitoring concept presented in the main five steps for this study.

The flood risk monitoring concept was applied in a retrospective analysis on administrative units of Switzerland (national, cantonal and municipal scale) between 2014 and 2023 and evaluated based on the following main criteria:

- consistency of data over the selected period and spatial scale
- resolution of data
- feasibility to analyze risk on an annual temporal resolution in the past
- possibility to quantify risk with the selected data and methods
- possibility to analyze each risk component separately

The following sections describe the data and methods selected for the quantification of hazard, exposure, vulnerability and flood risk evolution, and the visualization approach.

3.2.1 Quantification of hazard evolution

We used the official hazard maps of Switzerland to gain information about flood endangered areas. In Switzerland, the elaboration of hazard maps for populated areas is obligatory since 1991.[29] As of 2021, the hazard maps are completed for 97% of the populated area.[30] Flood hazard maps identify the possible flood hazard as a combination of intensity and probability of an event (see Appendix 13 for the assessment matrix to identify hazard levels in Switzerland) and assign each combination to one distinct hazard class: high (red), medium (blue), low (yellow), residual (yellow-white striped) and no hazard (white).[28,31,32] The differentiation of weak and medium intensity is at 0.5m (water depth) or 0.5m/s^2 (water depth x velocity) and at 2m or 2m/s^2 for the differentiation between medium and high intensity.[28,32,33] The probability is divided into return periods of 300 (slight), 100 (medium) and 30 (high) years.[28,32,33] The map is produced on municipal and cantonal level. The development of the hazard maps is in accordance with the Swiss flood protection guidelines through numerical flood modelling, historical event analysis and expert assessment guidelines.[33–35] Fluvial flooding is the main type of flood considered for the hazard maps. However, depending on cantonal regulations, pluvial flooding is also included in the elaboration process. As a final product, hazard maps consist of digitized polygons for each hazard class (residual, low, medium, high) that represent the corresponding hazard zones. The hazard maps are updated either after a flood event, the implementation of flood risk management measures, before/after the implementation of spatial planning measures (e.g. new building zones) or (at the latest) periodically every 10-15 years. In this study, we focus on the low (yellow), medium (blue), and high (red) hazard classes.

We have harmonized, geometrically adjusted and merged the hazard maps of Switzerland and compiled them in a geodatabase every year between 2014 and 2023, resulting in an annually updated dataset of all hazard maps. However, this does not necessarily mean that all municipalities have changed their hazard maps from one year to the next. The hazard maps are updated on an irregular basis according to the above mentioned criteria. On average, the hazard zone areas were changed three times per municipality between 2014 and 2023. In one year, on average 34% (median 40%) of the municipalities in Switzerland made changes to their hazard zone areas compared to the previous year. From 2018 to 2019, only 9% of the municipalities have changed their hazard zone areas whereas from 2019 to 2020 53% have changed their hazard zone areas. If the hazard map of a municipality did not changed in a subsequent year, it is considered that the hazard remained unchanged. The area of the hazard zones (low, medium, high [m^2]) was used as a proxy to calculate hazard evolution. For the aggregation of hazard zone areas on municipal and cantonal scale, the hazard maps were intersected with the boundaries of the spatial units (municipalities, cantons) and related to the respective ID of each spatial unit. After this step, the sums of the hazard zone areas were calculated according to the respective ID of each spatial unit and each year between 2014 and 2023. In total, 2'152 municipalities were analyzed of which 562 (26%) had no hazard map in 2014 (i.e. total hazard zone area equals zero). Therefore, the hazard zone areas were calculated twice for the national aggregation. The first calculation summed-up the hazard zone areas for each year from each municipality. The second calculation excluded municipalities (562 of 2'152) where no hazard map was available in 2014 (i.e. total hazard zone area equals zero). This adjustment has been made to avoid the effect of increasing hazard due to newly elaborated hazard maps after 2014.

3.2.2 Quantification of exposure evolution

The aim of this step is to analyze all exposed buildings located in Switzerland. Buildings are defined as exposed when they are located in either the low (yellow), medium (blue), or high (red) hazard zone of the hazard map. The building datasets of Switzerland were collected between 2014 and 2023 in an annual updated version from the Topographic Landscape Model (TLM). The TLM provides polygons of all building footprints including their exact location.[36] We noticed that the building footprints (and therefore also exposure and potential damage) changed from year to year, even though the buildings did not change. In the product details provided by the Federal Office of Topography (swisstopo), we found that the TLM was improved during the first years of our analysis and a comprehensive 3D-building model was established by the end of 2017. New methods for drawing finer contours have been introduced as part of these improvements. To avoid falsification in exposure-, and potential damage evolution analysis due to data improvements, we adjusted the building datasets. For this purpose, we used the building dataset of 2023 as a base layer and made a retrospective adjustment of the building datasets of the years 2014-2022 with an intersection of the building footprints. For example, the building footprints of 2023 replaced the building footprints of 2014 if they intersect. If they did not intersect, the new building footprints of 2023 were removed and the building footprints of 2014 were kept for the 2014 building dataset.

After the data correction, the evolution of exposure, i.e., the number of exposed buildings per hazard zone, was calculated by overlaying the homogenized building footprint layers with the appropriate hazard map for each spatial reference unit (municipalities, cantons) and year from 2014 to 2023. As described in the previous section, 2'152 municipalities were analyzed of which 562 (26%) had no hazard map in 2014 (i.e. total hazard zone area equals zero). For these 562 municipalities, a comparison of exposed buildings from 2014 to 2023 was not possible due to a lack of data. For the national aggregation, the exposure was calculated twice to avoid the effect of increasing exposure due to newly elaborated hazard maps after 2014. The first calculation summed-up the exposed buildings for each year from each municipality. The second calculation excluded municipalities (562 of 2'152) where no hazard map was available in 2014 (i.e. total hazard zone area equals zero).

Additionally, the building values for each building in Switzerland were calculated by multiplying the building surface area (m^2) with an average monetary value per unit area of land use category (CHF/m^2) taken from the study by Röthlisberger et al.[27]. To this aim, the buildings of 2014 were intersected with the building zone polygon (BZP) layer of 2012, the buildings of 2015-2019 were intersected with the BZP layer of 2017, and the buildings of 2020-2023 were intersected with the BZP layer of 2022. Finally, the building values were calculated for each year with the new building dataset, i.e. new surface area, intersected with new building zone polygons but the same average monetary value per unit area of land use category. The costs were not adjusted for inflation.

3.2.3 Quantification of vulnerability

In this study, we focus on the physical vulnerability defined as "the degree of loss resulting from the hazard impact on buildings".[37,38] The degree of loss is expressed on a scale of zero (no loss) to one (total loss). The degree of loss per hazard zone in Switzerland was calculated based on flood loss claims from documented flood events spanning up to 34 years (1979-2013) from 13 cantonal insurance companies, including insured building values and amount of loss.[39] The ratio between the monetary damage and the building value is calculated for each claim, which corresponds to the vulnerability per claim. To calculate the degree of loss per hazard zone, the buildings with a known vulnerability were overlaid with a hazard map.[3] The degree of loss is 0.018 for the low (yellow) hazard zone, 0.028 for the medium (blue) hazard zone, and 0.032 for the high (red) hazard zone. The restoration value of each building was multiplied with the degree of loss to calculate the potential damage across all scenarios synthesized in the hazard maps. Due to a lack of data, the degree of loss values, and therefore, the vulnerability was kept constant for this study.

3.2.4 Quantification of risk evolution

Flood risk evolution is analyzed by calculating the potential damage per hazard zone for each spatial unit (municipal, cantonal, national scale) and each year between 2014 and 2023. The potential damage is taken as a proxy because the hazard maps of Switzerland (see section 3.2.1) give a mixed identification of probability and intensity. For example, the blue hazard zone indicates areas with high probability (30 year return period) and medium intensity but as well areas with medium probability (100 year return period) and medium intensity. Therefore, risk in terms of the probability of a loss within a certain time period,[3] cannot be calculated based on the information provided by the hazard maps.

The potential damage for each building was calculated by multiplying the building value with the degree of loss (see section 3.2.3) depending on the hazard zone in which the building is located. For the evolution of potential damage in space and time, the potential damage for a certain spatial unit (municipal, cantonal, national scale) and hazard zone (low, medium, high) were aggregated for each year. Therefore, the risk evolution is the result of a change in hazard and exposure with constant vulnerability. As described in the previous section, 2'152 municipalities were analyzed of which 562 (26%) had no hazard map in 2014 (i.e. total hazard zone area equals zero). For these 562 municipalities, a comparison of potential damage from 2014 to 2023 was not possible due to a lack of data. For the national aggregation, the potential damage was calculated twice to avoid the effect of increasing potential damage due to newly elaborated hazard maps after 2014. The first calculation summed-up the potential damage for each year from each municipality. The second calculation excluded municipalities (562 of 2'152) where no hazard map was available in 2014 (i.e. total hazard zone area equals zero).

3.2.5 Visualization of hazard, exposure and potential damage evolution

For visualizing the evolution curves of hazard, exposure, and potential damage, the absolute numbers for each hazard class and spatial unit (municipal, cantonal, national scale) between 2015 and 2023 were converted into values of percentage change in comparison with the baseline year 2014 (see section 3.1).

The spatial differences in the evolution of hazard, exposure, and potential damage were mapped on the municipal scale between 2014 and 2023 without considering the values of the years in between. For this purpose, we divided the values of each hazard class and municipality into categories based on percentage change between 2014 and 2023. Municipalities were chosen as the mapping unit because hazard maps are produced at the municipal level (see section 3.2).

The variability in the evolution of risk components per municipality was evaluated by taking the values and categories from the spatial difference analysis (see section 3.2). After the classification, we calculated the number of municipalities showing a certain increase in hazard and exposure, a decrease in hazard and exposure or an increase in hazard and a decrease in exposure or vice-versa (see section 3.3). We did the same for the combination of hazard and potential damage and the combination of exposure and potential damage for each hazard zone (see Appendix 11 and Appendix 12).

3.3 Results

The results from the application of the flood risk monitoring concept are presented in three sub-sections. The first section (3.3.1) describes the annual flood risk evolution between 2014 and 2023 in Switzerland. The second section (3.3.2) describes the spatial differentiated flood risk evolution between 2014 and 2023 on a municipal scale. The third section (3.3.3) describes the variability in the evolution of risk components per municipality.

3.3.1 Annual flood risk evolution in Switzerland

The annual evolution of flood risk is presented for the risk components (*H, E*) and the potential damage (*PD*) representing risk. The focus is on national scale evolution, supplemented with regional examples (canton of Bern and municipality Burgdorf). The canton of Bern was chosen as an example because all municipalities in the canton already had a hazard map in 2014. The municipality Burgdorf in the canton of Bern was selected as an example because of local knowledge from previous studies.[40] The absolute and relative values underlying the graphs of **Figure 3-2**, **Figure 3-3** and **Figure 3-4** are in the Appendix 1-Appendix 9.

In the following paragraphs, we focus for the national scale evolution on the values calculated with the updated hazard maps only (i.e. aggregation across 1'590 of 2'152 municipalities) (**Figure 3-2**, solid lines). The values in brackets indicate the percentage change values calculated across all municipalities (including values from the 562 municipalities that elaborated a first hazard map after 2014) (**Figure 3-2**, dashed lines).

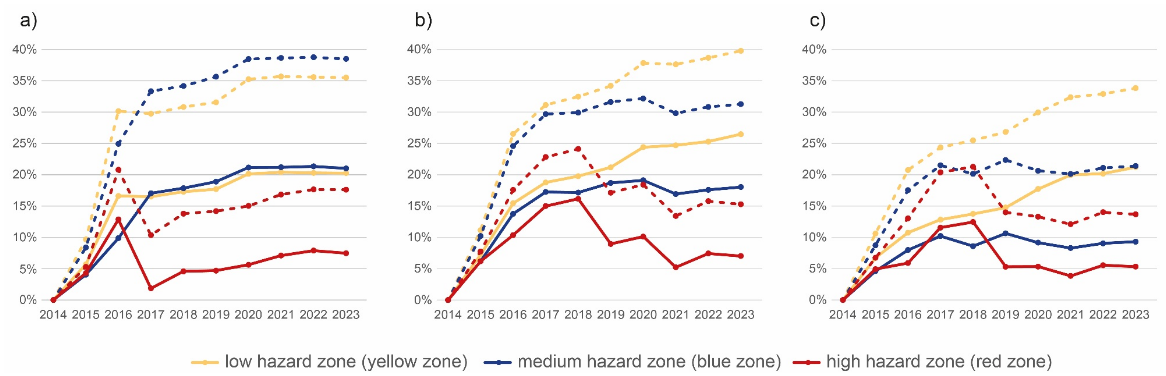


Figure 3-2. Flood risk evolution in Switzerland. Panel a) shows the hazard evolution. Panel b) shows the exposure evolution. Panel c) shows the potential damage evolution. Dashed lines indicate the total evolution (sum of all municipalities). Solid lines indicate the total evolution without the municipalities that had no hazard map in 2014. Yellow lines indicate the evolution in the low (yellow) hazard zone. Blue lines indicate the evolution in the medium (blue) hazard zone. Red lines indicate the evolution in the high (red) hazard zone.

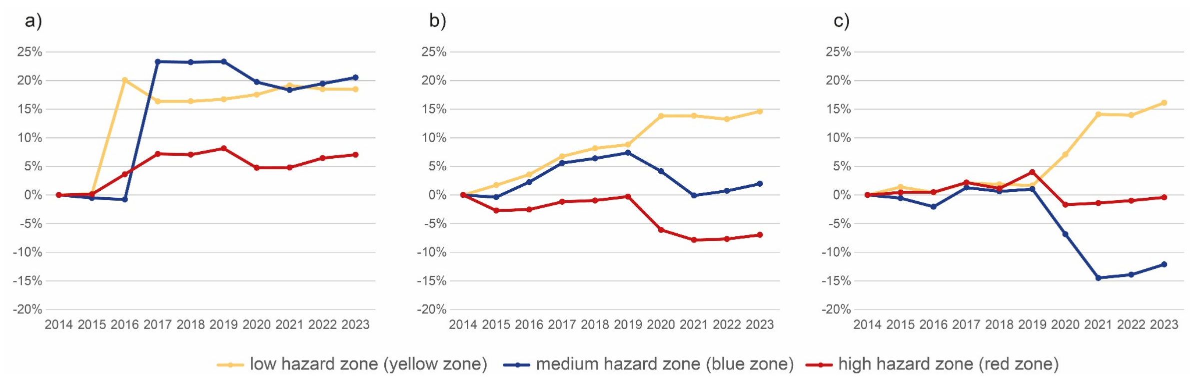


Figure 3-3. Flood risk evolution in the canton of Bern. Panel a) shows the hazard evolution. Panel b) shows the exposure evolution. Panel c) shows the potential damage evolution. Yellow lines indicate the evolution in the low (yellow) hazard zone. Blue lines indicate the evolution in the medium (blue) hazard zone. Red lines indicate the evolution in the high (red) hazard zone.

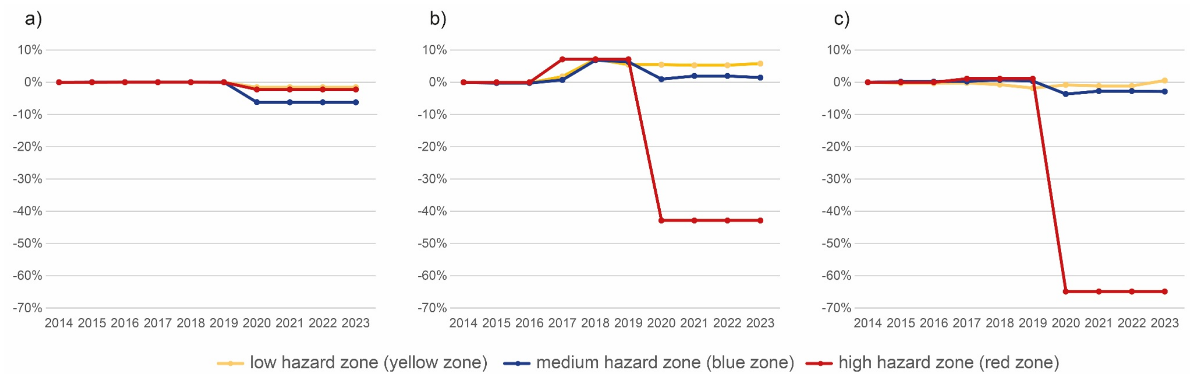


Figure 3-4. Flood risk evolution in the municipality Burgdorf. Panel a) shows the hazard evolution. Panel b) shows the exposure evolution. Panel c) shows the potential damage evolution. Yellow lines indicate the evolution in the low (yellow) hazard zone. Blue lines indicate the evolution in the medium (blue) hazard zone. Red lines indicate the evolution in the high (red) hazard zone.

3.3.1.1 Hazard evolution

Between 2014 and 2023, the total hazard map area (including high (red), medium (blue), low (yellow), residual, and no hazard zone) of Switzerland increased by around 21% if we consider only those municipalities with an existing hazard map in 2014 and 41% if we consider all municipalities. There was a small decrease of 5% (4%) between 2016 and 2017 and a 5% (8%) decrease between 2021 and 2023.

The share of the low (yellow), medium (blue) and high (red) hazard zone area of the total hazard map area (including residual and no hazard level) is around 20%. Over the last ten years, the share of the low, medium and high hazard zone area from the total hazard area fluctuated and even decreased by around 4% between 2017 and 2021. The area of the low, medium and high hazard zone increased by around 17% (32%) between 2014 and 2023, with an increase of 13% (26%) occurring between 2014 and 2016. The low hazard zone is the largest (~8%), followed by the medium hazard zone (~7%) and the high hazard zone (4%). In comparison with the total hazard map area evolution, the sum of low, medium and high hazard zone areas increased less and more constantly.

Between 2014 and 2023, the low hazard zone increased by around 20% (35%), the medium hazard zone by around 20% (38%) and the high hazard zone by around 7% (18%) (**Figure 3-2a**). Since 2017, the medium hazard zone increased more than the low hazard zone compared with the respective hazard zone in 2014. The high hazard zone area decreased by around 11% (11%) between the year 2016 and 2017. The decrease in the high hazard zone, the increase in the medium hazard zone and the stability in the total area of the low, medium and high hazard zones indicates rezoning, most likely due to implemented flood risk management measures. In the last two years (2022, 2023), it seems that the peak of increasing hazard zone areas is reached.

In the canton of Bern, the low hazard zone increased by around 18%, the medium hazard zone by around 21% and the high hazard zone by around 7% between 2014 and 2023 (**Figure 3-3a**). These values are in line with the evolution over Switzerland (**Figure 3-2a**). However, the shape of the cantonal evolution curve differs from the national curve. Overall, the evolution curve on cantonal scale fluctuates more than on national scale. The low hazard zone evolution is a little more distinctive to the one over Switzerland. The shape of the medium hazard zone evolution differs significantly compared to that one observed for Switzerland. The maximum peak of increase occurred earlier, and between 2019 and 2021, the medium hazard zone decreased, while there was an overall increase across Switzerland. In the high hazard zone, the strongest difference occurred between 2016 and 2017. While the high hazard zone decreased across Switzerland during this period, it increased in the canton of Bern.

The example of the municipality Burgdorf shows a different shape of the hazard evolution curve (**Figure 3-4a**). Between 2014 and 2023, the low hazard zone decreased by around 2%, the medium hazard zone by around 6% and the high hazard zone by around 2%. This evolution stands in contrast with the overall evolution in Switzerland and the canton of Bern. The evolution curve shows slight differences between 2014 and 2019, the main decrease between 2019 and 2020, and slight differences between 2020 and 2023.

3.3.1.2 Exposure evolution

Between 2014 and 2021, the total number of buildings in the hazard map area (including high (red), medium (blue), low (yellow), residual and no hazard zone) increased by around 37% if we consider only those municipalities with an existing hazard map in 2014 and 63% if we consider all municipalities. There was a small decrease of 4% (1%) between 2016 and 2017, and another decrease between 2021 and 2023 by around 4% (8%). The decrease between 2016 and 2017 is in line with the hazard map evolution.

The share of exposed buildings in the low (yellow), medium (blue) and high (red) hazard zone of the total number of buildings within the hazard map perimeter is around 19%. Between 2014 and 2023, the sum of exposed buildings in the low, medium and high hazard zone increased by around 22% (35%). On average, around 10% of all analyzed buildings are in the low hazard zone, around 6% in the medium hazard zone and 1% in the high hazard zone.

Between 2014 and 2023, the number of exposed buildings in the low hazard zone increased by around 26% (40%), in the medium hazard zone by 18% (31%) and in the high hazard zone by 7% (15%) (**Figure 3-2b**). Whereas the number of exposed buildings in the low hazard zone constantly increased over the last ten years, the number of exposed buildings in the medium hazard zone increased until 2016 and then shows only small fluctuations or even stagnates since 2017. The number of exposed buildings in the high hazard zone increased by around 16% (24%) until 2018 and decreased by around 9% (9%) until 2023 (**Figure 3-2b**). In comparison with the hazard evolution, the evolution curves of exposure are different. For example, in the high hazard zone area a decrease is detected between 2016 and 2017 and the number of exposed buildings further increased between 2016 and 2018. Whereas the high hazard zone area increased again between 2017 and 2022 (**Figure 3-2a**), the evolution of exposed buildings is mostly negative (**Figure 3-2b**).

In the canton of Bern, the exposed buildings in the low hazard zone increased by around 15%, in the medium hazard zone by around 2% and decreased by around 7% between 2014 and 2023 (**Figure 3-3b**). Between 2019 and 2021, a decrease in the medium (7%) and high hazard (8%) zone is detected, whereas exposure increased in the low hazard zone (5%). In comparison with the hazard evolution, there are two major findings in the evolution of exposure in the medium and the high hazard zone. Firstly, even though the medium hazard zone area increased by around 21% until 2019 (**Figure 3-3a**), the number of exposed buildings increased only by around 7%. Secondly, there is an increase of the high hazard zone area but a decrease of the number of exposed buildings. Compared to the exposure evolution of Switzerland (**Figure 3-2b**), the exposure evolution curve in the low hazard zone shows almost the same shape, whereas the medium and high zones show a different shape. In particular, the exposure evolution in the high hazard zone between 2019 and 2023 (**Figure 3-3b**) shows a decreasing evolution as well as a decrease compared to the year 2014, while the exposure evolution in the high hazard zone shows a decreasing evolution but still an increase compared to the year 2014.

In Burgdorf, the number of exposed buildings increased around 6% in the low hazard zone and 1% in the medium hazard zone between 2014 and 2023 (**Figure 3-4b**). In the same period, the number of exposed buildings in the high hazard zone decreased 43% with the main decrease between 2019 and 2020. Compared to the hazard evolution (**Figure 3-4a**), the exposure evolution in Burgdorf shows more changes. Especially, the number of exposed buildings in the high hazard zone slightly increased between 2016 and 2017 whereas no hazard evolution is detected. Furthermore, the evolution curve of the exposed buildings in the high hazard zone shows a significant decrease between 2019 and 2020 of around 50%. However, it is important to keep in mind that small absolute changes with a small population have a great impact on the percentage evolution on municipal scale. Compared to the evolution of Switzerland, the evolution curves of exposure are very different in Burgdorf.

3.3.1.3 Risk evolution

The potential damage is calculated for the low (yellow), medium (blue) and high (red) hazard zone. Between 2014 and 2023, the sum of potential damage in all three hazard zones increased by 14% if we consider only those municipalities with an existing hazard map in 2014 and 26% if we consider all municipalities. The share of potential damage in the low hazard zone increased from 42% to 45% of the sum in low, medium and high hazard zone. The share of potential damage in the medium hazard zone decreased from 46% to 44%, and the share of potential damage in the high hazard zone decreased from 12% to 11 % of the overall sum in low, medium and high hazard zone.

Between 2014 and 2023, the potential damage in the low hazard zone increased by around 21% (34%) between 2014 and 2023 (**Figure 3-2c**). The potential damage in the medium hazard zone increased by 9% (21%). After an increase of 12% (21%) in the high hazard zone between 2014 and 2018, the potential damage decreased by 8% (8%) between 2018 and 2021. Since 2021, the potential damage in the high hazard zone increased again by 1% (1%). Compared to 2014, the potential damage increased by 5% in the high hazard zone. An interesting evolution occurred between 2017 and 2018, when the potential damage in the high hazard zone increased more than in the medium hazard zone. The evolution of the potential damage is in line with the exposure evolution (**Figure 3-2b**).

In the canton of Bern, the potential damage evolution shows almost no changes between 2014 and 2019 (**Figure 3-3c**). Between 2019 and 2021, the potential damage evolution in the low hazard zone increased by around 12%, and decreased by 15% in the medium hazard zone. Since 2021, the potential damage in the medium hazard zone increased again by around 2%. The potential damage in the high hazard zone decreased by around 6% between 2019 and 2020 and increased again by around 2% between 2020 and 2023. The potential damage evolution in the canton of Bern is in line with the exposure evolution (**Figure 3-3b**). Nevertheless, the exposure evolution between 2014 and 2019 is not seen in the evolution curve of potential damage. The evolution of potential damage is different compared to the evolution over Switzerland (**Figure 3-2c**). Whereas the potential damage, for example, in the low hazard zone over Switzerland constantly increased between 2014 and 2023, the potential damage in the low hazard zone in the canton of Bern had nearly no changes between 2014 and 2019 and suddenly increased by 12% between 2019 and 2021.

In Burgdorf, the potential damage in the low, medium and high hazard zone shows only very small changes between 2014 and 2019 (**Figure 3-4c**). After 2018, the potential damage in the low hazard zone fluctuates around 0% with an overall increase of 2% until 2023. The potential damage in the medium hazard zone decreased by 3% between 2019 and 2023. The greatest change occurred in the high hazard zone, where the potential damage decreased by 66% between 2019 and 2020. This evolution is also in line with the hazard and exposure evolution in Burgdorf (**Figure 3-4a,b**). Interestingly, the potential damage in the medium hazard zone is lower in 2020 compared to 2014, even though the exposure increased slightly between 2014 and 2020. Compared to the evolution over Switzerland (**Figure 3-2c**) and the canton of Bern (**Figure 3-3c**), the evolution curve of the potential damage evolution is very different.

3.3.2 Spatial variability of flood risk evolution in Switzerland

In addition to the analysis of annual flood risk evolution (evolution curves in section 3.1), the flood risk evolution was mapped and analyzed on a municipal scale over Switzerland to detect the spatial variability in flood risk evolution on a high resolution (**Figure 3-6**, **Figure 3-7**). In this section, the percentage change of the values in 2023 compared to that in 2014 was investigated instead of analyzing each year as in section 3.3.1. The objective was to analyze and visualize the differences in the evolution (increase or decrease) at the smallest administrative level.

3.3.2.1 Hazard evolution

Between 2014 and 2023, the low (yellow) and medium (blue) hazard zone increased by around 20%, and the high (red) hazard zone increased by around 7%, calculated and aggregated on the national scale considering the municipalities that had already a hazard map in 2014 (1'590 of 2'152) (**Figure 3-6a-c** (values in right lower corner), Appendix 10). Even though the hazard zone area in the low, medium and high hazard zone increased on national scale between 2014 and 2023, on average 26% of the municipalities indicate a decrease in hazard evolution (see **Figure 3-6a-c** for the spatial pattern (municipalities in blue color) and **Figure 3-7a-c** for the absolute values of municipalities in the respective evolution category).

In the low hazard zone, 25% of the analyzed municipalities show a decrease in hazard evolution, 4% show no changes, 37% show an increase and 35% have no values for comparison (**Figure 3-6a**, **Figure 3-7a**). In the medium hazard zone, 31% of the analyzed municipalities show a decrease in hazard evolution, 3% show no changes, 31% show an increase and 34% have no values for comparison (**Figure 3-6b**, **Figure 3-7b**). In the high hazard zone, 22% of the analyzed municipalities indicate a decrease in hazard evolution, 7% show no changes, 31% show an increase and 41% have no values for comparison (**Figure 3-6c**, **Figure 3-7c**). In general, apart from the municipalities with no values for comparison, most of the municipalities counted for the hazard evolution analysis are in the 0-25% increase or decrease category (**Figure 3-6a-c**, **Figure 3-7a-c**) indicate no clear spatial pattern for the single hazard zones. However, when comparing the evolution of the different hazard zones, it is seen that the low, medium and high hazard zones have changed differently per municipality (**Figure 3-6a-c**)

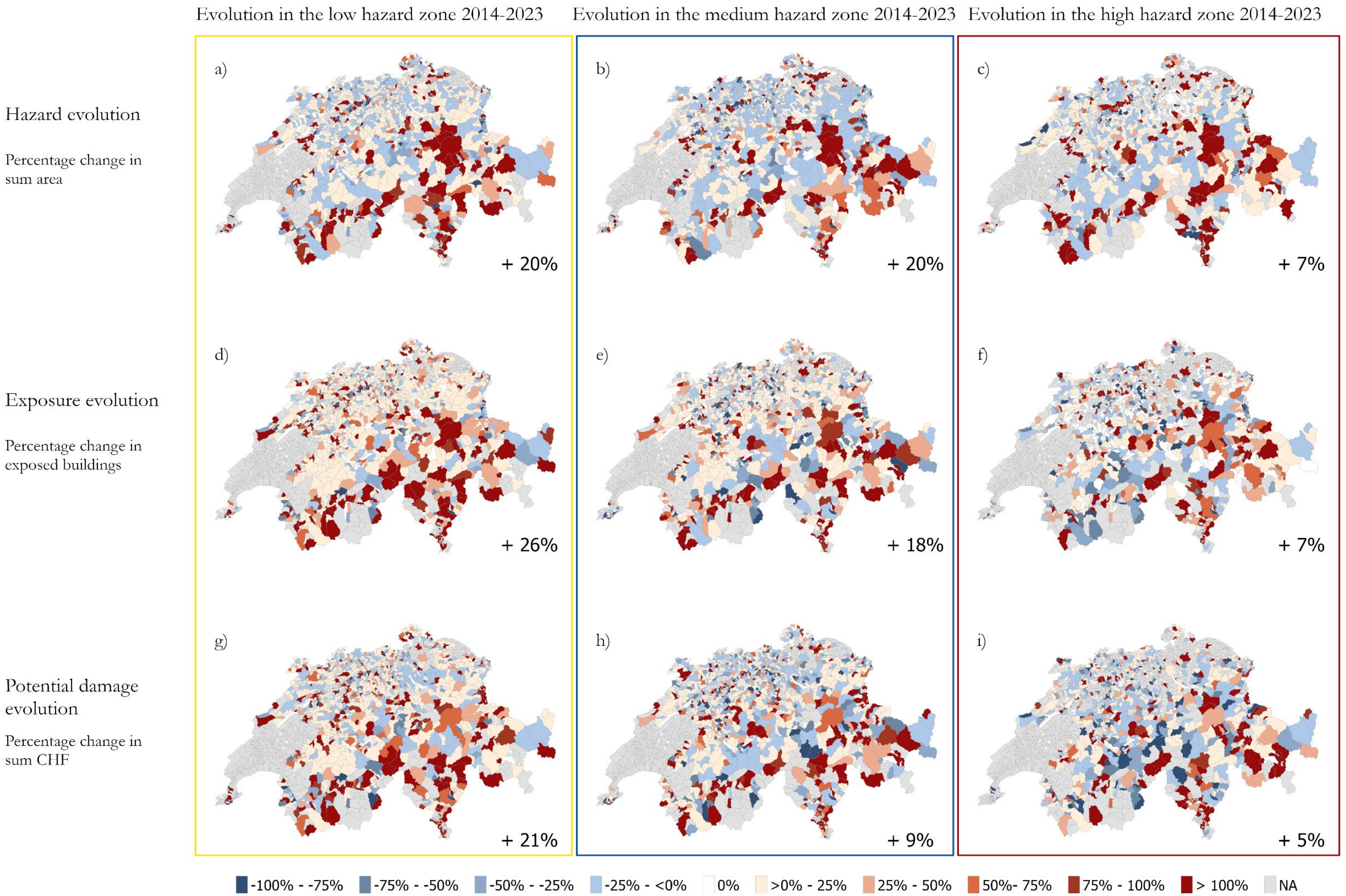


Figure 3-5. Map of hazard, exposure and potential damage evolution on municipal scale. Panels a) to c) show the hazard evolution, panels d) to f) show the exposure evolution and panels g) to i) the potential damage evolution. Blue municipalities indicate a decrease from 2014 to 2023. Red municipalities indicate an increase from 2014 to 2023. The municipalities in grey have no reference value in 2014 to calculate percentage change. The relative numbers on the right bottom of panel a) to i) are the percentage evolution from 2014 to 2023, summarized across all municipalities (absolute numbers are in Appendix A, S.10). The color of the frames indicate the low (yellow), medium (blue) and high (red) hazard zone.

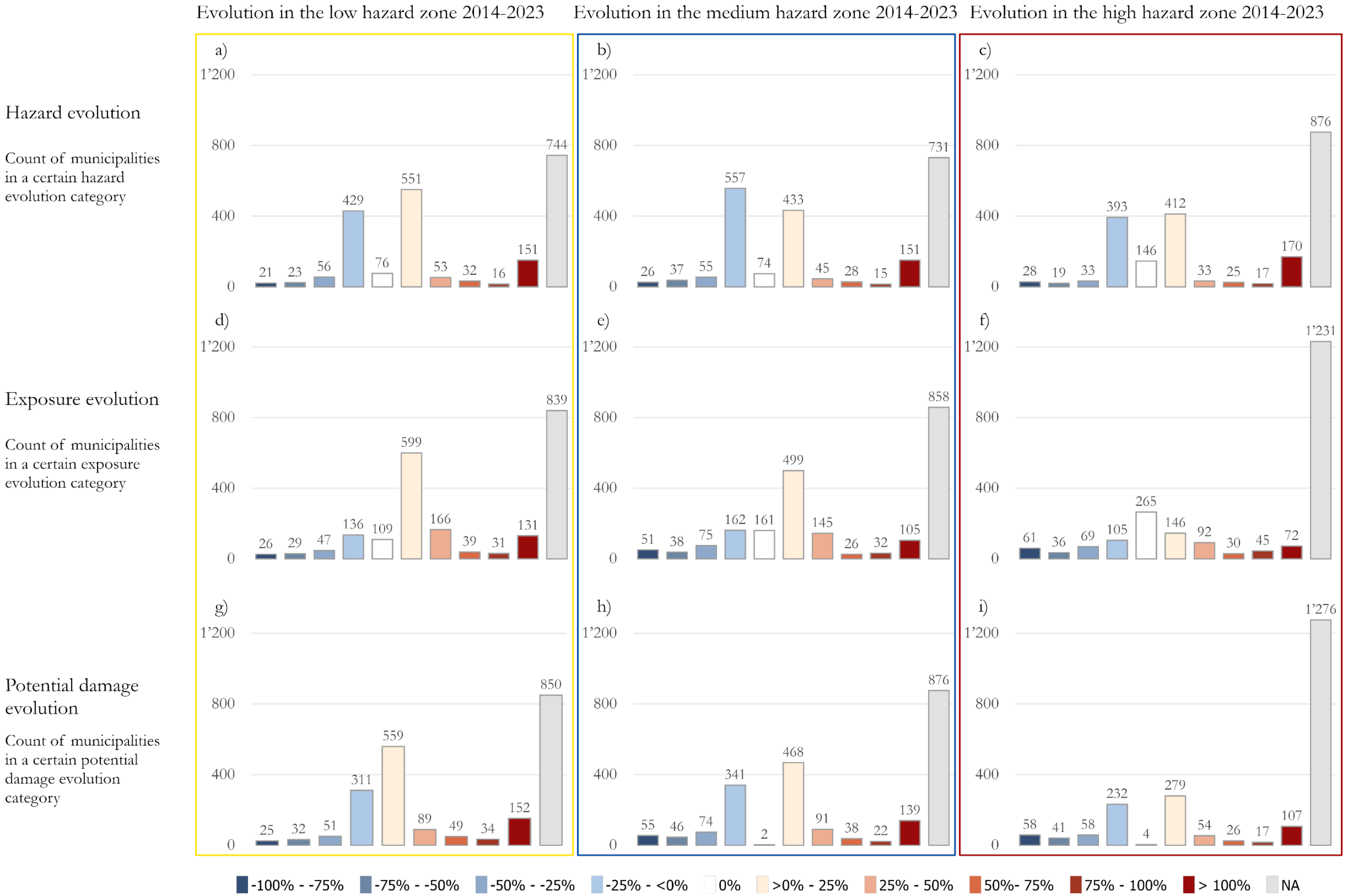


Figure 3-6. Count of municipalities with a certain hazard, exposure, potential damage evolution. Panels a) to c) show the hazard evolution, panels d) to f) show the exposure evolution and panels g) to i) the potential damage evolution. Blue boxes indicate the count of municipalities showing a decrease in hazard, exposure, and potential damage evolution. Red boxes indicate the count of municipalities showing an increase in hazard, exposure, and potential damage evolution. Grey boxes indicate the municipalities that have no reference value in 2014. The color of the frames indicate the yellow (low), blue (medium) and red (high) hazard zone.

3.3.2.2 Exposure evolution

Between 2014 and 2023, the number of exposed buildings in the low (yellow) hazard zone increased by around 26%, in the medium (blue) hazard zone by around 18%, and in the high (red) hazard zone by around 7%, calculated and aggregated on the national scale considering the municipalities that had already a hazard map in 2014 (1'590 of 2'152) (**Figure 3-6d-f** (values in right lower corner), Appendix 10). Even though the number of exposed buildings in the low, medium and high hazard zone increased between 2014 and 2023, on average 13% of the municipalities indicate a decrease in exposure evolution (see **Figure 3-6d-f** for the spatial pattern (municipalities in blue color) and **Figure 3-7d-f** for the absolute numbers of municipalities in the respective evolution category). However, compared to the percentage of municipalities indicating a decrease in hazard evolution (26%), only half of the municipalities indicate a decrease in exposure evolution (13%). Additionally, more municipalities lacked a hazard map in 2014, leaving no reference value to calculate percentage change.

In the low hazard zone, 11% of the analyzed municipalities show a decrease in the number of exposed buildings, 5% show no changes, 45% show an increase and 39% have no values for comparison (**Figure 3-6d**, **Figure 3-7d**). In the medium hazard zone, 15% of the analyzed municipalities indicate a decrease in the number of exposed buildings, 7% show no changes, 38% show an increase and 40% have no values for comparison (**Figure 3-6e**, **Figure 3-7e**). In the high hazard zone, 13% of the analyzed municipalities show a decrease in the number of exposed buildings, 12% show no changes, 18% show an increase and 57% have no values for comparison (**Figure 3-6f**, **Figure 3-7f**). Most of the municipalities with a reference value in 2014 are in the category of 0-25% increase in exposure in the low and medium hazard zone, whereas in the high hazard zone most of the municipalities have no change in exposure. As with the hazard evolution maps, the exposure evolution maps indicate different changes in the low, medium and high hazard zones per municipality.

3.3.2.3 Risk evolution

Between 2014 and 2023, the potential damage in the low (yellow) hazard zone increased by around 21%, in the medium (blue) hazard zone by around 9%, and in the high (red) hazard zone by around 5%, calculated and aggregated on the national scale considering the municipalities that had already a hazard map in 2014 (1'590 of 2'152) (**Figure 3-6g-i**, (values in right lower corner), Appendix 10). Even though the value of potential damage in the low, medium and high hazard zone increased between 2014 and 2023, on average 21% of the municipalities indicate a decrease in potential damage evolution (see **Figure 3-6d-f** for the spatial pattern (municipalities in blue color) and **Figure 3-7d-f** for the absolute numbers of municipalities in the respective evolution category). This average of 21% of municipalities indicating a decrease in potential damage evolution is less than in the hazard evolution (26%) but more than in the exposure evolution (13%). Additionally, more municipalities have no values for comparison.

In the low hazard zone, 19% of the analyzed municipalities show a decrease in potential damage, 41% show an increase and 39% have no values for comparison (**Figure 3-6g**, **Figure 3-7g**). In the medium hazard zone, 24% of the analyzed municipalities show a decrease in potential damage, 0.1% show no changes, 35% show an increase and 41% have no values for comparison (**Figure 3-6h**, **Figure 3-7h**). In the high hazard zone, 18% of the analyzed municipalities show a decrease in potential damage, 0.2% show no changes, 22% show an increase and 59% have no values for comparison of potential damage (**Figure 3-6i**, **Figure 3-7i**). Beside the municipalities having no values for comparison, most of the municipalities are in the category of 0-25% increase or decrease (**Figure 3-7g-i**).

3.3.3 Variability in evolution of flood risk components

The high-resolution analysis of the evolution of single risk components on a municipality scale allows additional evaluation of the variability in risk components evolution per municipality. As an example, we illustrate in the manuscript the variability of hazard and exposure evolution per municipality (**Figure 3-8**). The evolution of hazard and potential damage, as well as exposure and potential damage is in the Appendix 11 and Appendix 12.

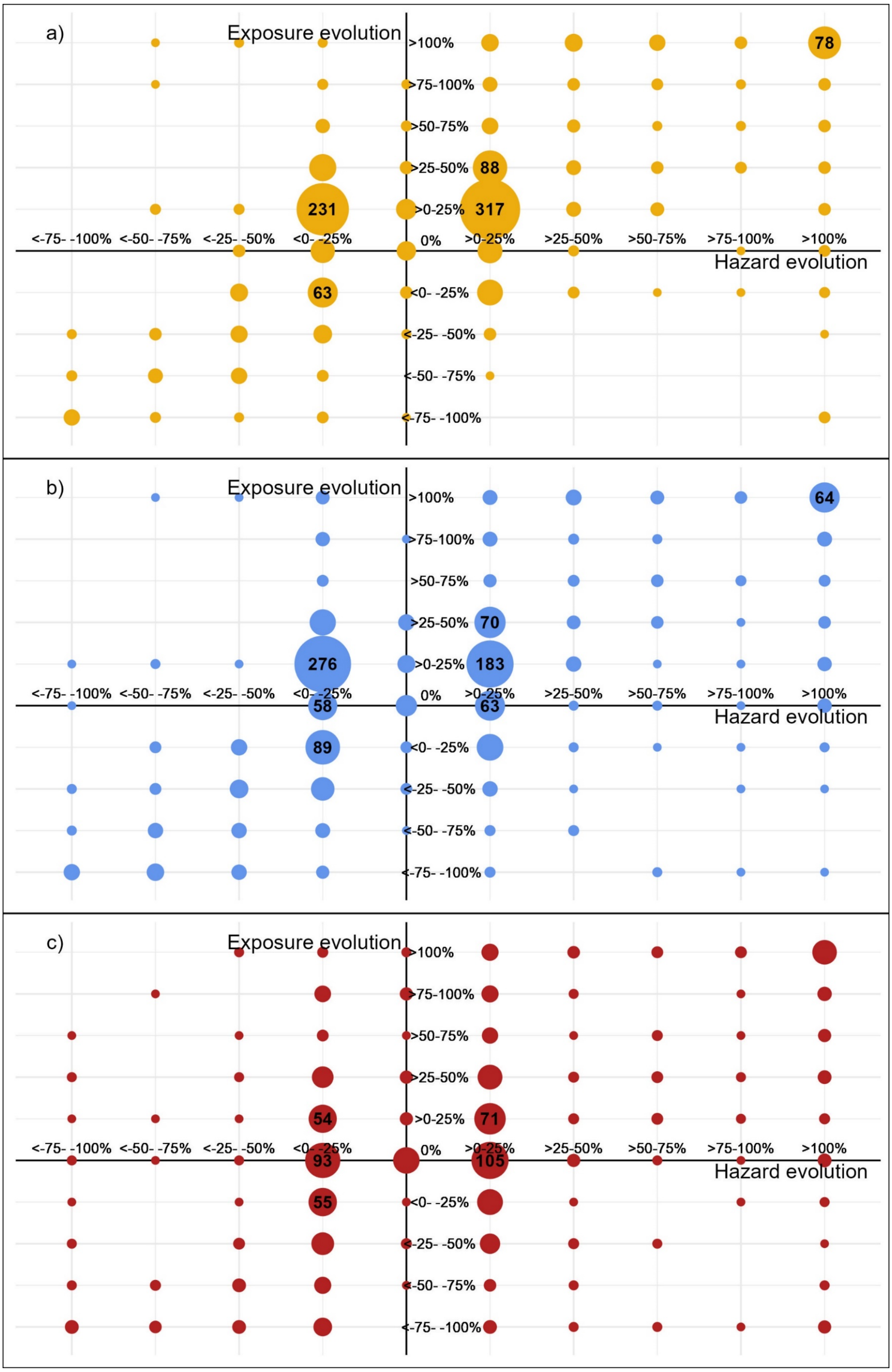


Figure 3-7. Count of municipalities with hazard (x-axis) and exposure (y-axis) evolution. Panel a), yellow dots indicate changes in the low (yellow) hazard zone, panel b), blue dots indicate changes in the medium (blue) hazard zone and panel c), red dots indicate changes in the high (red) hazard zone. For each panel, dots in the first quadrant count the municipalities with an increase in hazard and exposure, dots in the second quadrant count the municipalities with a decrease in hazard and increase in exposure, dots in the third quadrant count the municipalities with a decrease in hazard and exposure, and dots in the fourth quadrant count the municipalities with an increase in hazard and decrease in exposure. Dots representing more than 50 municipalities are labeled with the exact number of counts.

In the low (yellow) hazard zone, most of the municipalities (317 out of 2'152) indicate a 0-25% increase in hazard and exposure between 2014 and 2023 (**Figure 3-8a**). In contrast, 231 municipalities show a decrease of 0%-25% in hazard and an increase of 0%-25% in exposure. The third largest group consists of 88 municipalities indicating a 25-50% increase in hazard and a 0-25% increase in exposure. In total, 62% of the municipalities show an equal evolution in hazard and exposure, 28% a contrastive evolution and 10% of the municipalities had no evolution in either hazard or exposure.

In the medium (blue) hazard zone, most of the municipalities (276 out of 2'152) indicate a 0-25% decrease in hazard and a 0-25% increase in exposure between 2014 and 2023 (**Figure 3-8b**). In contrast, the second largest group consists of 183 municipalities indicating a 0-25% increase in hazard and exposure. The third largest group consists of 89 municipalities with a 0-25% decrease in hazard and exposure. In total, 54% of the municipalities show an equal evolution in hazard and exposure, 33% show an opposite evolution and 13% of the municipalities show no evolution in either hazard or exposure.

In the high (red) hazard zone, most of the municipalities (105 out of 2'152) indicate a 0-25% increase in hazard and no change in exposure (**Figure 3-8c**). The second largest group consists of 93 municipalities indicating a 0-25% decrease in hazard and no change in exposure. The third largest group consists of 71 municipalities indicating a 0-25% increase in hazard and exposure. In total, 50% of the municipalities show an equal evolution in hazard and exposure, 24% a contrastive evolution, and 27% had no evolution in either hazard or exposure.

In all three hazard zones, the scattering in the first and third quarter (equal evolution) is greater than in the second and fourth (contrastive evolution). This indicates that even if a contrastive evolution exists, the differences in the categories are not so distinct.

3.4 Discussion

In this study, a flood risk monitoring concept based on the principles of flood risk monitoring[24] was applied in a retrospective analysis over the last ten years between 2014 and 2023 in Switzerland. The application enabled us to prove a monitoring concept based on various criteria (see introduction to section 2) and deduce new insights to further develop risk evolution analysis and monitoring for adaptive risk management. In the following section, we discuss the data, methods and results of the evaluation of the hazard, exposure and risk evolution. Afterwards, we discuss the challenges and lessons learnt from applying and evaluating the flood risk monitoring concept in Switzerland between 2014 and 2023.

3.4.1 Hazard evolution

Hazard evolution is assessed by calculating the area of each hazard zone and year from the homogenized hazard maps of Switzerland. Therefore, a change in hazard zone area leads to an increase or decrease of hazard. The map is produced on municipal and cantonal level and in accordance with the Swiss flood protection guidelines through numerical flood modelling, historical event analysis and expert assessment guidelines.[33–35] The hazard maps must be updated periodically after an event and/or after the realization of flood risk management measures. Thus, an increase in the hazard zone area can appear due to an update of the hazard map and the associated increase in selected perimeters for the hazard analysis or the integration of new hazard sources or processes (e.g. surface water floods). Reasons for a decrease in hazard zone areas are, for example, the implementation of flood protection measures and the associated rezoning (see the study of Löschner and Nordbeck[41] for an overview about the shift towards integrated flood risk management in Switzerland). On the national scale, the implementation of flood protection measures is seen in the evolution curve between 2016 and 2017.

Beside the operational reasons for a change in hazard map area, the selected methodology of the flood risk monitoring concept had an effect on the increase in hazard evolution. The aggregation on the national scale led to an overestimation of new hazard zone areas because in 2014 not all municipalities had a hazard map. To avoid the effect of just adding new hazard maps in the following years, we calculated the evolution as well without the municipalities that had no hazard map in 2014 (see section 3.2.1 and **Figure 3-2a**). Without these municipalities, the increase between 2014 and 2016/2017 was not that steep but in comparison with the following years still remarkable.

A possible explanation would be the continuous buildup of the hazard maps (new perimeters, new hazard sources). Thus, the implementation of flood risk monitoring gives the possibility to prove the implementation of policy recommendations and regulations.

The annual analysis of hazard evolution on different administrative units (national, cantonal and municipal scale) indicates differences in the hazard evolution curves across spatial scales. Further, the mapping and spatial analysis on municipal scale allows the detection of spatial differences of percentage changes in hazard. With the high-resolution data, regions with increasing or decreasing hazard can be identified. For example, even though the overall hazard increased by around 20% in the low hazard zone, 25% of the municipalities show a decrease in hazard. We see two possible explanations for the spatial differences: the different implementation status of the hazard maps and flood risk management strategies and the time lag between policy regulations and implementation of these regulations.

The hazard maps are valuable data for monitoring the hazard evolution on administrative units in Switzerland. The proof criteria for the evaluation of the risk monitoring concept (see section 3.2) are partly fulfilled and partly, the data need additional adjustments to ensure the applicability for flood risk monitoring. In detail, we conclude that the consistency of the data over the selected period and spatial scale is sufficient to analyze the hazard evolution. However, as mentioned in the previous sections, some uncertainties remain in terms of consistency due to new regulations or improvements in hazard mapping. This uncertainty has already been addressed in previous studies[20–22] and requires further efforts at the national level to harmonize the methodology. The resolution of the hazard maps is adequate for the analysis of the hazard evolution. As the hazard maps are expensive to produce, the municipalities do not update them annually. This means that the hazard evolution cannot be determined annually based on the hazard maps at the smallest administrative units. At the national scale, developments can be determined annually because the municipalities that have made changes are recorded. Nevertheless, it can be assumed that the hazard maps are an important dataset for determining the development, as they are adapted when changes occur. This means that as soon as something changes in the system, the hazard is reassessed. The change is thus recognized in the monitoring concept.

3.4.2 Exposure evolution

The exposure evolution is assessed by calculating the number of exposed buildings for each year in a certain hazard zone. Data for the analysis of buildings are from the annual updated topographical landscape model (TLM) of Switzerland. A change in exposure can appear due to smaller or larger hazard zone areas and less or new buildings in a certain hazard zone. Similar results for regional different evolutions with increases and decreases of exposed residential buildings in the three hazard zones were identified for a longer time period (1919-2014) and aggregate mainly in decade steps by Röthlisberger et al. (2016) for Switzerland and by Fuchs et al. (2017) for Switzerland and Austria. The example of the evolution curve of the high hazard zone between 2014 and 2017 in Switzerland shows that the exposure can also increase (**Figure 3-2b**) even though the hazard map area decreases (**Figure 3-2a**). In this case, a detailed analysis of the single drivers on the municipal scale allows to detect possible reasons for the evolution. A possible explanation could be that the existing high hazard zones were rezoned due to protection measures but new hazard zones with smaller areas and additional buildings were aggregated in the analysis for Switzerland.

The mapping and spatial analysis on municipal scale allows for further disentangling the drivers of changes. For example, in the low hazard zone, the second largest group of municipalities (231) indicates a decrease in hazard but an increase in exposure. In the medium hazard zone, the largest group of municipalities (276) indicates a decrease in hazard but an increase in exposure. This points out that even though the hazard zone areas decreased, the number of exposed buildings in these hazard zones increased. Meaning that buildings were built up in the low and medium hazard zones. The rapid urban growth in flood zones is acknowledged in many scientific literatures and poses major challenges for flood risk management.[7,43–46] For risk management, it is important to consider that both systems (exposure dynamics and management paradigms) are deeply interrelated, with increases in exposure necessitating further mitigation measures.[42]

The dataset selected for the analysis of exposure evolution fulfils mainly the criteria for a monitoring concept. However, as with the hazard maps, the development of the data set is not entirely consistent over time and had to be pre-adjusted before it could be used for the risk analysis (see section 2.2). With the appropriate knowledge, this lack of data consistency can be addressed to avoid bias in the data analysis. The resolution of the data is sufficient for the analysis of the exposure evolution. The exposure evolution can be analyzed on an annual temporal resolution.

3.4.3 Risk evolution

Risk can be quantified in several ways. One approach is to use the expected annual damage as an indicator to describe flood risk, as for example analyzed by Elmer et al[26] or Zischg et al.[40] However, this approach needs detailed information about the probability of a loss in a certain period.[3] As the hazard maps of Switzerland give a mixed identification of probability and intensity (see Appendix 13), the potential damage is taken as proxy for the risk analysis. The potential damage is assessed by calculating the sum of the exposed building values multiplied by a degree of loss in a certain hazard zone. This is a common approach to integrate vulnerability into the flood risk analysis.[38,47] Therefore, the potential damage evolution depends on the evolution of the sum of building surface area (m^2) per land use category and hazard zone. Reason for an increase/decrease in potential damage is an increase/decrease in building surface area in the hazard zones and/or changed land use categories. However, the increase in potential damage does not necessarily require an increase in exposure. For example, when in year *A* two buildings are in the high hazard zone and in year *B* one of these buildings is not in the high hazard zone anymore, but two new or other buildings with the same surface area are in the high hazard zone, we have an increase in exposure but the damage potential remains the same. This example shows that the disentangling of risk drivers is important to understand the complexity in risk evolution and find solutions for flood risk management.[26] In Switzerland, the hazard map is completed for 97% of the country since 2017. Since then, the potential damage in the high hazard zone decreased, remained stable in the medium hazard zone, and increased in the low hazard zone. The exposed buildings increased as well in the low hazard zone, but the low hazard zone area only slightly increased between 2017 and 2020 and remained stable since 2020. This evolution is a clear indicator that new buildings are mainly built in the low hazard zone, leading to an overall increase in potential damage over ten years in Switzerland.

Following up the research questions, we conclude that the data and method used in this study gives a valuable starting point to set up a monitoring concept on a national scale. By collecting and analyzing the individual risk components, the risk can be systematically quantified on an annual basis. The insights deduced from the systematic analysis could be presented in the previous sections. However, some challenges and limitations exist while applying the monitoring concept. The challenges, limitations and lessons learnt are presented in the following section 4.4.

3.4.4 Challenges and lessons learnt

In contrast to previous flood risk evolution studies,[24] the elaboration and application of a flood risk monitoring concept aims to focus on the data and method selection that is available over many years and on a high spatial resolution for enabling the systematical detection of flood risk evolution to gain constant knowledge for the implementation into adaptive flood risk management. Following these objectives, we proved a flood risk monitoring concept for Switzerland.

In Switzerland, the hazard maps and the TLM are provided on an annual basis. This data provides a basis for high spatial and temporal resolution flood risk analysis. However, with the retrospective application of the flood risk monitoring concept, we detected that the majority of hazard maps for Switzerland were only available from 2017 onwards. Additionally, we detected that the TLM was improved during the first years of our analysis leading to undesired changes in the data over the selected period of analysis. These two examples reveal that the criterion of the consistency of data is only partially fulfilled for the years between 2014 and 2023 and the knowledge about the data origin is very important to gain robust results. Although vulnerability is integrated in the analysis, this risk component cannot be distinguished individually in the evolution analysis. Further data and analysis would be necessary to calculate the vulnerability evolution for Switzerland.

Thus, the quantification of risk is only partially possible with the selected data and methods. However, the potential damage as a proxy for flood risk gives as well important information for adaptive flood risk management.

In general, the proof of concept demonstrates that applying the monitoring concept in Switzerland is feasible and enhances the understanding of flood risk evolution. The criteria for evaluating the flood risk monitoring concept are fulfilled. Flood risk monitoring helps to identify spatiotemporal differences and contrasting trends in flood risk evolution.

3.5 Concluding remarks

In this study, a new environmental monitoring concept was developed and evaluated through a retrospective application. The hazard maps of Switzerland were used to evaluate the hazard evolution; the number of exposed buildings per hazard zone and building values per land use category were used to assess the exposure evolution; the degree of loss per hazard zone was used to integrate the physical vulnerability of buildings; and finally, the three risk components were combined into a potential damage analysis to evaluate the risk. With the data and methods selected for the flood risk monitoring concept, we were able to systematically quantify the annual flood risk on national, cantonal and municipal scale in Switzerland between 2014 and 2023. Thus, the monitoring of single risk factors leads to the monitoring of risk evolution and confirms the flood risk monitoring concept. Evolution curves of flood risk were created to gain a better understanding of flood risk evolution. The results indicate that flood risk is decreasing or increasing depending on the analyzed spatial and temporal scale. The finer resolution on municipal scale allowed the mapping and detection of spatial differences. Even though flood risk is increasing on the aggregated scale of Switzerland, the risk evolution on finer scales shows areas as well with decreasing risk. In addition, municipalities were detected that show contrastive evolutions in hazard, exposure and potential damage. The detection of low- and high-increase areas at a high spatial resolution is an important basis for decision-making in flood risk management. This study shows that the proof and knowledge of data origin is a very important component to gain robust results. Moreover, data consistency is key for comparability and therefore, the successful application of flood risk monitoring. For example, without having detailed knowledge of the updated land use data and the associated changes in the resolution of building footprints, the exposure and potential damage evolution would have been less robust. We conclude that the storage and comparison of data, along with consistently understanding "how risk evolves" are important components of adaptive flood risk management. Management systems should update and store their data over time to enable comparisons over years. With the comparison, it is possible to contextualize risk evolution and gain knowledge about the evolution and risk drivers. This data could be used for further decisions in risk management. In addition, flood risk monitoring enables the quantification of the positive effects of flood protection measures. This gives arguments for quantifying the benefits of the invested public funds for society in regions that gained from protection measures. However, new methodologies for data provision that emerge during the monitoring period can hinder the comparability of data over time. Therefore, it is important to create knowledge with case studies and learn from these case studies for setting up a robust data model and methodology for flood risk monitoring. For the example of Switzerland, further improvements for the flood risk monitoring could be to make flood simulations for detailed risk evolution analysis, analyze the evolution of exposed building values, analyze and include dynamic vulnerability and try to engage stakeholders to create a flood risk monitoring concept.

Appendix 1

Relative and absolute numbers of the hazard evolution analysis for Switzerland (CH).

"All" stands for the aggregation over all municipalities and "rem 0" stands for the aggregation without the municipalities that had no hazard maps in 2014. Calculation was made for the total hazard map area (no hazard, residual hazard, yellow hazard, blue hazard, red hazard zone), the yellow, blue, red hazard zone (ybr), yellow hazard zone (y), blue hazard zone (b), and red hazard zone (r).

Hazard CH (all)		2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	total_area [m^2]	5'296'595'671	5'785'226'446	6'240'196'061	6'038'349'113	6'515'853'168	6'811'550'775	7'148'783'000	7'872'834'928	7'648'590'852	7'483'783'322
	ybr_area [m^2]	1'066'210'169	1'153'166'654	1'344'383'521	1'345'628'734	1'362'278'477	1'371'987'898	1'400'770'951	1'408'001'852	1'410'121'983	1'408'763'645
	y_area [m^2]	446'126'416	489'174'068	580'601'089	578'812'191	583'574'149	586'943'330	603'359'850	605'281'041	604'847'396	604'498'837
	b_area [m^2]	359'100'074	389'201'953	448'570'121	478'813'554	481'747'707	487'070'546	497'233'683	497'809'236	498'253'026	497'312'100
	r_area [m^2]	260'983'679	274'790'633	315'212'311	288'002'989	296'956'621	297'974'022	300'177'418	304'911'575	307'021'561	306'952'708
	% of ybr of total	20	20	22	22	21	20	20	18	18	19
	% total area of 2014	0	9	18	14	23	29	35	49	44	41
	% ybr area of 2014	0	8	26	26	28	29	31	32	32	32
	yellow hazard zone	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	% of total area	8	8	9	10	9	9	8	8	8	8
	% of ybr area	42	42	43	43	43	43	43	43	43	43
	% of 2014	0	10	30	30	31	32	35	36	36	35
	blue hazard zone	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	% of total area	7	7	7	8	7	7	7	6	7	7
	% of ybr area	34	34	33	36	35	36	35	35	35	35
	% of 2014	0	8	25	33	34	36	38	39	39	38
	red hazard zone	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	% of total area	5	5	5	5	5	4	4	4	4	4
	% of ybr area	24	24	23	21	22	22	21	22	22	22
	% of 2014	0	5	21	10	14	14	15	17	18	18

Hazard CH (rem 0)		2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	total_area [m^2]	5'296'303'831	5'555'056'889	5'525'903'324	5'260'639'739	5'698'512'412	5'950'821'584	6'100'864'269	6'651'489'401	6'488'900'213	6'409'555'938
	ybr_area [m^2]	1'066'209'473	1'117'287'295	1'209'281'054	1'201'668'961	1'215'148'983	1'221'079'755	1'242'552'034	1'247'166'041	1'249'493'491	1'247'059'000
	y_area [m^2]	446'126'415	471'463'017	520'192'380	517'755'589	521'219'277	523'126'500	534'020'604	535'090'451	534'731'911	534'557'844
	b_area [m^2]	359'100'074	373'597'496	394'539'088	418'438'014	421'355'132	425'077'124	433'225'042	432'993'532	433'600'160	432'428'481
	r_area [m^2]	260'982'984	272'226'782	294'549'586	265'475'358	272'574'574	272'876'131	275'306'388	279'082'058	281'161'420	280'072'675
	% of ybr of total	20	20	22	23	21	21	20	19	19	19
	% total area of 2014	0	5	4	-1	8	12	15	26	23	21
	% ybr area of 2014	0	5	13	13	14	15	17	17	17	17
	yellow area	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	% of total area	8	8	9	10	9	9	9	8	8	8
	% of ybr area	42	42	43	43	43	43	43	43	43	43
	% of 2014	0	6	17	16	17	17	20	20	20	20
	blue area	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	% of total area	7	7	7	8	7	7	7	7	7	7
	% of ybr area	34	33	33	35	35	35	35	35	35	35
	% of 2014	0	4	10	17	17	18	21	21	21	20
	red area	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	% of total area	5	5	5	5	5	5	5	4	4	4
	% of ybr area	24	24	24	22	22	22	22	22	23	22
	% of 2014	0	4	13	2	4	5	5	7	8	7

Appendix 2

Relative and absolute numbers of the hazard evolution analysis for the Canton of Bern (CH).
Y: Yellow hazard zone, B: blue hazard zone, R: red hazard zone

Hazard Canton Bern		2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	y_area [m^2]	97'619'168	97'824'797	117'207'762	113'595'291	113'605'932	113'957'738	114'742'680	116'301'402	115'688'230	115'654'133
	% of 2014	0	0	20	16	16	17	18	19	19	18
	b_area [m^2]	71'996'723	71'627'442	71'443'158	88'761'408	88'701'151	88'778'135	86'211'137	85'201'748	86'005'056	86'776'000
	% of 2014	0	-1	-1	23	23	23	20	18	19	21
	r_area [m^2]	27'777'420	27'812'428	28'784'508	29'771'816	29'737'753	30'037'550	29'093'832	29'109'167	29'571'453	29'731'979
	% of 2014	0	0	4	7	7	8	5	5	6	7

Appendix 3

Relative and absolute numbers of the hazard evolution analysis for the Municipality Burgdorf (CH).
Y: Yellow hazard zone, B: blue hazard zone, R: red hazard zone

Hazard Municipality Burgdorf		2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	y_area [m^2]	2'376'210	2'376'528	2'376'522	2'376'522	2'376'522	2'376'539	2'339'958	2'339'806	2'339'806	2'339'806
	% of 2014	0	0	0	0	0	0	-2	-2	-2	-2
	b_area [m^2]	1'026'329	1'026'712	1'026'717	1'026'717	1'026'717	1'026'707	962'938	962'557	962'556	962'557
	% of 2014	0	0	0	0	0	0	-6	-6	-6	-6
	r_area [m^2]	292'942	292'949	292'961	292'961	292'961	292'934	286'375	286'391	286'391	286'390
	% of 2014	0	0	0	0	0	0	-2	-2	-2	-2

Appendix 4

Relative and absolute numbers of the exposure evolution analysis for Switzerland (CH).

"All" stands for the aggregation over all municipalities and "rem 0" stands for the aggregation without the municipalities that had no hazard maps in 2014. Calculation was made for the total hazard map area (no hazard, residual hazard, yellow hazard, blue hazard, red hazard zone), the yellow, blue, red hazard zone (ybr), yellow hazard zone (y), blue hazard zone (b), and red hazard zone (r).

Exposure CH (all)		2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	total_buildings (#)	1'131'512	1'356'629	1'556'317	1'552'503	1'671'042	1'729'082	1'783'673	1'842'452	1'835'961	1'753'561
	ybr_buildings (#)	226'167	250'016	282'995	293'980	296'055	298'498	303'724	300'664	303'208	304'887
	y_buildings (#)	125'042	138'977	158'175	163'971	165'628	167'776	172'327	172'075	173'377	174'763
	b_buildings (#)	84'790	93'438	105'615	109'947	110'154	111'588	112'057	110'062	110'918	111'294
	r_buildings (#)	16'335	17'601	19'205	20'062	20'273	19'134	19'340	18'527	18'913	18'830
	% ybr of total	20	18	18	19	18	17	17	16	17	17
	% total of 2014	0	20	38	37	48	53	58	63	62	55
	% ybr of 2014	0	11	25	30	31	32	34	33	34	35
	yellow hazard zone	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	% of total	11	10	10	11	10	10	10	9	9	10
	% of ybr	55	56	56	56	56	56	57	57	57	57
	% of 2014	0	11	26	31	32	34	38	38	39	40
	blue hazard zone	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	% of total	7	7	7	7	7	6	6	6	6	6
	% of ybr	37	37	37	37	37	37	37	37	37	37
	% of 2014	0	10	25	30	30	32	32	30	31	31
	red hazard zone	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	% of total	1	1	1	1	1	1	1	1	1	1
	% of ybr	7	7	7	7	7	6	6	6	6	6
	% of 2014	0	8	18	23	24	17	18	13	16	15

Exposure CH (rem 0)		2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	total_buildings (#)	1'131'505	1'273'344	1'334'520	1'295'537	1'407'605	1'453'335	1'507'042	1'555'330	1'541'860	1'507'479
	ybr_buildings (#)	226'167	241'474	258'835	266'685	268'065	269'943	274'515	272'242	273'916	275'690
	y_buildings (#)	125'042	134'097	144'354	148'497	149'759	151'513	155'538	155'920	156'671	158'129
	b_buildings (#)	84'790	90'032	96'453	99'404	99'333	100'633	100'989	99'133	99'696	100'079
	r_buildings (#)	16'335	17'345	18'028	18'784	18'973	17'797	17'988	17'189	17'549	17'482
	% ybr of total	20	19	19	21	19	19	18	18	18	18
	% total of 2014	0	13	18	14	24	28	33	37	36	33
	% ybr of 2014	0	7	14	18	19	19	21	20	21	22
	yellow hazard zone	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	% of total	11	11	11	11	11	10	10	10	10	10
	% of ybr	55	56	56	56	56	56	57	57	57	57
	% of 2014	0	7	15	19	20	21	24	25	25	26
	blue hazard zone	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	% of total	7	7	7	8	7	7	7	6	6	7
	% of ybr	37	37	37	37	37	37	37	36	36	36
	% of 2014	0	6	14	17	17	19	19	17	18	18
	red hazard zone	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	% of total	1	1	1	1	1	1	1	1	1	1
	% of ybr	7	7	7	7	7	7	7	6	6	6
	% of 2014	0	6	10	15	16	9	10	5	7	7

Appendix 5

Relative and absolute numbers of the exposure evolution analysis for the Canton of Bern (CH).
Y: Yellow hazard zone, B: blue hazard zone, R: red hazard zone

Exposure Canton Bern		2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	y_buildings (#)	26'383	26'839	27'327	28'163	28'539	28'708	30'024	30'034	29'880	30'237
	% of 2014	0	2	4	7	8	9	14	14	13	15
	b_buildings (#)	18'183	18'116	18'592	19'199	19'346	19'525	18'939	18'166	18'316	18'541
	% of 2014	0	0	2	6	6	7	4	0	1	2
	r_buildings (#)	2'955	2'875	2'880	2'920	2'927	2'947	2'775	2'723	2'728	2'749
	% of 2014	0	-3	-3	-1	-1	0	-6	-8	-8	-7

Appendix 6

Relative and absolute numbers of the exposure evolution analysis for the Municipality Burgdorf (CH).
Y: Yellow hazard zone, B: blue hazard zone, R: red hazard zone

Exposure Municipality Burgdorf		2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	y_buildings (#)	948	946	946	965	1'016	1'000	1'000	998	998	1'003
	% of 2014	0	0	0	2	7	5	5	5	5	6
	b_buildings (#)	410	409	409	413	438	436	414	418	418	416
	% of 2014	0	0	0	1	7	6	1	2	2	1
	r_buildings (#)	14	14	14	15	15	15	8	8	8	8
	% of 2014	0	0	0	7	7	7	-43	-43	-43	-43

Appendix 7

Relative and absolute numbers of the potential damage evolution analysis for Switzerland (CH).

"All" stands for the aggregation over all municipalities and "rem 0" stands for the aggregation without the municipalities that had no hazard maps in 2014. Calculation was made for the yellow, blue, red hazard zone (ybr), yellow hazard zone (y), blue hazard zone (b), and red hazard zone (r).

Potential damage CH (all)		2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	ybr_pd [CHF]	1'419'322'411	1'550'744'117	1'679'376'260	1'739'430'557	1'738'842'199	1'748'441'627	1'754'654'185	1'763'689'268	1'776'490'300	1'783'185'795
	y_pd [CHF]	593'768'495	656'595'994	716'973'025	738'397'129	745'095'684	752'948'253	771'623'915	785'964'396	789'117'620	794'576'138
	b_pd [CHF]	651'599'694	708'488'098	765'770'495	791'647'509	782'785'636	797'198'231	785'951'614	782'739'042	789'046'547	790'868'690
	r_pd [CHF]	173'954'223	185'660'025	196'632'740	209'385'919	210'960'879	198'295'143	197'078'656	194'985'830	198'326'133	197'740'967
	% ybr of 2014	0	9	18	23	23	23	24	24	25	26
	yellow hazard zone	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	% of ybr	42	42	43	42	43	43	44	45	44	45
	% of 2014	0	11	21	24	25	27	30	32	33	34
	% of 2017				100	101	102	104	106	107	108
	blue hazard zone	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	% of ybr	46	46	46	46	45	46	45	44	44	44
	% of 2014	0	9	18	21	20	22	21	20	21	21
	% of 2017				100	99	101	99	99	100	100
	red hazard zone	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	% of ybr	12	12	12	12	12	11	11	11	11	11
	% of 2014	0	7	13	20	21	14	13	12	14	14
	% of 2017				100	101	95	94	93	95	94

Potential damage CH (rem 0)		2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	ybr_pd [CHF]	1'419'322'411	1'497'840'187	1'545'418'353	1'582'012'859	1'578'579'592	1'585'473'391	1'593'454'746	1'598'513'063	1'607'596'665	1'615'167'338
	y_pd [CHF]	593'768'495	633'709'650	657'577'121	669'907'795	675'416'849	681'373'904	698'990'127	712'287'747	713'497'139	719'704'675
	b_pd [CHF]	651'599'694	681'600'620	703'621'864	718'055'733	707'553'601	720'911'180	711'230'952	705'589'867	710'485'662	712'249'100
	r_pd [CHF]	173'954'223	182'529'917	184'219'368	194'049'331	195'609'141	183'188'307	183'233'667	180'635'450	183'613'864	183'213'563
	% ybr of 2014	0	6	9	11	11	12	12	13	13	14
	yellow hazard zone	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	% of ybr	42	42	43	42	43	43	44	45	44	45
	% of 2014	0	7	11	13	14	15	18	20	20	21
	% of 2017				100	101	102	104	106	107	107
	blue hazard zone	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	% of ybr	46	46	46	45	45	45	45	44	44	44
	% of 2014	0	5	8	10	9	11	9	8	9	9
	% of 2017				100	99	100	99	98	99	99
	red hazard zone	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	% of ybr	12	12	12	12	12	12	11	11	11	11
	% of 2014	0	5	6	12	12	5	5	4	6	5
	% of 2017				100	101	94	94	93	95	94

Appendix 8

Relative and absolute numbers of the potential damage evolution analysis for the Canton of Bern (CH).

Y: Yellow hazard zone, B: blue hazard zone, R: red hazard zone

Potential damage Canton Bern		2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	yellow area	92'683'242	93'987'107	93'115'355	94'637'637	94'420'025	94'231'559	99'252'629	105'754'848	105'607'959	107'621'772
	% of 2014	0	1	0	2	2	2	7	14	14	16
	blue area	112'423'145	111'813'663	110'110'076	113'883'406	113'141'770	113'580'269	104'724'008	96'136'045	96'788'651	98'795'717
	% of 2014	0	-1	-2	1	1	1	-7	-14	-14	-12
	red area	22'642'997	22'744'171	22'753'096	23'136'981	22'904'287	23'548'735	22'260'354	22'323'514	22'421'471	22'549'709
	% of 2014	0	0	0	2	1	4	-2	-1	-1	0

Appendix 9

Relative and absolute numbers of the potential damage evolution analysis for the Municipality Burgdorf (CH).

Potential damage Municipality Burgdorf		2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	yellow area	6'275'141	6'258'515	6'258'515	6'263'208	6'230'326	6'162'863	6'224'300	6'204'370	6'204'370	6'309'013
	% of 2014	0	0	0	0	-1	-2	-1	-1	-1	1
	blue area	4'854'983	4'865'189	4'865'189	4'867'817	4'890'255	4'871'624	4'678'633	4'722'162	4'722'162	4'715'152
	% of 2014	0	0	0	0	1	0	-4	-3	-3	-3
	red area	292'121	292'121	292'121	295'356	295'356	295'356	102'559	102'559	102'559	102'559
	% of 2014	0	0	0	1	1	1	-65	-65	-65	-65

Appendix 10

Evolution per hazard zone from 2014 to 2023, aggregated on municipality scale.

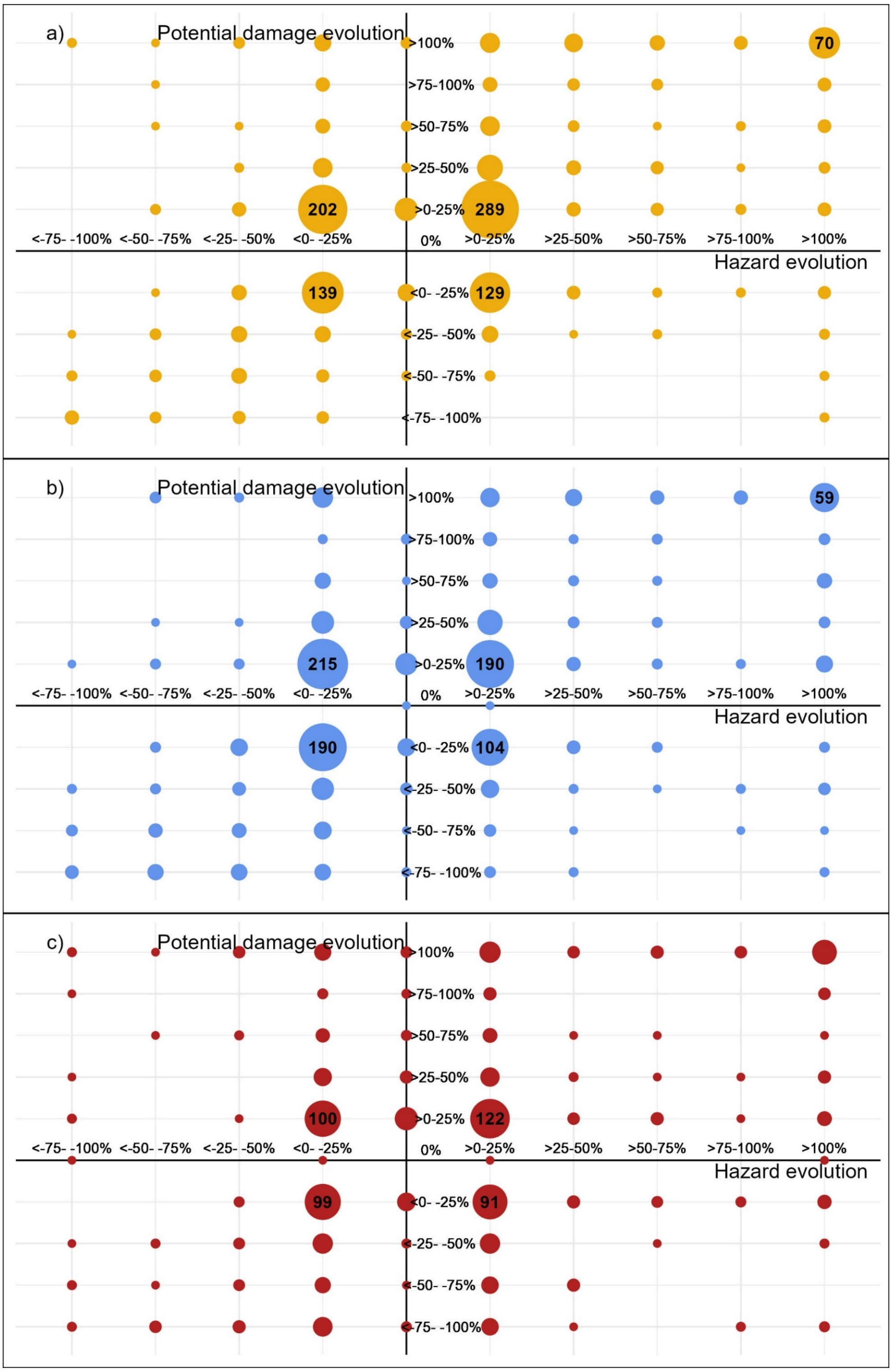
Hazard (m^2)	2014	2023	% Diff 2014 - 2023
yellow hazard zone	446'126'415	534'557'844	19.8
blue hazard zone	359'100'074	432'428'481	20.4
red hazard zone	260'982'984	280'072'675	7.3

Exposure (#)	2014	2023	% Diff 2014 - 2023
yellow hazard zone	125'042	158'129	26.5
blue hazard zone	84'790	100'079	18.0
red hazard zone	16'335	17'482	7.0

Potential damage (CHF)	2014	2023	% Diff 2014 - 2023
yellow hazard zone	593'768'495	719'704'675	21.2
blue hazard zone	651'599'694	712'249'100	9.3
red hazard zone	173'954'223	183'213'563	5.3

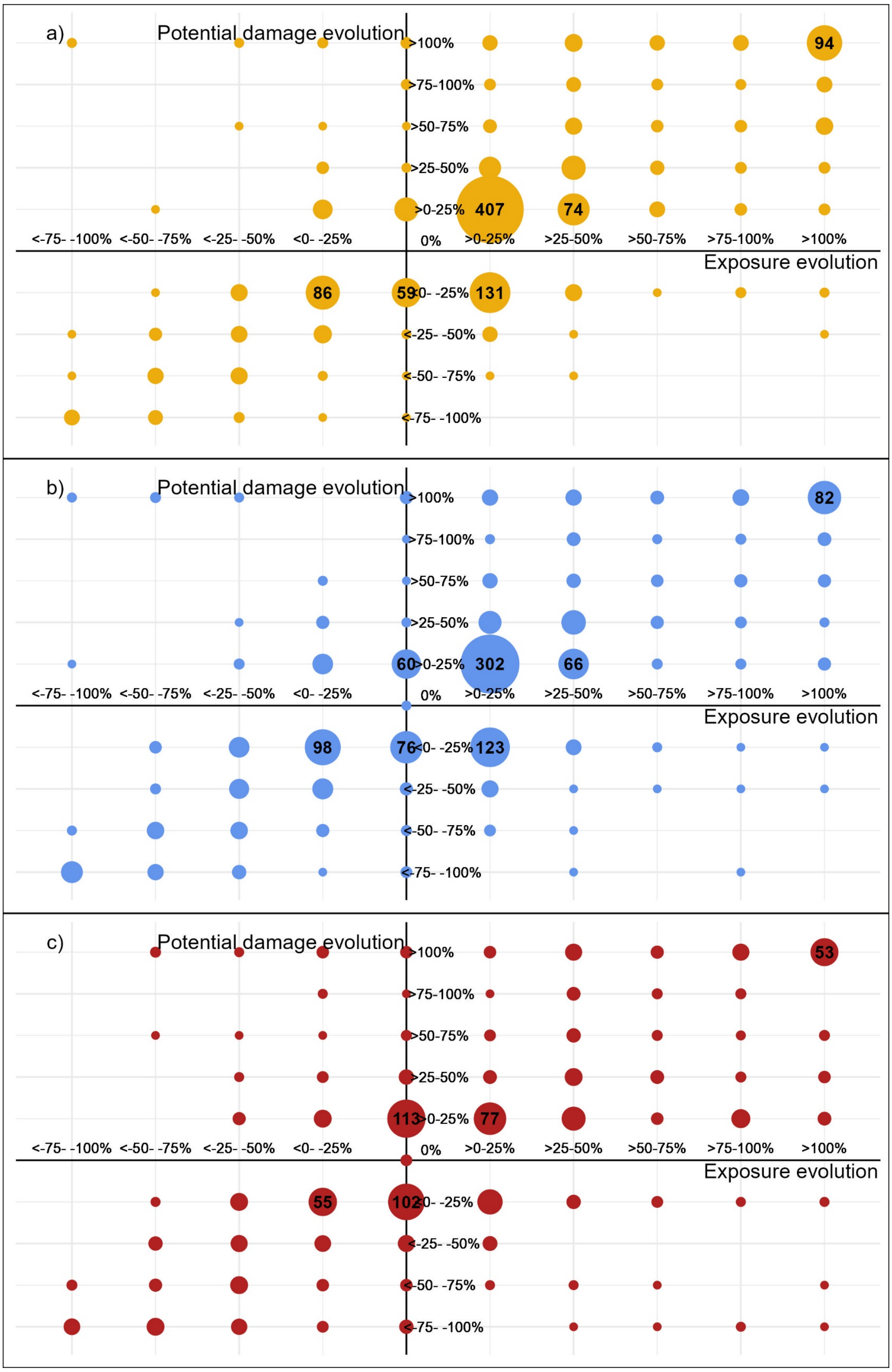
Appendix 11

Count of municipalities with hazard (x-axis) and potential damage (y-axis) evolution. For each panel, dots in the first quadrant count the municipalities with an increase in hazard and potential damage, dots in the second quadrant count the municipalities with a decrease in hazard and increase in potential damage, dots in the third quadrant count the municipalities with a decrease in hazard and potential damage, and dots in the fourth quadrant count the municipalities with an increase in hazard and decrease in potential damage. Dots with more than 50 municipalities are numbered the exact value of counts. a) provides the results fort he yellow hazard zone, b) fort he blue hazard zone and c) for the red hazard zone.



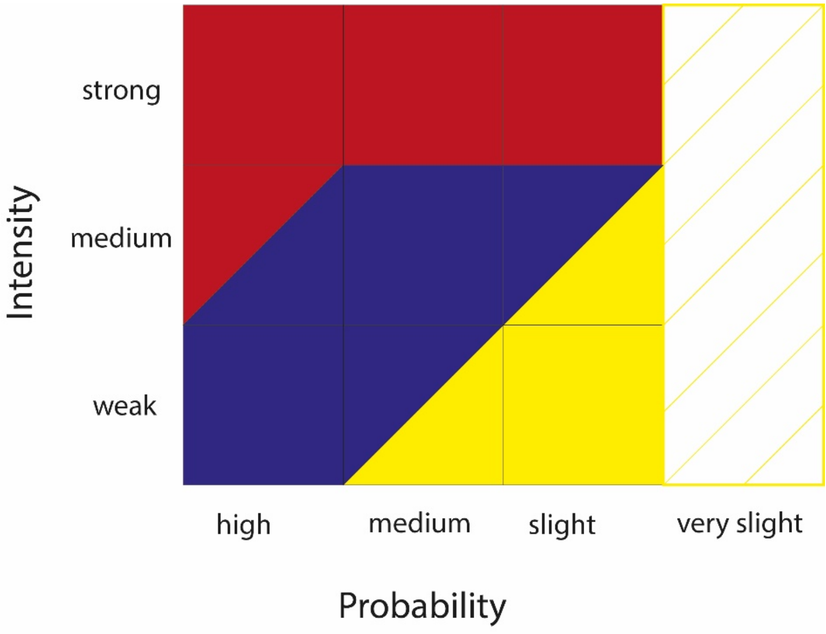
Appendix 12

Count of municipalities with exposure (x-axis) and potential damage (y-axis) evolution. For each panel, dots in the first quadrant count the municipalities with an increase in exposure and potential damage, dots in the second quadrant count the municipalities with a decrease in exposure and increase in potential damage, dots in the third quadrant count the municipalities with a decrease in exposure and potential damage, and dots in the fourth quadrant count the municipalities with an increase in exposure and decrease in potential damage. Dots with more than 50 municipalities are numbered the exact value of counts. a) provides the results fort he yellow hazard zone, b) fort he blue hazard zone and c) for the red hazard zone.



Appendix 13

Assessment matrix for the identification of hazard classes in Switzerland: high (red), medium (blue), low (yellow), residual (yellow-white striped), no or negligible hazard (white).



References

1. Swiss Re (2023). Floods: Natural catastrophes in focus. https://www.swissre.com/risk-knowledge/mitigating-climate-risk/floods.html.

2. UNDRR [United Nations Office for Disaster Risk Reduction] (2022). Global Assessment Report on Disaster Risk Reduction 2022: Our World at Risk: Transforming Governance for a Resilient Future.

3. Zischg, A. (2023). Flood risk change: a complexity perspective (Elsevier).

4. Klijn, F., Kreibich, H., de Moel, H., and Penning-Rowsell, E. (2015). Adaptive flood risk management planning based on a comprehensive flood risk conceptualisation. Mitig Adapt Strateg Glob Change *20*, 845–864. https://doi.org/10.1007/s11027-015-9638-z.

5. Papathoma-Köhle, M., Kappes, M., Keiler, M., and Glade, T. (2011). Physical vulnerability assessment for alpine hazards: state of the art and future needs. Nat Hazards *58*, 645–680. https://doi.org/10.1007/s11069-010-9632-4.

6. Klinke, A., and Renn, O. (2021). The Coming of Age of Risk Governance. Risk Analysis *41*, 544–557. https://doi.org/10.1111/risa.13383.

7. Hemmati, M., Ellingwood, B.R., and Mahmoud, H.N. (2020). The Role of Urban Growth in Resilience of Communities Under Flood Risk. Earth's Future *8*. https://doi.org/10.1029/2019EF001382.

8. Kundzewicz, Z.W., Su, B., Wang, Y., Wang, G., Wang, G., Huang, J., and Jiang, T. (2019). Flood risk in a range of spatial perspectives - From global to local scales. Natural Hazards and Earth System Sciences *19*, 1319–1328. https://doi.org/10.5194/nhess-19-1319-2019.

9. Mazzoleni, M., Mård, J., Rusca, M., Odongo, V., Lindersson, S., and Di Baldassarre, G. (2021). Floodplains in the Anthropocene: A Global Analysis of the Interplay Between Human Population, Built Environment, and Flood Severity. Water Res. *57*. https://doi.org/10.1029/2020WR027744.

10. de Ruiter, M.C., and van Loon, A.F. (2022). The challenges of dynamic vulnerability and how to assess it. iScience *25*, 104720. https://doi.org/10.1016/j.isci.2022.104720.

11. Merz, B., Hall, J., Disse, M., and Schumann, A. (2010). Fluvial flood risk management in a changing world. Nat. Hazards Earth Syst. Sci. *10*, 509–527. https://doi.org/10.5194/nhess-10-509-2010.

12. Fuchs, S., Keiler, M., Sokratov, S., and Shnyparkov, A. (2013). Spatiotemporal dynamics: the need for an innovative approach in mountain hazard risk management. Nat Hazards *68*, 1217–1241. https://doi.org/10.1007/s11069-012-0508-7.

13. Mishra, A., Mukherjee, S., Merz, B., Singh, V.P., Wright, D.B., Villarini, G., Paul, S., Kumar, D.N., Khedun, C.P., Niyogi, D., et al. (2022). An Overview of Flood Concepts, Challenges, and Future Directions. Journal of Hydrologic Engineering *27*. https://doi.org/10.1061/(ASCE)HE.1943-5584.0002164.

14. Schanze, J., and Maleska, V. (2019). Towards a more systemic understanding of flood risks. J Flood Risk Management *12*. https://doi.org/10.1111/jfr3.12569.

15. Wassénius, E., and Crona, B.I. (2022). Adapting risk assessments for a complex future. One Earth *5*, 35–43. https://doi.org/10.1016/j.oneear.2021.12.004.

16. Emami, K. (2020). Adaptive Flood Risk Management. Irrig. and Drain. *69*, 230–242. https://doi.org/10.1002/ird.2411.

17. Haasnoot, M., Kwakkel, J.H., Walker, W.E., and ter Maat, J. (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. Global Environmental Change *23*, 485–498. https://doi.org/10.1016/j.gloenvcha.2012.12.006.

18. UNDRR [United Nations Office for Disaster Risk Reduction] (2015). Sendai Framework for Disaster Risk Reduction 2015-2030.

19. European Commission (2007). Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks (Text with EEA relevance).

20. Priest, S.J., Suykens, C., Van Rijswick, H.F.M.W., Schellenberger, T., Goytia, S., Kundzewicz, Z.W., van Doorn-Hoekveld, W.J., Beyers, J.-C., and Homewood, S. (2016). The European Union approach to flood risk management and improving societal resilience: lessons from the implementation of the Floods Directive in six European countries. ECOLOGY AND SOCIETY *21*. https://doi.org/10.5751/ES-08913-210450.

21. Rauter, M., Thaler, T., Attems, M.-S., and Fuchs, S. (2019). Obligation or Innovation: Can the EU Floods Directive Be Seen as a Tipping Point Towards More Resilient Flood Risk Management? A Case Study from Vorarlberg, Austria. Sustainability *11*, 5505. https://doi.org/10.3390/su11195505.

22. European Commission and Directorate-General for Environment (2021). Current practice in flood risk management in the European Union: September 2021 (Publications Office of the European Union).

23. Mazzorana, B., Levaggi, L., Keiler, M., and Fuchs, S. (2012). Towards dynamics in flood risk assessment. Nat. Hazards Earth Syst. Sci. *12*, 3571–3587. https://doi.org/10.5194/nhess-12-3571-2012.

24. Rindsfüser, N., Zischg, A.P., and Keiler, M. (2024). Monitoring Flood Risk Evolution: a systematic review. iScience *0*. https://doi.org/10.1016/j.isci.2024.110653.

25. Chen, Y., Li, J., and Chen, A. (2021). Does high risk mean high loss: Evidence from flood disaster in southern China. Science of the Total Environment *785*. https://doi.org/10.1016/j.scitotenv.2021.147127.

26. Elmer, F., Hoymann, J., Düthmann, D., Vorogushyn, S., and Kreibich, H. (2012). Drivers of flood risk change in residential areas. Nat. Hazards Earth Syst. Sci. *12*, 1641–1657. https://doi.org/10.5194/nhess-12-1641-2012.

27. Röthlisberger, V., Zischg, A.P., and Keiler, M. (2018). A comparison of building value models for flood risk analysis. Nat. Hazards Earth Syst. Sci. *18*, 2431–2453. https://doi.org/10.5194/nhess-18-2431-2018.

28. Röthlisberger, V., Zischg, A., and Keiler, M. (2016). Spatiotemporal aspects of flood exposure in Switzerland. E3S Web Conf. *7*, 08008. https://doi.org/10.1051/e3sconf/20160708008.

29. BAFU [Bundesamt für Umwelt] (2016). Umgang mit Naturgefahren in der Schweiz.

30. PLANAT, [Nationale Plattform Naturgefahren] (2022). PLANAT. Publikationen. https://www.planat.ch/de/publikationen.

31. ARE [Bundesamt für Raumentwicklung], BWG [Bundesamt für Wasser und Geologie], and BUWAL [Bundesamt für Umwelt, Wald und Landschaft] (2005). Empfehlung Raumplanung und Naturgefahren [Recommendation Spatial Planning and Natural Hazards].

32. BAFU [Bundesamt für Umwelt] (2016). Gefahrenkarten, Intensitätskarten und Gefahrenhinweiskarten.

33. BWW [Bundesamt für Wasserwirtschaft], BRP [Bundesamt für Raumplanung], and BUWAL [Bundesamt für Umwelt, Wald und Landschaft] (1997). Berücksichtigung der Hochwassergefahren bei raumwirksamen Tätigkeiten.

34. Borter, P. (1999). Risikoanalyse bei gravitativen Naturgefahren. Methode. (Bundesamt für Umwelt, Wald und Landschaft (BUWAL)).

35. BAFU [Bundesamt für Umwelt] (1999). Risikoanalyse bei gravitativen Naturgefahren. https://www.bafu.admin.ch/bafu/de/home/themen/thema-naturgefahren/naturgefahren--publikationen/publikationen-naturgefahren/risikoanalyse-bei-gravitativen-naturgefahren.html.

36. Swisstopo [Bundesamt für Landestopografie] (2024). Das Topografische Landschaftsmodell (TLM). Wissen. https://www.swisstopo.admin.ch/de/informationen-topografisches-landschaftsmodell.

37. Fuchs, S., Heiser, M., Schlögl, M., Zischg, A., Papathoma-Köhle, M., and Keiler, M. (2019). Short communication: A model to predict flood loss in mountain areas. Environmental Modelling & Software *117*, 176–180. https://doi.org/10.1016/j.envsoft.2019.03.026.

38. Papathoma-Köhle, M., Schlögl, M., Dosser, L., Roesch, F., Borga, M., Erlicher, M., Keiler, M., and Fuchs, S. (2022). Physical vulnerability to dynamic flooding: Vulnerability curves and vulnerability indices. Journal of Hydrology *607*, 127501. https://doi.org/10.1016/j.jhydrol.2022.127501.

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

40. Zischg, A.P., Hofer, P., Mosimann, M., Röthlisberger, V., Ramirez, J.A., Keiler, M., and Weingartner, R. (2018). Flood risk (d)evolution: Disentangling key drivers of flood risk change with a retro-model experiment. Science of The Total Environment *639*, 195–207. https://doi.org/10.1016/j.scitotenv.2018.05.056.

41. Löschner, L., and Nordbeck, R. (2020). Switzerland's transition from flood defence to flood-adapted land use–A policy coordination perspective. Land Use Policy *95*, 103873. https://doi.org/10.1016/j.landusepol.2019.02.032.

42. Fuchs, S., Röthlisberger, V., Thaler, T., Zischg, A., and Keiler, M. (2017). Natural Hazard Management from a Coevolutionary Perspective: Exposure and Policy Response in the European Alps. Annals of the American Association of Geographers *107*, 382–392. https://doi.org/10.1080/24694452.2016.1235494.

43. Andreadis, K.M., Wing, O.E.J., Colven, E., Gleason, C.J., Bates, P.D., and Brown, C.M. (2022). Urbanizing the floodplain: global changes of imperviousness in flood-prone areas. Environ. Res. Lett. *17*, 104024. https://doi.org/10.1088/1748-9326/ac9197.

44. Hemmati, M., Mahmoud, H.N., Ellingwood, B.R., and Crooks, A.T. (2021). Shaping urbanization to achieve communities resilient to floods. Environmental Research Letters *16*. https://doi.org/10.1088/1748-9326/ac1e3c.

45. O'Donnell, E.C., and Thorne, C.R. (2020). Drivers of future urban flood risk. Phil. Trans. R. Soc. A. *378*, 20190216. https://doi.org/10.1098/rsta.2019.0216.

46. Rentschler, J., Avner, P., Marconcini, M., Su, R., Strano, E., Vousdoukas, M., and Hallegatte, S. (2023). Global evidence of rapid urban growth in flood zones since 1985. Nature *622*, 87–92. https://doi.org/10.1038/s41586-023-06468-9.

47. Fuchs, S., and Thaler, T. eds. (2018). Vulnerability and Resilience to Natural Hazards 1st ed. (Cambridge University Press) https://doi.org/10.1017/9781316651148.

4 Neglecting property-level flood risk adaptation measures lead to overestimation in flood risk analysis – an empirical study

Nele Rindsfüser[1,2*], Markus Mosimann[1,2], Sibilla Ernst[2], Margreth Keiler[3,4] and Andreas Paul Zischg[1,2]

[1] *Oeschger Centre for Climate Change Research, Mobiliar Lab for Natural Risks, University of Bern, Bern, Switzerland*
[2] *Institute of Geography, University of Bern, Bern, Switzerland*
[3] *Department of Geography, University of Innsbruck, Innsbruck, Austria*
[4] *Institute for Interdisciplinary Mountain Research, Austrian Academy of Sciences, Innsbruck, Austria*

Published in: International Journal of Disaster Risk Reduction, Volume 119, March 2025, 105326
https://doi.org/10.1016/j.ijdrr.2025.105326

Abstract

Combining structural and non-structural mitigation measures is a strategy for managing flood risk. Besides structural flood alleviation schemes and land-use planning, property-level flood risk adaptation (PLFRA) measures are complementary measures for effective flood risk management. However, quantitative knowledge about the implementation and damage-reducing effects on building structure of PLFRA measures is scarce. Accordingly, the mitigation of vulnerability is rarely considered in flood risk assessment. Here, we collect data on PLFRA measures through a field survey, present a method for incorporating PLFRA into flood risk analysis, and conduct an analysis of their damage-reducing effects. With this approach, flood risk analysis is based on known object-specific vulnerability, rather than on assumptions on overall risk reduction by PLFRA measures. The results show that 16% of the buildings are protected through PLFRA measures, and the expected annual damage (EAD) is reduced by around 18%. On average, the PLFRA measures protect the respective houses against flood damage up to a flow depth of 0.6m. Further, 17% of the buildings had a level of protection that could not be attributed to explicit PLFRA measures but was still considered effective. The average protection level of all buildings is up to 0.3m, and the EAD is reduced by around 23%. If all buildings in the hazard zones were protected by PLFRA measures with a protection level of 0.5m, the EAD could be reduced by 50%. The results presented provide robust evidence that neglecting PLFRA measures in flood risk analysis leads to an overestimation of flood risk.

Keywords: Flood risk adaptation, private precautionary measures, natural hazard, exposure, vulnerability, land-use planning, damage reduction, flood management

4.1 Introduction

River floodplains are popular areas for residential- and economic development.[1–4] In recent decades, there has been a significant increase in population in flood-prone areas.[5,6] The continuous accumulation of population and economic assets in risk-prone areas leads to an increase in flood damage.[7–10] The trend in economic damage is likely to continue as climate change, land-use change, human intervention, and socio-economic development all influence hazard, exposure, and vulnerability, and thus contribute to augmented and evolving flood risk.[8,11–15] Flood risk is defined as the potential (negative) consequences of an event that are determined probabilistically as a function of hazard, exposure, and vulnerability.[16,17]

Flood risk management aims to reduce risk to an acceptable level for the affected society through prevention, mitigation, preparedness, and response.[17] In many countries, flood risk management is based on an integrated approach that recognizes that structural flood alleviation schemes (e.g. dikes) may fail and that additional non-structural measures such as property-level flood risk adaptation (PLFRA) measures, land use planning, and insurance are needed to complement flood protection.[3,18–20] The complexity and dynamic nature of risk pose new challenges for flood risk management.[18,21,22] To ensure that the current level of safety can be maintained under changing conditions in the future, new assessment tools are needed.[23] Flood risk monitoring is a strategy for enabling adaptive flood risk management.[15] Flood risk monitoring provides a comprehensive view of critical hazard, exposure, and vulnerability trends, providing timely alerts to decision-makers as critical thresholds in flood risk evolution are approached.[15] In addition, flood risk monitoring enables the evaluation of flood risk management policies. However, it requires risk models capable of accounting for variations in hazard, exposure, and vulnerability.

Flood risk analysis provides important information for risk governance,[24] and is essential for effective risk management. Various methodologies exist to calculate and quantify flood risk and its components hazard, exposure, and vulnerability. However, for example, Metin et al.[25] and Rindsfüser et al.[15] stated that studies on changes in flood risk including all risk components are scarce. Moreover, the most neglected component of risk is vulnerability. Risk models that account for variation in vulnerability, for example, due to PLFRA measures, are essential for evaluating the temporal dynamics of flood risk.[19]

Vulnerability is defined as "the propensity or predisposition to be adversely affected".[26] It describes "the conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impact of hazards".[17] The vulnerability analysis depends on the concept of vulnerability (physical, social, economic, or institutional vulnerability) that is used in the research study.[27] The vulnerability analysis includes, for example, the analysis of structural resistance, direct and indirect consequences, and/or human conditions.[27–29] Due to the different backgrounds of multiple disciplines analyzing vulnerability, there exists a multitude of factors, proxies, and indices to analyze vulnerability.

For our study, we focus on physical vulnerability. Physical vulnerability describes the susceptibility of buildings to damage from flooding due to different spatial and temporal intensities of the flood process, such as flow depth and flow velocity.[27,30–32] Physical vulnerability is assessed on the basis of factors such as building types, construction materials and techniques, and the presence of protective structures.[31] To analyze and integrate physical vulnerability into risk calculations, vulnerability functions are set up. They are either developed with statistical analyses of region-specific damage data,[33,34] physical modeling,[35,36] or synthetic models and expert knowledge.[37–39]

The physical vulnerability of buildings can be altered by building characteristics and PLFRA measures.[3,19,20,40] PLFRA measures refer to structural or technical measures that are implemented directly on or around the object itself. It can be categorized into two main categories: wet flood-proofing (flood-adapted use and equipment of buildings, water-resistant materials) and dry flood-proofing (sealing, shielding, reinforcement).[3,41,42] In addition, a distinction is made between permanent and temporary or mobile measures. Examples of PLFRA measures include raising light wells, constructing protective walls, installing watertight doors and windows, and installing backflow flaps to reduce damage caused by flooding.

The study of Attems et al.[41] gives an overview/catalog of different PLFRA measures. Holub et al.[31], Kreibich et al.[3] and Lai et al.[43] have quantified and evaluated the effectiveness of various PLFRA measures for buildings against flooding. It appears that there is a wide range in the assessment of the effectiveness of PLFRA measures, or that only qualitative information is provided.

In Switzerland, the built-up area increased by 23% between 1985 and 2009,[44] and there has been a growth in settlements in floodplains since the 1960s.[45] Nowadays, around 20% of the built-up area of Switzerland are prone to fluvial floods. Hazard maps are the most important tool and well established instruments for the integral flood risk management. Since 1991, the elaboration of hazard maps has been obligatory, and the maps are binding for land use planning.[44] They are developed through numerical flood modelling, historical event analysis, and expert assessment guidelines.[46–48] Hazard classes (high/red, medium/blue, low/yellow) are determined by a combination of the intensity and probability of a possible hazard event.[49,50] These hazard maps are crucial for land-use planning and the design of new buildings or modifications to existing buildings. In the high hazard zone, new constructions are prohibited. In the medium hazard zone, new constructions are permitted according to regulations. In both hazard zones, alterations to existing buildings are subject to building regulations. PLFRA measures to protect buildings are mandatory for new constructions in the medium hazard zones and for modifications to existing buildings in high hazard zones. They are voluntarily in the low hazard zone. In recent years, insurance companies have been advertising subsidies for the construction of PLFRA measures. However, there is a lack of knowledge about the implementation of these regulations and about their effectiveness in reducing the risks.

Hence, the main objective of our study is to analyze the implementation level of PLFRA measures and to quantify the effect of PLFRA measures on the overall flood risk in the Swiss municipality of Burgdorf, Canton of Bern. To this aim, we collect data on PLFRA measures with a field survey, incorporate PLFRA measures into the flood risk analysis that is based on a comprehensive risk modelling chain (hazard, exposure, vulnerability to risk), and conduct an analysis of their damage-reducing effects. In order to analyze the damage-reducing effects of PLFRA measures, we built four scenarios and compared the results. One scenario is the risk calculation without considering differentiated vulnerability due to PLFRA measures, two scenarios include the collected data on PLFRA measures and one scenario is a counterfactual scenario in which all buildings have a certain protection level.

4.2 Data and methods

In order to analyze and discuss the effects of the integration of PLFRA measures into the flood risk analysis, we conducted a comprehensive flood risk study for the municipality of Burgdorf in the Canton of Bern, Switzerland. The key to studying flood risk is to develop spatial datasets representing the three risk components: hazard, exposure, and vulnerability. The risk was calculated in terms of the expected annual damage (EAD [CHF/year]) by combining the damage results for different return periods and integrating the area under the risk curve. The focus is on structural damage to buildings (residential, public, and industrial buildings). The study design is visualized in **Figure 4-1**.

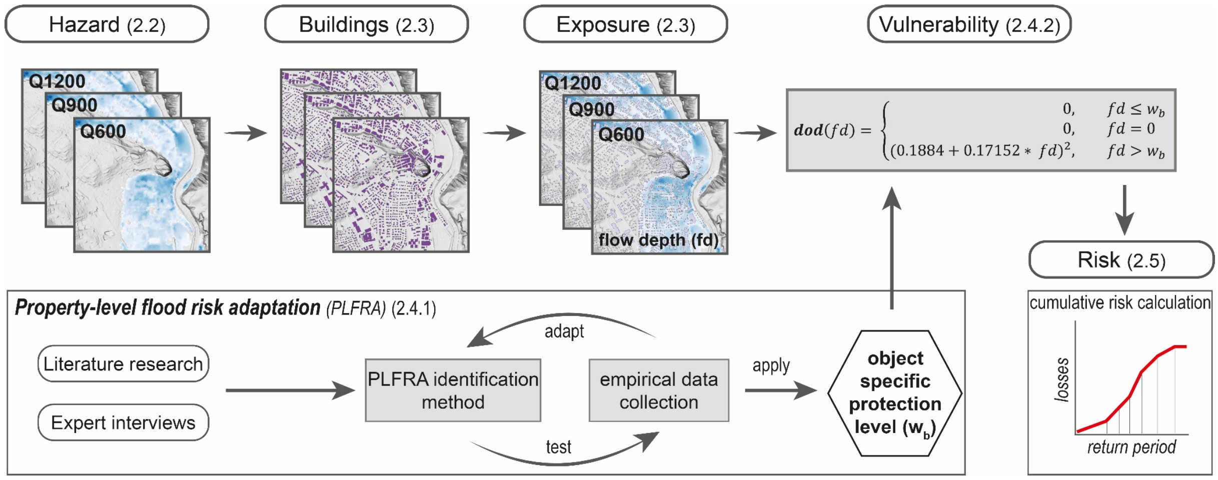


Figure 4-1. Study design. The numbers in brackets indicate the section where the data and methods are described. Q600 (as an example) indicates a flood with a peak discharge Q of 600 m3/s used for the risk calculation. Dod denotes the degree of damage and the vulnerability function used for the risk calculation.[39]

4.2.1 Case study

Figure 4-2 provides an overview of the study area. We focus on the floodplain of the River Emme in Burgdorf (Canton of Bern, Switzerland). The catchment of the Emme River upstream of the study area is 660 km². The average altitude of the pre-alpine catchment is about 987 m a.s.l. The municipality of Burgdorf has an area of 15.5 km² and 17’000 inhabitants. After the floods of 1764, 1868, and 1876, the authorities began to regulate the main course of the Emme River and to build lateral dikes to protect human settlements and agricultural areas. After these measures, the riverbed incised, and the erosion had to be stopped by the construction of riverbed stabilization measures.[51] The measures taken have enabled the region to protect areas from flooding and create space for economic growth. As a result, the region experienced significant economic growth in the late 19th and throughout the 20th century, leading to an increase in exposure. For more detailed information on the evolution of risk and its drivers in the Emme catchment from 1820 to 2015, see the study by Zischg et al.[51]

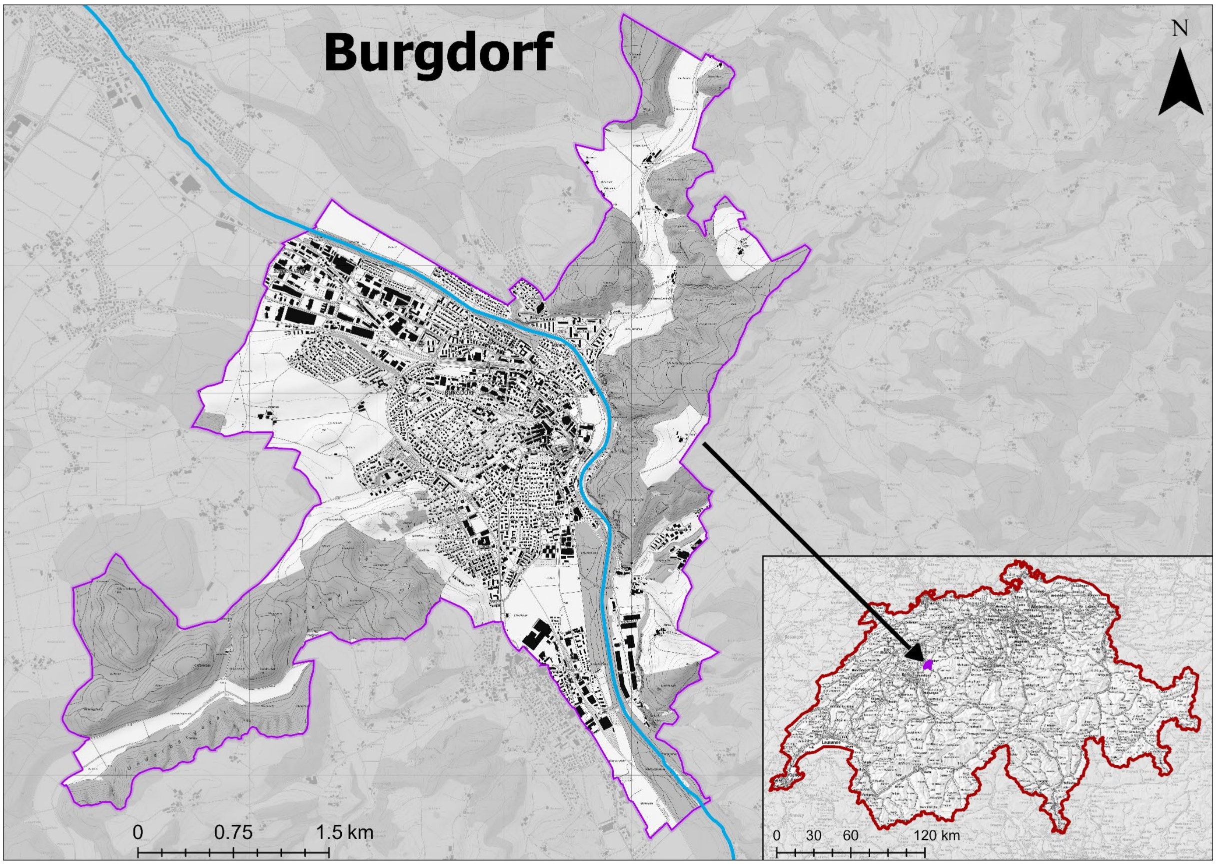


Figure 4-2. Overview of the study area. Municipality of Burgdorf with the Emme River, Switzerland. Background map: Swisstopo.[52]

4.2.2 Quantification of flood hazard

The hazard analysis is based on pre-calculated flood extent and flow depths from a library-based surrogate flood model described by Mosimann et al.[53] The surrogate models are pre-simulated scenarios for a specific river section and peak discharge. To generate the surrogate models, synthetic hydrographs over a range of peaks, specific for the floodplain, are used to model floods based on a high-resolution flood model. The synthetic hydrographs were derived from discharge measurements and normalized for event duration and peak discharge.[51,53,54] The probability of occurrence of each hydrograph was derived from the extreme statistics of the Emme Wiler gauge (provided by the Federal Office of Environment[55]). Since the municipality of Burgdorf is located upstream of the Emme Wiler gauge station, where extreme value statistics are available, the discharge values were adjusted to account for differences in catchment area. This adjustment incorporates an empirical exponent to reflect non-linearities in how discharge scales with catchment size, ensuring a more accurate representation of hydrological processes.[56] The BASEMENT-ETH software was used for flood modeling.[57] Detailed information on the hydrodynamic simulations can be found in Mosimann et al.[53] The high-resolution (50cm) digital terrain model of the Canton Bern and the cross sections of the Federal Office of Environment from 2014 were used as input data for the flood simulations of the Emme River. The surrogate models are stored as libraries in a database which allows the analysis of the spatial relationship between flood hazard and exposure data in a computationally efficient way.

For the risk analysis of our study, we select the flooded area and water depth as hazard variables from the surrogate library for events with a peak discharge between 400 m^3/s – 1200 m^3/s (50 m^3/s intervals). This range is selected because a peak discharge of 400 m^3/s is the local threshold for flood early warning, and a peak discharge of more than 1200 m^3/s is not plausible for the catchment area.

4.2.3 Quantification of exposure

The exposure analysis is based on the building dataset of Switzerland from the Topographic Landscape Model (TLM). This contains polygons of all building footprints provided with their exact location.[58,59] The number of affected buildings is calculated by overlaying the homogenized building footprint layer with the modeled flood extent in Burgdorf. Within this intersection step, the maximum flow depth is assigned to the exposed objects, as suggested by Bermúdez and Zischg[60] to analyze the object-specific damage of a flood event.

The reconstruction building values for each building in the municipality of Burgdorf are calculated by multiplying the building volume (m^3) with an average monetary value per building volume (CHF/m^3), differentiated by land use category and building purpose, using the model M4 (based on average value per building volume, differentiated by building features) taken from the study by Röthlisberger et al.[61]

4.2.4 Quantification of vulnerability

4.2.4.1 Property-level flood risk adaptation measures

We conducted an empirical study in Burgdorf to collect data on the implementation of PLFRA measures and, finally, to analyze their effect on flood risk assessment. The approach for the evaluation of buildings was developed in an iterative process and is visualized in **Figure 4-1**. A literature review on PLFRA measures combined with consultations with experts from the cantonal building insurance company and the cantonal natural hazards department yielded a deeper understanding of PLFRA measures. The experts provided the SIA Norms 260/1 (norms for architects to build in flood hazard zones) and building applications for new or modified buildings in the hazard zone since September, 2009. Since this date, the implementation of PLFRA measures in the medium hazard zone has been mandatory. With this information, the evaluation system was developed and tested to enable the systematic collection and evaluation of PLFRA measures in the field. After three days of testing in Burgdorf, hundred analyzed buildings, and several adjustments to the collection and evaluation method, the system for identifying PLFRA measures was ready for empirical data collection. The main survey of all buildings in the floodplain area of Burgdorf (approx. 1'500) was carried out during several days from March 2024 to August 2024. To conduct data collection and geolocate the inspected buildings, we utilized a tablet and developed a QField (professional mobile app for QGIS) project containing the locations of all buildings along with a customizable attribute table for data entry. Since we did not have access to all buildings, and the assessment was mainly done from the perspective of the adjacent streets, we collected the following parameters: PLFRA measures (yes/no), dry flood-proofing PLFRA measures (type), avoidance of flood discharge PLFRA measures (type), flood protection level above ground [m]. Dry flood-proofing PLFRA measures prevent buildings from entering water. For our study, we considered the following dry-flood proofing PLFRA measures: sealing building openings (flood-proof basement windows and sealed light shafts), elevated light shafts, check valves, backup valves, and overhead sewers (see for an overall overview/catalog[41]). Avoidance of flood discharge PLFRA measures avoid flood discharges by adapting the surroundings of a building, or the building itself. We considered the following measures: landscape design, design and shape of building, elevating building and raising the ground floor level (see for an overview/catalog[41]). The flood protection level above ground of the PLFRA measures was the main parameter for the flood risk analysis. The protection level was used to adjust the vulnerability of buildings. A building with a certain protection level is considered less vulnerable against flooding. After the data collection, the protection levels were incorporated into the vulnerability analysis. This step is described in the next section. Objectivity and consistency were ensured through peer collaboration, tools (meter and handheld laser to estimate protection levels), and re-inspection of buildings from the first testing days.

4.2.4.2 Physical vulnerability

The object-specific vulnerability is calculated by a vulnerability function that provides a degree of damage based on the flow depth at each building.[62,63] The degree of damage ranges from 0 (no damage) to 1 (total damage). We used the vulnerability function based on Swiss insurance data developed by Zischg et al.[39] The function is based on expert knowledge of a representative sample of buildings in flood prone areas. The vulnerability function is described by Equation (4-1)(4-1) as follows:

$$\boldsymbol{dod}(fd) = \begin{cases} 0, & fd \leq w_b \\ 0, & fd = 0 \\ (0.1884 + 0.17152 * fd)^2, & fd > w_b \end{cases} \tag{4-1}$$

where *dod* is the degree of damage of an exposed building *b*, *fd* is the flood depth above ground surface attributed to an exposed building and w_b is the protection level of an exposed building.

To consider the effect of PLFRA measures, the vulnerability function is modified by integrating an attribute related to the flood protection level of each individual building. If the calculated flow depth is zero or less than the protection level of the building, the vulnerability (degree of damage) is set to zero. If the calculated flow depth is greater than the protection level of the building, the vulnerability function calculates the degree of damage by considering the flood depth. We assume that the PLFRA measures are 100% effective if flow depth is below the assessed level of protection and 0% effective if flow depth is above.

In order to analyze the impact of PLFRA measures on the overall flood risk (calculated as expected annual damage) in Burgdorf, we have created a model experiment with four scenarios. Scenario 0 is the baseline scenario consisting of the risk calculation method without considering a differentiated vulnerability (flood protection level) of buildings.[51] Scenario 1 integrates the flood protection level due to PLFRA measures mapped in the case study area. Scenario 2 is based on Scenario 1, but includes additional buildings with a level of protection that cannot be categorized as explicit PLFRA measure due to a lack of object-specific knowledge. Specifically, these are buildings that are located on elevated terrain that provides flood protection and can be interpreted as a PLFRA measure to avoid flood discharge (see section 4.2.4.1). However, if the building is older than the federal regulations (built before 2009), and it is not known whether the building was built on higher ground, for example, for better views or for protection, the building could not be classified as having implemented PLFRA measures. This distinction of Scenario 1 and Scenario 2 was made to differentiate the results and avoid an overestimation of implemented PLFRA measures in Burgdorf. Scenario 3 is a future-oriented-counterfactual scenario in which all buildings have a protection level of 0.5m.

4.2.5 Flood damage modeling and risk calculation

After the preparation of hazard, exposure, and vulnerability data, the data is combined to calculate the expected annual damage (EAD) as indicator to determine flood risk. To estimate the object-specific damage, the reconstruction value of the building (see section 4.2.3) was multiplied by the degree of damage of each scenario (0-3) (see section 4.2.4) and for each flood with a certain peak discharge (see section 4.2.2). The object-specific damage were summed up for each scenario and peak discharge flood to calculate the cumulative damage. Finally, the risk was defined as the cumulative damage [CHF] of each flood scenario multiplied with the probability of the flood scenario. The flood scenarios were attributed to their return period based on the official extreme value statistic of the Emme Wiler gauge station of the Federal Office for the Environment[55] and adjusted to the respective catchment area (see section 4.2.2). The EAD [CHF/year] was calculated by integrating the area under the risk curve.[51,64] The risk curve was derived through interpolation of the flood scenarios used in this study.[51,64]

4.3 Results and discussion

4.3.1 Property-level flood risk adaptation measures in Burgdorf

A total of 1'243 buildings were inspected during the field survey to collect data on PLFRA measures. The results show that 202 buildings (16%) had implemented PLFRA measures, and a further 213 buildings (17%) had a level of flood protection that could not be attributed to explicit PLFRA measures but was still considered effective. As described in section 4.2.4.2, these buildings were protected due to micro-structures of the terrain but clear indications that these modified terrains were PLFRA measures lacked. The mean protection level of the 202 buildings is ~0.6m. The mean protection level of all 415 buildings is ~0.3m.

Figure 4-3. Example of a newly-built building in the medium hazard zone and two implemented PLFRA measures at the entrance of an underground parking garage (elevated entrance and devices for temporary embankments (black arrow)).

Figure 4-4. Example of implemented PLFRA measure (elevated building entrance).

Figure 4-3 and Figure 4-4 present examples of PLFRA measures at/around buildings in Burgdorf. **Figure 4-3** shows an underground parking garage of a new building in the medium hazard zone. In this hazard zone, PLFRA measures must be taken according to Swiss law. This example displays that the regulations have been implemented. The entrance to the underground parking garage is protected on the one hand permanently by the elevated terrain, and, on the other hand, steel frames for temporary embankments are fastened to the walls. In case of a flood event, temporary embankments can be installed. In addition to the measures at the entrance of the underground garage, the entrances to the building are at the same height as the protection level of the garage. This building was assigned a protection level of 0.5m. **Figure 4-4** shows another example of the field survey. This building is protected with a raised building entrance.

The field survey provided important information on the implementation and level of PLFRA measures. It was possible to empirically determine how many buildings in the municipality are protected in addition to the levees along the Emme River. A first set of object-specific vulnerability data was generated that could be incorporated into the risk analysis. Consistent with previous studies, the results indicate that many flood-prone households are still not taking PLFRA measures.[3] In the following section, we discuss some of the difficulties encountered during the survey, certain compromises that had to be made, and existing uncertainties in the dataset.

The main difficulty and uncertainty lies in the assessment of the buildings on site. Despite the preliminary clarifications about PLFRA measures with the literature review and expert consultations, the development of an evaluation method and the iterative adjustment process, a degree of uncertainty remains when making assessments (i.e., considering whether and what type of PLFRA measures are implemented at buildings) in the field. For example, the visibility of the buildings is a limiting factor. Some buildings were difficult to access from the street or were not visible from the street on all sides. Access to the buildings (inside and outside) would be necessary to analyze the full range of possible PLFRA measures.

As access was not possible, the study is limited to dry-proof PLFRA measures that are visible from the streets along the buildings. Hence, the analysis may underestimate the effects of the PLFRA measures on flood risk reduction at some extent. Another difficulty is to assess whether a measure has been taken specifically for flood protection or whether a supposed measure has been created for aesthetic reasons (e.g., terrain elevation to have a better view or increase natural light on the ground floor). This decision was easier for buildings constructed in the medium hazard zone after 2009, as the building applications from the cantonal authorities could be used as a guide and the implementation of PLFRA measures is mandatory for new buildings in the medium hazard zone. However, most of the buildings in the study region are older than 2009 or are in the low hazard zone where the implementation is not mandatory. Experiences from the field survey and other studies have shown that discussions with homeowners provide useful information about the implementation of flood protection measures [65]. For example, Sairam et al.[19] analyzed the vulnerability reduction due to PLFRA measures by selecting data through telephone surveys of private households. To improve the accuracy of the data, we propose a follow-up study that includes inputs from the population and/or architects and experts to assess the implementation of PLFRA measures.

4.3.2 Hazard, exposure, vulnerability quantification

The hazard analysis is based on pre-calculated flood extent and flow depths from a surrogate library (see section 4.2.2). Synthetic floods with a peak discharge of 400 m^3/s to 1’200 m^3/s are considered for the study. However, the results show that buildings in the municipality of Burgdorf are only exposed to floods with a peak discharge of 600 m^3/s or higher. Therefore, the results displayed in **Figure 4-5, Figure 4-6, Figure 4-7, and Figure 4-8** are presented for the floods with a peak discharge of 600 m^3/s or higher.

Figure 4-5 shows the distribution of the maximum flow depths attributed to the exposed buildings by overlaying the pre-simulated flood extents of each synthetic flood with the building dataset. The median ranges from 0.1m to 0.9m with an increasing trend from the lowest to the highest peak discharge. The maximum flow depths attributed to the exposed buildings of the analyzed floods range from 0.9m (max. value, Q600) to 4.4m (max. outlier, Q1200). As explained by Bermúdez and Zischg[60], the maximum flow depth assignment method can lead to an overestimation of damage because the flow depth over a single building can vary. However, the maximum flow depth method is more robust regarding the choice of the mesh set-up of the flood modelling. In addition, this method is reliable for our study because we analyze the effect of PLFRA measures and assume that these measures are located at the weakest points of the buildings where the highest flow depths can be expected. This means that even if the total damage is overestimated, the effect of PLFRA measures is correctly calculated.

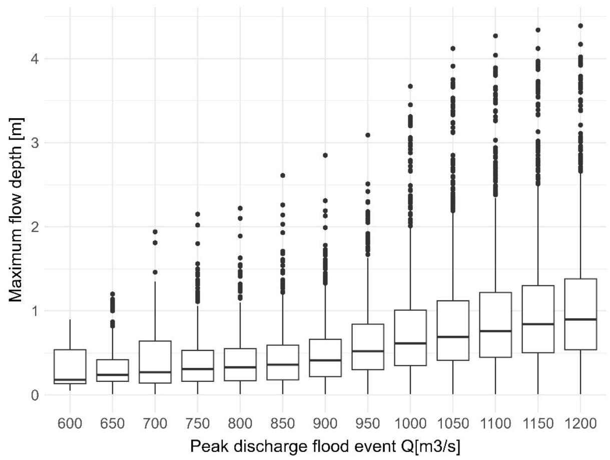


Figure 4-5. Distribution of maximum flow depths at the individual buildings per flood magnitude (i.e., peak discharge).

Figure 4-6 shows the number of exposed respectively affected buildings per peak discharge flood for each vulnerability scenario. The number of exposed buildings is visualized within Scenario 0 (without consideration of protection levels) and ranges from 16 to 1’443 buildings. In Scenario 1 (considering protection level of PLFRA measures), the number of affected buildings ranges from 16 to 1’393. In Scenario 2 (considering protection level), the number of affected buildings ranges from 15 to 1’361 buildings. In

Scenario 3 (considering a protection level of 0.5m for all buildings), the number of affected buildings ranges from 5 to 1'124 buildings. In each of the scenarios (1-3), the highest number of buildings protected by PLFRA measures is by a flood with a peak discharge of 900 m^3/s. In flood scenarios of a magnitude up to this peak discharge, most of the buildings have an effective level of protection for the calculated flood depths of the event and/or most of the buildings with an effective level of protection are within the calculated floodplain. In flood magnitudes beyond this peak discharge, the efficacy of PLFRA measures is declining.

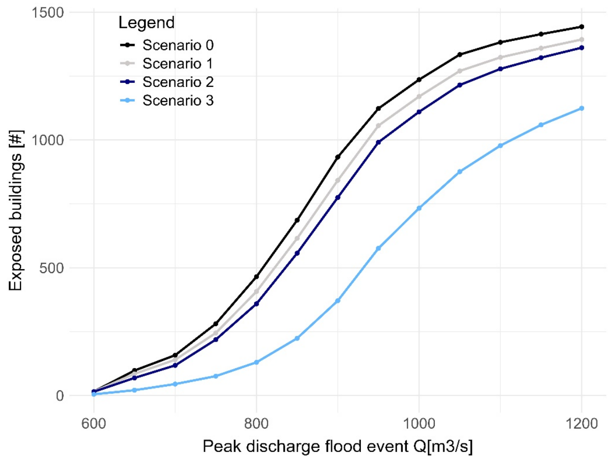


Figure 4-6. Number of exposed buildings per peak discharge flood and vulnerability scenario. Scenario 0: Without protection measures. Scenario 1: Considering PLFRA measures. Scenario 2: Considering PLFRA measures and protection level on all buildings. Scenario 3: Considering a protection level of 0.5m for all buildings.

Figure 4-7 shows an example of the simulated flood extent and flow depths from a flood simulation with a peak discharge of 1'200 m^3/s. This peak discharge is the highest flood magnitude considered in the study. Within this flood, a total of 1'443 buildings are exposed, and the maximum flow depth attributed to a building is 4.39m. However, the median flood depth for this event is approximately 0.9m (**Figure 4-5**). In the vulnerability Scenario 1, 202 buildings (14%) are protected by PLFRA measures. However, only 50 buildings (3%) are effectively protected (**Figure 4-6**). This indicates that for 75% of the protected buildings, the protection level of the PLFRA measures is not sufficient for the flood depths of a flood with a peak discharge of 1'200 m^3/s. In vulnerability Scenario 2, 414 buildings (29%) are protected with a certain protection level. However, only 82 buildings (5%) are effectively protected against the 1'200 m^3/s peak discharge flood (**Figure 4-6**). Considering a protection level of 0.5m for all buildings (Scenario 3) indicates that this protection level is sufficient for 319 buildings (22%) (**Figure 4-6**). The results show that the effect of PLFRA measures against flooding is highly dependent on the local flow depths and the protection level of each individual building. In summary, 3% of the buildings in Burgdorf are effectively protected through PLFRA measures (Scenario 1), 5% of the buildings in Burgdorf are protected by PLFRA measures or an assigned protection level, and 22% could be protected if each building would have a protection level of 0.5m.

Figure 4-7. Map of a flood simulation with a peak discharge of 1200 m3/s. Light blue symbolize low flow depths and dark blue symbolize high flow depths. The upstream boundary is in the South, water flows from South to North. Building footprints are visualized in yellow58. Background: Digital Terrain model, swissALTI3D66.

The results show that the combination of flood extent, flow depth, buildings, and the level of protection provided by PLFRA measures is highly complex. The presence of PLFRA measures does not necessarily guarantee protection against flood damage. The effectiveness of these measures depends on factors such as the location of the buildings, the expected flood depths, and whether the PLFRA measures provide the appropriate level of protection. In addition, the effectiveness of PLFRA measures depends on several interrelated aspects within the risk management system.[67] However, in the case of the municipality of Burgdorf, exposure and vulnerability of a relevant number of buildings are reduced due to PLFRA measures. A major uncertainty of the applied method is the assumption that the PLFRA measures fully protect the buildings. We assumed that the degree of damage equals zero if the maximum flow depth is less than the protection level of the implemented measures. However, previous studies (see e.g., Attems et al.[41], Holub et al.[31]) have shown that the implementation of PLFRA measures does not guarantee 100 % effective risk reduction. However, this would have been beyond the scope of our research study. Nevertheless, we recommend that future research studies extend the analyses by integrating an additional attribute of the effectiveness of PLFRA measures.

4.3.3 Differences in risk quantification by consideration of property-level flood risk adaptation measures

The overall risk calculation is based on the expected damage calculation of each peak discharge flood. **Figure 4-8** visualizes the values for each pre-simulated flood and vulnerability scenario. The calculated expected damage ranges from 1.9 Mio. CHF (Q600, Scenario 0) to 603 Mio. CHF (Q1200, Scenario 0). Taking into account the evaluated level of protection from the field survey (Scenario 1 and 2), the expected damage can be reduced by 2-43%, depending on the peak discharge. If all buildings in Burgdorf have had a protection level of 0.5m (Scenario 3), the expected damage could have been reduced by 5-80% (Q1200-Q600). In all scenarios, the highest absolute damage reduction due to the protection measures is for the flood with a peak discharge of 900 m^3/s. This is consistent with the exposure analysis described in the previous chapter (see section 4.3.2, **Figure 4-6**). The expected damage for this flood (Q900) is 239 Mio. CHF. In Scenario 1, the damage is reduced by 24 Mio. CHF (10%) compared to Scenario 0, in Scenario 2 by 30 Mio. CHF (13%), and in Scenario 3 by 63 Mio. CHF (26%).

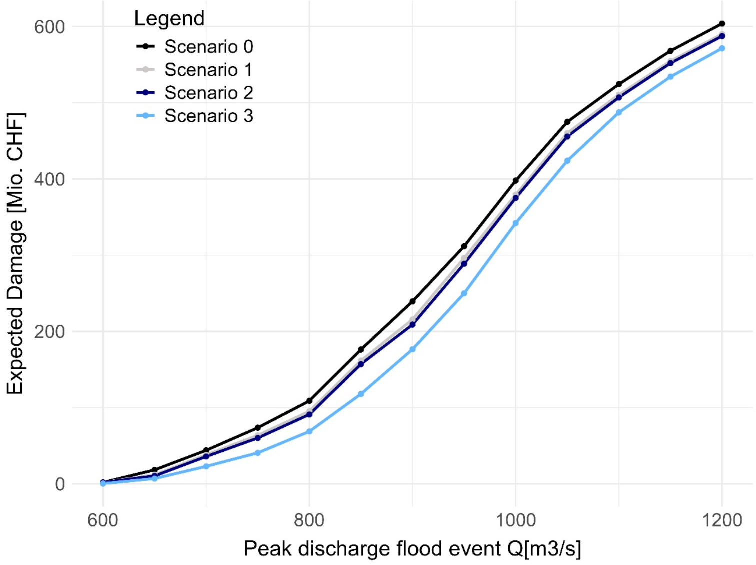


Figure 4-8. Damage per flood simulation and vulnerability scenario.

The flood scenarios were attributed to their return period based on the official extreme value statistic of the Emme Wiler gauge station of the Federal Office for the Environment[55] and adjusted to the respective catchment area (see section 4.2.2). It is crucial to acknowledge the inherent limitations of extreme value statistics, particularly the high degree of uncertainty they entail. Interpretations of these statistics must, therefore, be approached with caution. At the Emme Wiler gauge station, the confidence interval for a 100-year flood event is estimated to be between 482-704 m^3/s, and a 300-year flood event is estimated to be between 506 and 835 m^3/s. The best fit of the distribution function underestimates the three most extreme discharges measured, suggesting it is not optimized for low-probability events. This may result in the underestimation of the EAD. However, since the primary objective of this study is to estimate the risk-reducing effect of PLFRA measures under different scenarios rather than calculate the expected annual damage, these uncertainties are considered acceptable. While the absolute values may be higher, the percentage reduction in risk due to PLFRA measures is expected to be broadly similar, though some degree of variation remains possible.

Flood risk in terms of expected annual damage to buildings for flood peak discharges between 400 m^3/s and 1200 m^3/s and calculated without considering PLFRA measures for the municipality of Burgdorf is around 60'000 CHF/year. However, with an additional level of protection due to PLFRA measures, the flood risk can be reduced by 18 to 50% (Table 4-1). These results are consistent with previous studies (see Kreibich et al.[3] for a general overview on studies quantifying the damage-reducing effects of PLFRA measures). For example, Thieken et al.[68] stated that flood risk can be reduced by 30% through stronger building restrictions and improved privat precautions.

Table 4-1 Expected annual damage per vulnerability scenario.

	Scenario 1	Scenario 2	Scenario 3
Expected annual damage under Scenario 0	59'749 [CHF/yr]	59'749 [CHF/yr]	59'749 [CHF/yr]
Expected annual damage with protection	49'155 [CHF/yr]	46'248 [CHF/yr]	30'234 [CHF/yr]
Risk reduction	**18%**	**23%**	**50%**

In Switzerland, since 2009 the implementation of PLFRA measures has been mandatory for new buildings in the medium hazard zone and for building alterations in the high hazard zone. In the low hazard zone, it is voluntary but is increasingly requested or supported by insurance companies. This is not only the case in Switzerland but also in other European countries.[3]

This evolution in flood risk management strategies, in addition to climate change and socio-economic development, is having a relevant influence on the entire flood risk system and requires an adaptation of flood risk analysis procedures. As shown in the results of our study, the risk in the municipality of Burgdorf is overestimated when calculating the risk without the effect of PLFRA measures. However, the integration of PLFRA measures affords high-resolution data sets. For micro-scale studies, this level of detail can be compiled through empirical studies, but for larger-scale analyses, the methods need to be further developed.

4.4 Concluding remarks

Several studies have analyzed the drivers of flood risk change, and most of the studies conclude that the change in exposure is the most important driver of flood risk evolution.[15] This seems quite obvious as river floodplains provide important space for living and economic development. Flood risk management is increasingly based on an integrated approach, where adaptation measures, including land-use planning and PLFRA measures, are becoming more important. However, knowledge on the implementation and effects of non-structural measures and their integration into the risk analysis procedures is scarce.

In our study, we established a method for flood risk analysis based on simulated floods, a comprehensive building dataset, and object-specific vulnerability data. The results show that the integration of PLFRA measures into the risk analysis has a significant impact on the calculated cumulative flood risk. The flood risk of the municipality of Burgdorf is overestimated without considering the effect of PLFRA measures. Including the PLFRA measures and their level of protection in the risk analysis reduces flood risk by 18% (Scenario 1). The consideration of all protection levels leads to a flood risk reduction of 23% (Scenario 2) Furthermore, a protection level of 0.5m for each building would reduce the risk by 50% (Scenario 3). This is consistent with the results of previous studies that PLFRA measures are an effective tool to reduce the vulnerability of buildings.

The results support the notion that adaptive flood risk management requires approaches that take into account the spatiotemporal evolution of all risk components (hazard, exposure, and vulnerability). In the case of Switzerland, building protection has been regulated by federal law since 2009, and future changes in the vulnerability are expected. Thus, to enable adaptive flood risk management, changes in vulnerability due to PLFRA measures need to be integrated into a flood risk monitoring approach to detect trends in hazard, exposure, and vulnerability. The newest developments in machine learning methods offer a high potential for detecting PLFRA measures from lateral aerial photographs.[69] Research in the automatic assessment of the vulnerability of buildings against floods is required for considering this highly relevant parameter in flood risk monitoring systems.

References

1. Alves, P.B.R., Djordjević, S., and Javadi, A.A. (2022). Addressing social and institutional vulnerabilities in the context of flood risk mitigation. J Flood Risk Management *15*, e12839. https://doi.org/10.1111/jfr3.12839.

2. de Moel, H., Aerts, J.C.J.H., and Koomen, E. (2011). Development of flood exposure in the Netherlands during the 20th and 21st century. Global Environmental Change *21*, 620–627. https://doi.org/10.1016/j.gloenvcha.2010.12.005.

3. Kreibich, H., Bubeck, P., Van Vliet, M., and De Moel, H. (2015). A review of damage-reducing measures to manage fluvial flood risks in a changing climate. Mitig Adapt Strateg Glob Change *20*, 967–989. https://doi.org/10.1007/s11027-014-9629-5.

4. Zischg, A.P., and Bermúdez, M. (2020). Mapping the Sensitivity of Population Exposure to Changes in Flood Magnitude: Prospective Application From Local to Global Scale. Front. Earth Sci. *8*, 390. https://doi.org/10.3389/feart.2020.534735.

5. Früh-Müller, A., Wegmann, M., and Koellner, T. (2015). Flood exposure and settlement expansion since pre-industrial times in 1850 until 2011 in north Bavaria, Germany. Regional Environmental Change *15*, 183–193. https://doi.org/10.1007/s10113-014-0633-9.

6. Han, Y., Huang, Q., He, C., Fang, Y., Wen, J., Gao, J., and Du, S. (2020). The growth mode of built-up land in floodplains and its impacts on flood vulnerability. Science of The Total Environment *700*, 134462. https://doi.org/10.1016/j.scitotenv.2019.134462.

7. Di Baldassarre, G., Kooy, M., Kemerink, J.S., and Brandimarte, L. (2013). Towards understanding the dynamic behaviour of floodplains as human-water systems. Hydrol. Earth Syst. Sci. *17*, 3235–3244. https://doi.org/10.5194/hess-17-3235-2013.

8. Mazzoleni, M., Mård, J., Rusca, M., Odongo, V., Lindersson, S., and Di Baldassarre, G. (2021). Floodplains in the Anthropocene: A Global Analysis of the Interplay Between Human Population, Built Environment, and Flood Severity. Water Res. *57*. https://doi.org/10.1029/2020WR027744.

9. Mechler, R., and Bouwer, L.M. (2015). Understanding trends and projections of disaster losses and climate change: is vulnerability the missing link? Climatic Change *133*, 23–35. https://doi.org/10.1007/s10584-014-1141-0.

10. Merz, B., Kundzewicz, Z.W., Delgado, J., Hundecha, Y., and Kreibich, H. (2012). Detection and attribution of changes in flood hazard and risk. In Changes in Flood Risk in Europe IAHS special publication. (International Association of Hydrological Sciences), p. 516.

11. Hemmati, M., Ellingwood, B.R., and Mahmoud, H.N. (2020). The Role of Urban Growth in Resilience of Communities Under Flood Risk. Earth's Future *8*. https://doi.org/10.1029/2019EF001382.

12. IPCC (2022). Summary for Policymakers. Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

13. Jongman, B., Hochrainer-Stigler, S., Feyen, L., Aerts, J.C.J.H., Mechler, R., Botzen, W.J.W., Bouwer, L.M., Pflug, G., Rojas, R., and Ward, P.J. (2014). Increasing stress on disaster-risk finance due to large floods. Nature Clim Change *4*, 264–268. https://doi.org/10.1038/nclimate2124.

14. Kundzewicz, Z.W., Su, B., Wang, Y., Wang, G., Wang, G., Huang, J., and Jiang, T. (2019). Flood risk in a range of spatial perspectives - From global to local scales. Natural Hazards and Earth System Sciences *19*, 1319–1328. https://doi.org/10.5194/nhess-19-1319-2019.

15. Rindsfüser, N., Zischg, A.P., and Keiler, M. (2024). Monitoring Flood Risk Evolution: a systematic review. iScience *0*. https://doi.org/10.1016/j.isci.2024.110653.

16. IPCC (2022). Annex II: Glossary. In Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, V. Möller, J. B. R. Matthews, R. van Diemen, C. Méndez, S. Semenov, J. S. Fuglestvedt, and A. Reisinger, eds. (Cambridge University Press), pp. 2897–2930. https://doi.org/10.1017/9781009325844.029.

17. UNDRR [United Nations Office for Disaster Risk Reduction] (2022). Global Assessment Report on Disaster Risk Reduction 2022: Our World at Risk: Transforming Governance for a Resilient Future.

18. Merz, B., Hall, J., Disse, M., and Schumann, A. (2010). Fluvial flood risk management in a changing world. Nat. Hazards Earth Syst. Sci. *10*, 509–527. https://doi.org/10.5194/nhess-10-509-2010.

19. Sairam, N., Schröter, K., Lüdtke, S., Merz, B., and Kreibich, H. (2019). Quantifying Flood Vulnerability Reduction via Private Precaution. Earth's Future *7*, 235–249. https://doi.org/10.1029/2018EF000994.

20. Hudson, P. (2020). The Affordability of Flood Risk Property-Level Adaptation Measures. Risk Analysis *40*, 1151–1167. https://doi.org/10.1111/risa.13465.

21. Fuchs, S., Keiler, M., Sokratov, S., and Shnyparkov, A. (2013). Spatiotemporal dynamics: the need for an innovative approach in mountain hazard risk management. Nat Hazards *68*, 1217–1241. https://doi.org/10.1007/s11069-012-0508-7.

22. Mishra, A., Mukherjee, S., Merz, B., Singh, V.P., Wright, D.B., Villarini, G., Paul, S., Kumar, D.N., Khedun, C.P., Niyogi, D., et al. (2022). An Overview of Flood Concepts, Challenges, and Future Directions. Journal of Hydrologic Engineering *27*. https://doi.org/10.1061/(ASCE)HE.1943-5584.0002164.

23. Zischg, A. (2023). Flood risk change: a complexity perspective (Elsevier).

24. Klinke, A., and Renn, O. (2021). The Coming of Age of Risk Governance. Risk Analysis *41*, 544–557. https://doi.org/10.1111/risa.13383.

25. Metin, A.D., Dung, N.V., Schroeter, K., Guse, B., Apel, H., Kreibich, H., Vorogushyn, S., and Merz, B. (2018). How do changes along the risk chain affect flood risk? NATURAL HAZARDS AND EARTH SYSTEM SCIENCES *18*, 3089–3108. https://doi.org/10.5194/nhess-18-3089-2018.

26. Intergovernmental Panel On Climate Change (Ipcc) (2023). Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change 1st ed. (Cambridge University Press) https://doi.org/10.1017/9781009325844.

27. Fuchs, S., and Thaler, T. eds. (2018). Vulnerability and Resilience to Natural Hazards 1st ed. (Cambridge University Press) https://doi.org/10.1017/9781316651148.

28. Birkmann, J., Cardona, O.D., Carreño, M.L., Barbat, A.H., Pelling, M., Schneiderbauer, S., Kienberger, S., Keiler, M., Alexander, D., Zeil, P., et al. (2013). Framing vulnerability, risk and societal responses: the MOVE framework. Nat Hazards *67*, 193–211. https://doi.org/10.1007/s11069-013-0558-5.

29. Fuchs, S. (2009). Susceptibility versus resilience to mountain hazards in Austria - paradigms of vulnerability revisited. Nat. Hazards Earth Syst. Sci. *9*, 337–352. https://doi.org/10.5194/nhess-9-337-2009.

30. Bründl, M., Romang, H.E., Bischof, N., and Rheinberger, C.M. (2009). The risk concept and its application in natural hazard risk management in Switzerland. Nat. Hazards Earth Syst. Sci. *9*, 801–813. https://doi.org/10.5194/nhess-9-801-2009.

31. Holub, M., Suda, J., and Fuchs, S. (2012). Mountain hazards: reducing vulnerability by adapted building design. Environ Earth Sci *66*, 1853–1870. https://doi.org/10.1007/s12665-011-1410-4.

32. Nasiri, H., Mohd Yusof, M.J., and Mohammad Ali, T.A. (2016). An overview to flood vulnerability assessment methods. Sustain. Water Resour. Manag. *2*, 331–336. https://doi.org/10.1007/s40899-016-0051-x.

33. Fuchs, S., Keiler, M., Ortlepp, R., Schinke, R., and Papathoma-Köhle, M. (2019). Recent advances in vulnerability assessment for the built environment exposed to torrential hazards: Challenges and the way forward. Journal of Hydrology *575*, 587–595. https://doi.org/10.1016/j.jhydrol.2019.05.067.

34. Papathoma-Köhle, M., Schlögl, M., Dosser, L., Roesch, F., Borga, M., Erlicher, M., Keiler, M., and Fuchs, S. (2022). Physical vulnerability to dynamic flooding: Vulnerability curves and vulnerability indices. Journal of Hydrology *607*, 127501. https://doi.org/10.1016/j.jhydrol.2022.127501.

35. Sturm, M., Gems, B., Keller, F., Mazzorana, B., Fuchs, S., Papathoma-Koehle, M., and Aufleger, M. (2018). Understanding impact dynamics on buildings caused by fluviatile sediment transport. GEOMORPHOLOGY *321*, 45–59. https://doi.org/10.1016/j.geomorph.2018.08.016.

36. Sturm, M., Gems, B., Keller, F., Mazzorana, B., Fuchs, S., Papathoma-Köhle, M., and Aufleger, M. (2018). Experimental analyses of impact forces on buildings exposed to fluvial hazards. Journal of Hydrology *565*, 1–13. https://doi.org/10.1016/j.jhydrol.2018.07.070.

37. Dottori, F., Figueiredo, R., Martina, M.L.V., Molinari, D., and Scorzini, A.R. (2016). INSYDE: a synthetic, probabilistic flood damage model based on explicit cost analysis. Nat. Hazards Earth Syst. Sci. *16*, 2577–2591. https://doi.org/10.5194/nhess-16-2577-2016.

38. Neubert, M., Naumann, T., Hennersdorf, J., and Nikolowski, J. (2016). The Geographic Information System-based flood damage simulation model HOWAD. J Flood Risk Management *9*, 36–49. https://doi.org/10.1111/jfr3.12109.

39. Zischg, A.P., Röthlisberger, V., Mosimann, M., Profico-Kaltenrieder, R., Bresch, D., Fuchs, S., Kauzlaric, M., and Keiler, M. (2021). Evaluating targeted heuristics for vulnerability assessment in flood impact model chains. J Flood Risk Management *14*. https://doi.org/10.1111/jfr3.12736.

40. Dillenardt, L., Bubeck, P., Hudson, P., Wutzler, B., and Thieken, A.H. (2024). Property-level adaptation to pluvial flooding: An analysis of individual behaviour and risk communication material. Mitig Adapt Strateg Glob Change *29*, 53. https://doi.org/10.1007/s11027-024-10148-y.

41. Attems, M., Thaler, T., Genovese, E., and Fuchs, S. (2020). Implementation of property-level flood risk adaptation (PLFRA) measures: Choices and decisions. WIREs Water *7*, e1404. https://doi.org/10.1002/wat2.1404.

42. Aerts, J.C.J.H. (2018). A Review of Cost Estimates for Flood Adaptation. Water *10*, 1646. https://doi.org/10.3390/w10111646.

43. Lai, X., Wen, J., Shan, X., Shen, L., Wan, C., Shao, L., Wu, Y., Chen, B., and Li, W. (2023). Cost-benefit analysis of local knowledge-based flood adaptation measures: A case study of Datian community in Zhejiang Province, China. International Journal of Disaster Risk Reduction *87*, 103573. https://doi.org/10.1016/j.ijdrr.2023.103573.

44. BAFU [Bundesamt für Umwelt] (2016). Umgang mit Naturgefahren in der Schweiz.

45. Martius, O., Viviroli, D., Rössler, O., Zischg, A., Röthlisberger, V., Aemisegger, F., Schulte, L., Stuber, M., Pena, J.C., Ruiz-Villanueva, V., et al. (2020). Understanding flood triggering mechanisms and flood risk changes (ETH Zurich) https://doi.org/10.3929/ETHZ-B-000462775.

46. BAFU [Bundesamt für Umwelt] (1999). Risikoanalyse bei gravitativen Naturgefahren. https://www.bafu.admin.ch/bafu/de/home/themen/thema-naturgefahren/naturgefahren--publikationen/publikationen-naturgefahren/risikoanalyse-bei-gravitativen-naturgefahren.html.

47. Borter, P. (1999). Risikoanalyse bei gravitativen Naturgefahren. Methode. (Bundesamt für Umwelt, Wald und Landschaft (BUWAL)).

48. BWW [Bundesamt für Wasserwirtschaft], BRP [Bundesamt für Raumplanung], and BUWAL [Bundesamt für Umwelt, Wald und Landschaft] (1997). Berücksichtigung der Hochwassergefahren bei raumwirksamen Tätigkeiten.

49. Röthlisberger, V., Zischg, A., and Keiler, M. (2016). Spatiotemporal aspects of flood exposure in Switzerland. E3S Web Conf. *7*, 08008. https://doi.org/10.1051/e3sconf/20160708008.

50. BAFU [Bundesamt für Umwelt] (2016). Gefahrenkarten, Intensitätskarten und Gefahrenhinweiskarten.

51. Zischg, A.P., Hofer, P., Mosimann, M., Röthlisberger, V., Ramirez, J.A., Keiler, M., and Weingartner, R. (2018). Flood risk (d)evolution: Disentangling key drivers of flood risk change with a retro-model experiment. Science of The Total Environment *639*, 195–207. https://doi.org/10.1016/j.scitotenv.2018.05.056.

52. Swisstopo [Bundesamt für Landestopografie] (2024). Landeskarte (grau).

53. Mosimann, M., Kauzlaric, M., Schick, S., Martius, O., and Zischg, A.P. (2024). Evaluation of surrogate flood models for the use in impact-based flood warning systems at national scale. Environmental Modelling & Software *173*, 105936. https://doi.org/10.1016/j.envsoft.2023.105936.

54. Serinaldi, F., and Grimaldi, S. (2011). Synthetic Design Hydrographs Based on Distribution Functions with Finite Support. J. Hydrol. Eng. *16*, 434–446. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000339.

55. BAFU [Bundesamt für Umwelt] (2024). Stations and data. https://www.hydrodaten.admin.ch/en/stations-and-data.html.

56. Scherrer, S. (2018). Verzeichnis grosser Hochwasserabflüsse in Schweizerischen Einzugsgebieten. Auswertung und graphische Aufbereitung. (Scherrer AG).

57. Vetsch, D., Siviglia, A., Caponi, F., Ehrbar, D., Gerke, E., and Kammerer, S. (2018). BASEMENT - Basic Simulation Environment for Computation of Environmental Flow and Natural Hazard Simulation. Version 2.8 (ETH Zürich, VAW).

58. Swisstopo [Bundesamt für Landestopografie] (2024). Das Topografische Landschaftsmodell (TLM). Wissen. https://www.swisstopo.admin.ch/de/informationen-topografisches-landschaftsmodell.

59. Röthlisberger, V., Zischg, A.P., and Keiler, M. (2017). Identifying spatial clusters of flood exposure to support decision making in risk management. Science of The Total Environment *598*, 593–603. https://doi.org/10.1016/j.scitotenv.2017.03.216.

60. Bermúdez, M., and Zischg, A.P. (2018). Sensitivity of flood loss estimates to building representation and flow depth attribution methods in micro-scale flood modelling. Nat Hazards *92*, 1633–1648. https://doi.org/10.1007/s11069-018-3270-7.

61. Röthlisberger, V., Zischg, A.P., and Keiler, M. (2018). A comparison of building value models for flood risk analysis. Nat. Hazards Earth Syst. Sci. *18*, 2431–2453. https://doi.org/10.5194/nhess-18-2431-2018.

62. Zischg, A., Schober, S., Sereinig, N., Rauter, M., Seymann, C., Goldschmidt, F., Bäk, R., and Schleicher, E. (2013). Monitoring the temporal development of natural hazard risks as a basis indicator for climate change adaptation. Nat Hazards *67*, 1045–1058. https://doi.org/10.1007/s11069-011-9927-0.

63. Zischg, A.P., Felder, G., Weingartner, R., Quinn, N., Coxon, G., Neal, J., Freer, J., and Bates, P. (2018). Effects of variability in probable maximum precipitation patterns on flood losses. Hydrol. Earth Syst. Sci. *22*, 2759–2773. https://doi.org/10.5194/hess-22-2759-2018.

64. Elmer, F., Hoymann, J., Düthmann, D., Vorogushyn, S., and Kreibich, H. (2012). Drivers of flood risk change in residential areas. Nat. Hazards Earth Syst. Sci. *12*, 1641–1657. https://doi.org/10.5194/nhess-12-1641-2012.

65. Dillenardt, L., Hudson, P., and Thieken, A.H. (2022). Urban pluvial flood adaptation: Results of a household survey across four German municipalities. J Flood Risk Management *15*, e12748. https://doi.org/10.1111/jfr3.12748.

66. Swisstopo [Bundesamt für Landestopografie] (2024). swissALTI3D (DEM). https://wms.geo.admin.ch/ https://wms.geo.admin.ch/.

67. Barendrecht, M.H., Sairam, N., Cumiskey, L., Metin, A.D., Holz, F., Priest, S.J., and Kreibich, H. (2020). Needed: A systems approach to improve flood risk mitigation through private precautionary measures. Water Security *11*, 100080. https://doi.org/10.1016/j.wasec.2020.100080.

68. Thieken, A.H., Cammerer, H., Dobler, C., Lammel, J., and Schöberl, F. (2016). Estimating changes in flood risks and benefits of non-structural adaptation strategies - a case study from Tyrol, Austria. Mitig Adapt Strateg Glob Change *21*, 343–376. https://doi.org/10.1007/s11027-014-9602-3.

69. Knighton, J., Buchanan, B., Guzman, C., Elliott, R., White, E., and Rahm, B. (2020). Predicting flood insurance claims with hydrologic and socioeconomic demographics via machine learning: Exploring the roles of topography, minority populations, and political dissimilarity. Journal of Environmental Management *272*, 111051. https://doi.org/10.1016/j.jenvman.2020.111051.

5 Synthesis

Floods are the most frequently occurring natural hazard worldwide, with an expanding impact on global societies. Dynamics related to climate change, land use change, human intervention, and socio-economic development lead to changes in hazard, exposure, vulnerability, and risk, requiring adaptive management strategies to ensure long-term safety. One strategy to enable adaptive flood risk management is the systematically monitoring of flood risk evolution. However, monitoring strategies are missing in current scientific literature, risk management strategies and their practical application.

This thesis significantly contributes to the development and enhancement of monitoring systems for adaptive flood risk management by reviewing the state of the art in flood risk evolution studies, elaborating and proofing a monitoring concept on a national scale and exploring the integration of dynamic vulnerability into flood risk analysis. The following chapter resumes the key findings of the three papers and contextualizes them within a broader context. After this section, identified limitations and an outlook is given, before the overall conclusion closes the thesis.

5.1 Summary of results and contributions

5.1.1 Review of flood risk evolution studies for the development of flood risk monitoring principles

Flood risk analysis plays a pivotal role in flood risk management, allowing for comprehensive risk assessment and the determination of suitable flood risk management measures. Since flood risk evolves through time, in recent decades, flood risk analysis studies focused increasingly on the analysis of the evolution of flood risk. In order to elaborate a flood risk monitoring system for adaptive flood risk management that guarantees the constant knowledge of flood risk evolution, it is necessary to identify the different approaches of flood risk evolution analyses and incorporate the knowledge into the development of flood risk monitoring principles.

Based on a systematic literature review of peer-reviewed flood risk evolution studies, in total, 111 papers on flood risk evolution were integrated in a content analysis and synthesis to deepen the understanding of flood risk evolution and to distill principles of flood risk monitoring. The studies included in this review showed a wide variety and diversity of approaches with different factors and methods depending on the selected risk conceptualization, research questions, spatiotemporal scale and data availability. Flood risk evolution is analyzed by repeating flood risk analyses periodically or for selected years of interest in the past, present and future. All spatial scales were represented, ranging from very small scale studies to catchment wide and national scale studies. The studies reviewed used comparative (statistical) data-, index-, model-, and scenario-based analysis approaches. The review shows that the analysis of flood risk evolution allows the identification of drivers of change and the system dynamics that lead to an increase or decrease in risk. It also identifies events and management strategies that have had or will have (delayed) effects on the risk system, as well as past developments that may constrain future evolutions (legacy effect). Additionally, predicting future risk through scenarios enables the detection of critical thresholds in risk evolution.

The results of this review allows to draw the main principles of flood risk monitoring, which is essential for detecting the evolution of flood risk and for enabling adaptive flood risk management. The main component of flood risk monitoring is the risk analysis framework (**Figure 2-4**). Within this framework, the methodology for quantifying risk and the selected factors that describe the three risk components hazard, exposure, and vulnerability are determined. Through repeated risk analysis, it is possible to compare risk values over time and detect trends. Following at least two repeated quantitative risk analyses, a risk monitoring reveals an additional dimension in risk analysis.

The study highlights the following key points:

- A one size fits all applicable risk monitoring strategy does not exist.
- Studies analyzing flood risk evolution indicate varying factors, methods and results of flood risk evolution. These studies provide a basis to elaborate principles of flood risk monitoring and to identify the key challenges for the development of flood risk monitoring.
- Risk results from the interactions between the risk components, consequently, risk itself cannot be monitored directly. It requires data and proxy data to analyze the evolving risk components and methods such as data mining, data modeling, data analyses, and data combination.
- The main principles for monitoring flood risk evolution are the repeated flood risk analyses consisting of the systematically measuring of factors influencing hazard, exposure, and vulnerability, modelling the risk components and combining them to quantify risk.
- The detailed monitoring of factors influencing hazard, exposure, and vulnerability allows disentangling changes and implement specific flood risk management measures.

Consequently, this study illustrates the potential use and application of analyzing and monitoring flood risk evolution for adaptive flood risk management. It provides examples of how to establish a risk monitoring system and a basis for the selection of factors and methods to be considered for the design of a risk monitoring approach. A number of challenges have been identified in the context of flood risk monitoring. These challenges include the consideration of data availability, completeness, accuracy, and scaling over time. Furthermore, uncertainties emerge when analyzing risk evolution based on scenarios.

5.1.2 Evaluation of a national flood risk monitoring concept

The Sendai Framework for Disaster Risk Reduction[1] and the EU Floods Directive[2] provides concrete actions and planning steps for flood risk management. Despite the explicit mentioning of monitoring flood risk[1] and updating the flood risk assessment in regular time steps[2], monitoring tools aiming to monitor flood risk evolution including the evolution of hazard, exposure, and vulnerability are still missing. In Switzerland, there is also a lack of approaches for the systematic detection and monitoring of risk evolution. As discussed in the previous section, studies analyzing flood risk evolution serve as a basis for elaborating principles of flood risk monitoring. In accordance with the established principles of flood risk monitoring, a novel concept for monitoring flood risk in Switzerland was developed and evaluated. Data streams for hazard (hazard maps), exposure (number of buildings in hazard-prone areas), and vulnerability (degree of potential damage) were collected and analyzed. The evolution of flood risk was quantified in terms of potential damage to buildings.

The findings indicate that flood risk in Switzerland is undergoing different annual evolutions in various administrative units. Between 2014 and 2023, the total flood risk in all three hazard zones (low, medium, high) in Switzerland increased by 26%, the hazard area increased by 32% and the exposure by 35%. The total flood risk in the canton of Bern increased by 1%, the hazard area increased by 18% and the exposure increased by 8%. Analyzing flood risk evolution in the municipality of Burgdorf shows that the total flood risk decreased by 3%, the hazard area decreased by 3% and the exposure increased by 4%. Beside the differences in flood risk evolution on different administrative units, the trend curves show varying shapes with varying percentage changes from one to another year depending on the risk components and analyzed hazard zones.

Furthermore, the results show spatial variability of the flood risk evolution in Switzerland. The finer resolution at the municipal scale enabled the mapping and identification of spatial variations. Despite the observed increase in flood risk, hazard, and exposure at the aggregated scale of Switzerland, the risk evolution at municipal scale reveals municipalities with declining risk. On average, 26% of the municipalities indicate a decrease in hazard, 13% of the municipalities indicate a decrease in exposure, and 21% a decrease in potential damage.

Finally, this study observed municipalities that have undergone contrasting evolutions in hazard, exposure, and potential damage. As an example, 317 out of 2'152 municipalities indicate a 0-25% increase in hazard and exposure in the low hazard zone between 2014 and 2023. However, 231 municipalities show a contrastive evolution with a 0-25% decrease in hazard and 0-25% increase in exposure.

The study highlights the following key points:

- The selection of data and methods for the flood risk monitoring concept enabled to quantify the annual flood risk on national, cantonal, and municipal scale. Moreover, results showed that the monitoring of single risk factors leads to the monitoring of risk evolution. Thus, the monitoring concept could be confirmed in this study.
- The monitoring concept allows to detect low- and high-increase areas at high spatial resolution. This is an important basis for decision-making in adaptive flood risk management.
- The proof of concept highlights the main challenges in analyzing flood risk evolution, as previously outlined in section 5.1.1. These challenges include data availability, data completeness, data accuracy, and scaling over time.

Consequently, this study highlights that the monitoring of flood risk evolution allows for the detection, quantification and contextualization of the varying annual and spatial evolution of flood risk and its components. The storage and comparison of data supports adaptive flood risk management by enabling a consistent understanding of "how risk evolves", thereby facilitating informed decision-making in risk management. Furthermore, it is possible to quantify the positive effects of flood protection measures and the benefits of public funds that have been invested. However, limitations exist and will be further discussed in section 5.2.

5.1.3 Consideration of vulnerability mitigation in flood risk analysis to improve flood risk monitoring

Flood risk analysis requires the quantitative knowledge about factors describing the three risk components hazard, exposure, and vulnerability. However, as discussed in the first study of this thesis, the inclusion of all risk components in flood risk analyses are scarce and the most neglected component is vulnerability. As we integrated vulnerability as well as constant variable in the second study of this thesis, in the third study, we aimed to prove the consequences of considering varying vulnerability due to property-level flood risk adaptation measures (PLFRA) in flood risk analysis and the implications for flood risk monitoring. In this empirical study, we used simulated floods to calculate the flood hazard, a comprehensive building dataset for the exposure analysis, and object-specific vulnerability data for the vulnerability analysis. The expected annual damage (EAD) is calculated as indicator of flood risk.

The results of the study indicate that 202 buildings out of 1'243 buildings (16%) are protected by PLFRA measures, reducing the EAD from 59'749 CHF/yr to 49'155 CHF/yr (-18%). A further 213 buildings (17%) had a level of flood protection due to micro-structures of the terrain that could not explicitly be attributed to PLFRA measures but was still considered effective. With these additional protected buildings, the EAD is reduced from 59'749 CHF/yr to 46'248 CHF/yr (-23%). Additionally, we included a future-oriented-counterfactual scenario in which all buildings have a protection level of 0.5m. The results of this scenario revealed a 50% decrease of EAD (i.e. around -30'000 CHF/yr).

The main findings of this study are:

- Neglecting the implementation of PLFRA measures on object-specific level leads to an overestimation of flood risk.
- Given that PLFRA measures are complementary measures for flood risk mitigation in flood risk management and their implementation is expected to evolve in the future, their integration into the design of flood risk monitoring approaches is essential.

5.2 Limitations and outlook

The work presented in the previous chapters establishes a foundation for the development of monitoring systems that enable adaptive flood risk management. However, as demonstrated by the research, the monitoring concept remains in its nascent stages and requires further investigation. This section summarizes the limitations encountered in chapters 2 to 4 and suggests ideas for advancing the concept of risk monitoring.

Flood risk evolution studies and flood risk monitoring principles

The initial step in establishing a scientific basis for risk monitoring in adaptive flood risk management was a systematic review of studies on flood risk evolution. One limitation of this study concerns the choice of methodology. We selected the literature systematically following a defined review design and process[3] (**Figure 2-1**). To select appropriate literature, we applied a search string that was elaborated and tested iteratively. This method enhance transparency and reproducibility within the review process. However, it is important to note that the selection process and the heterogeneity in terminology usage may result in the exclusion of literature that could offer significant insights into the evolution of flood risk and the development of a monitoring concept. The evaluation of studies selected on the basis of specific criteria, consistent with the objectives of a monitoring concept that have been previously defined, would certainly contribute to the additional identification of components for developing flood risk monitoring concepts.

A further limitation is the considerable heterogeneity in the definition and conceptualization of the terms risk, hazard, exposure, and vulnerability, as well as approaches used to evaluate flood risk evolution. The findings of the review indicated that 65% of the studies lacked a clear definition of risk. This inconsistency hampers comparability between different studies, the assignment of factors analyzed to evaluate the evolution of risk components and how they can be implemented in a risk monitoring concept. Further, only 36% of the studies included all three risk components in their analysis. However, the consideration of potential drivers of changes in all risk components is needed due to their (outweighing) effects on flood risk.[4] Thus, further research is needed in holistic flood risk evolution analyses, including dynamics in hazard, exposure, and vulnerability to enhance the understanding of flood risk drivers and implement this knowledge into the elaboration of flood risk monitoring concepts. For enhancing flood risk monitoring, the focus of these studies should be on data mining, validation, warranty of consistency and modeling frameworks. As discussed already in previous literature (e.g. Fuchs et al.[5] and Merz et al.[6]) considering spatiotemporal dynamics and developing new approaches for flood risk management are needed to adapt to a changing world.

In general, it would be worthwhile to further develop and focus on the systemic understanding of flood risks from a complex systems perspective.[7–10] The focus on complex systems would allow for the analysis of non-linearity, interaction between and co-evolution in risk components, and feedback mechanisms to support decision-making in flood risk monitoring and adaptive risk management. For example, conceptual system models, in the form of causal loop diagrams, can help identify key variables, interactions and feedbacks in a defined system.[11] The additional information on interactions and feedbacks could be incorporated in the analysis of possible delayed or legacy effects of single variables to anticipate future developments in flood risk for adaptive management measures.

Flood risk monitoring on national scale

The monitoring of flood risk evolution over a ten-year period on a national scale necessitates a substantial dataset to calculate dynamics in hazard, exposure, vulnerability, and risk. In Switzerland, hazard maps are produced at the municipal level to investigate hazard-prone areas. The Topographic Landscape Model of the Federal Office of Topography provides polygons delineating the precise location of all building footprints. The vulnerability of buildings for each hazard zone in Switzerland was calculated by Bernet et al.[12] and Zischg[13] based on flood loss claims and the overlay from known vulnerabilities with a hazard map. Based on this datasets, the flood risk was quantified in terms of potential damage to buildings. Finally, the storage of the hazard and exposure data over a ten-year period and calculation of flood risk for each year allowed to monitor flood risk evolution in Switzerland.

A key limitation of this study lies in the quantification of risk due to the limitation of the available data for hazard analysis. As the hazard maps of Switzerland provide mixed intensity and probability classes (see Appendix A, S.13), detailed information about the probability of a loss in a certain period is not available for the calculation of expected annual damage.

The calculation of expected annual damage would give an additional, valuable information for decision-making in adaptive flood risk management and calculating the cost-benefits of (implemented) flood risk management measures. Thus, further improvements for the flood risk monitoring could be to make flood simulations for detailed risk evolution analysis.

Additionally, as described by Klijn et al.[14], where monitoring of variables cannot provide sufficient information in a timely manner, e.g. in the case of climate signals, ex-ante assessments and anticipatory planning can provide further support for adaptive flood risk management. Beside the limitations in risk analysis due to missing hazard information, the quantification of risk evolution is only partly fulfilled due to the constant building values and vulnerability. Further improvements for the flood risk monitoring could be to analyze the evolution of exposed building values (e.g. Elmer et al.[15]) and analyze and include dynamic vulnerability to create a flood risk monitoring concept. It is important to create knowledge with case studies and learn from these case studies for setting up a robust data model and methodology for flood risk monitoring.

A secondary limitation pertains to the completeness and accuracy of the data that was utilized. For instance, in 2014, 562 out of 2'152 (26%) municipalities had no hazard map. Consequently, the hazard evolution could not be detected for the entire period of the study in these municipalities. When establishing a risk monitoring system on an operational basis, it is imperative to ensure the availability of data over a long period of time. Furthermore, the implementation of novel regulations or improvements in hazard mapping techniques has the potential to hamper the consistency of the data. The uncertainty arising from adapted approaches has been previously addressed by Priest et al.[16] and Rauter et al.[17] Further efforts are needed at national level to harmonize the methodology to allow the monitoring of risk evolution. A similar effect was detected when analyzing the building dataset of the Federal Office of Topography. The development of the data set is not entirely consistent over time and had to be pre-adjusted before it could be used for the risk analysis. Consequently, the implementation of a flood risk monitoring system for adaptive flood risk management at the national level necessitates further enhancements in risk government, such as stakeholder engagement to facilitate an exchange between data collectors, data providers and data users.

Vulnerability

The analysis of the implementation level of property-level flood risk adaptation (PLFRA) measures, and damage-reducing effects on the flood risk assessment, requires object-specific knowledge and data. In the empirical study conducted in Burgdorf (CH), data was collected through a field survey. During the field survey, we encountered a number of difficulties, which resulted in limitations and uncertainties with regard to the study. The decision to conduct the fieldwork from the street, without contacting the homeowners, resulted in a key limitation, primarily due to reduced visibility and restricted access to the buildings. This impeded the assessment of the implementation of PLFRA measures on the buildings, including whether these measures were specifically implemented for flood protection or for other reasons, such as aesthetic enhancement. Furthermore, the study is constrained to dry-proof PLFRA measures that are visible from the streets along the buildings. Consequently, the analysis may, to a certain extent underestimate the effects of the PLFRA measures on flood risk reduction. To analyze the full range of possible PLFRA measures, further research is recommended, including discussions with homeowners (e.g. Sairam et al.[18] and Dillenardt et al.[19]), input from the population and/or architects and experts. This would improve the accuracy of the data.

A second limitation of the study is the method used to calculate the impact of PLFRA measures on flood risk. The degree of damage was assumed to be zero if the maximum flow depth was less than the level of protection provided by the PLFRA measures implemented. Thus, we assumed that PLFRA measures fully protect buildings. However, it should be noted that previous studies (see e.g., Attems et al.[20], Holub et al.[21]) have demonstrated that the implementation of PLFRA measures does not guarantee 100% effective risk reduction. It is recommended that future research studies extend the analyses by integrating an additional attribute of the effectiveness of PLFRA measures.

The results support the notion that changes in vulnerability resulting from PLFRA measures must be incorporated into flood risk monitoring approaches. Nevertheless, the study also demonstrated that the analysis of individual buildings is time-consuming and that there are limitations in the assessment of PLFRA measures. If a monitoring system is to be set up for larger regions or at the national level, it will no longer be feasible to undertake object-specific assessment. Consequently, it is recommended that future research studies focus on methods to detect PLFRA measures in a faster way.

One such approach involves the analysis of lateral aerial photographs through machine learning methods, which has the potential to offer novel solutions for the detection of PLFRA measures.[22] Furthermore, in order to analyze the effect of PLFRA measures on flood risk, it is necessary to assign flow depths on building levels. This necessitates the acquisition of substantial data. Consequently, risk governance should consider the need to collect data on PLFRA measures and floods in order to integrate the spatiotemporal evolution of all risk components into a flood risk monitoring concept for adaptive flood risk management.

Here, it is important to state that PLFRA measures are only one factor having an effect on the physical vulnerability mitigation. Other factors such as building type and age have as well an effect on the physical vulnerability. It is recommended to consider additional factors that have an effect on the physical vulnerability when setting up a flood risk monitoring concept. Additionally, research studies analyzing the high dynamic and complexity in vulnerability evolution offer significant knowledge to set up a reliable flood risk monitoring concept.[23,24]

5.3 Concluding remarks

By reviewing flood risk evolution studies, this dissertation elucidated that a deeper understanding of flood risk evolution is a foundation for developing robust risk monitoring concepts. Our findings suggest that a detailed, iterative analysis helps to identify key drivers of risk change, thereby supporting the selection of appropriate factors and methodologies for analyzing flood risk evolution and/ or establishing a risk monitoring concept (Chapter 2).

Based on the flood risk monitoring principles developed in the first study, I have developed a new flood risk monitoring concept for Switzerland and evaluated this concept through a retrospective application. This study demonstrates the effectiveness of a national monitoring concept that provides valuable insights into flood risk evolution when based on robust data management and comparison over time. The monitoring of flood risk evolution enables the quantification of low and high areas of increase or decrease at high spatial resolution. Furthermore, the monitoring of flood risk provides evidence and quantifiable data regarding the efficacy of implemented flood mitigation measures. This underscores the value of public funds invested in the region. By contextualizing risk changes and identifying their drivers, such systems support informed decision-making in adaptive flood risk management. Consequently, effective risk governance should provide a framework for the systematic updating and storage of data over time, thereby facilitating comparisons across multiple years (Chapter 3).

In order to further improve our understanding of the implementation of property-level flood risk adaptation (PLFRA) measures, a field survey was conducted to collect data on PLFRA measures. In order to analyze the effect of PLFRA measures on risk quantification, a method for incorporating PLFRA measures into the flood risk analysis was developed and an analysis of their damage-reducing effects was carried out. The study indicates that neglecting object-specific vulnerability leads to an overestimation of flood risk. The integration of PLFRA measures into the risk analysis demonstrates a risk reduction of 18-23% in Burgdorf (CH). The findings of the second study indicate a 26% increase in risk over the past decade in Switzerland. Consequently, if the implementation and efficacy of PLFRA measures in Burgdorf can be extrapolated to Switzerland, the implementation of PLFRA measures and their consideration in flood risk analysis could offset the risk increase over the last ten years. Therefore, PLFRA measures can be regarded as effective tools for maintaining risk levels in a warmer climate, thereby substantiating their suitability as climate adaptation measures. The study emphasizes the necessity of incorporating the spatiotemporal evolution of all risk components (hazard, exposure, vulnerability) in monitoring systems for adaptive flood risk management approaches (Chapter 4).

Overall, by reviewing the state of the art in flood risk evolution studies, elaborating and proofing a monitoring concept on a national scale and exploring the integration of dynamic vulnerability into flood risk analysis, this thesis makes a significant contribution to our understanding of flood risk monitoring for the purpose of adaptive flood risk management. Flood risk monitoring is a multifaceted task that requires a deep understanding and extensive knowledge of the evolution of flood risk. A primary challenge confronting practitioners is the identification of the factors and methods to be integrated within the monitoring concept, given that the scope of the monitoring concept determines its capacity for monitoring flood risk evolution. Conversely, the practical application of monitoring concepts through studies that develop and validate these concepts can enhance our comprehension of risk evolution and provide targeted information on constantly available data over extended periods. Consequently, a dualistic approach, integrating both top-down and bottom-up methodologies, is required in the development of monitoring systems for the purpose of adaptive flood risk management.

References

1. UNDRR [United Nations Office for Disaster Risk Reduction] (2015). Sendai Framework for Disaster Risk Reduction 2015-2030.

2. European Commission (2007). Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks (Text with EEA relevance).

3. Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., and The PRISMA Group (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLoS Med *6*, e1000097. https://doi.org/10.1371/journal.pmed.1000097.

4. Metin, A.D., Dung, N.V., Schroeter, K., Guse, B., Apel, H., Kreibich, H., Vorogushyn, S., and Merz, B. (2018). How do changes along the risk chain affect flood risk? NATURAL HAZARDS AND EARTH SYSTEM SCIENCES *18*, 3089–3108. https://doi.org/10.5194/nhess-18-3089-2018.

5. Fuchs, S., Keiler, M., Sokratov, S., and Shnyparkov, A. (2013). Spatiotemporal dynamics: the need for an innovative approach in mountain hazard risk management. Nat Hazards *68*, 1217–1241. https://doi.org/10.1007/s11069-012-0508-7.

6. Merz, B., Hall, J., Disse, M., and Schumann, A. (2010). Fluvial flood risk management in a changing world. Nat. Hazards Earth Syst. Sci. *10*, 509–527. https://doi.org/10.5194/nhess-10-509-2010.

7. Hochrainer-Stigler, S. (2020). Extreme and Systemic Risk Analysis: A Loss Distribution Approach (Springer Singapore) https://doi.org/10.1007/978-981-15-2689-3.

8. Renn, O. (2021). New challenges for risk analysis: systemic risks. Journal of Risk Research *24*, 127–133. https://doi.org/10.1080/13669877.2020.1779787.

9. Renn, O., Laubichler, M., Lucas, K., Kröger, W., Schanze, J., Scholz, R.W., and Schweizer, P. (2022). Systemic Risks from Different Perspectives. Risk Analysis *42*, 1902–1920. https://doi.org/10.1111/risa.13657.

10. Schanze, J., and Maleska, V. (2019). Towards a more systemic understanding of flood risks. J Flood Risk Management *12*. https://doi.org/10.1111/jfr3.12569.

11. Hossain, M.S., Ramirez, J.A., Haisch, T., Speranza, C.I., Martius, O., Mayer, H., and Keiler, M. (2020). A coupled human and landscape conceptual model of risk and resilience in Swiss Alpine communities. Science of The Total Environment *730*, 138322. https://doi.org/10.1016/j.scitotenv.2020.138322.

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

13. Zischg, A. (2023). Flood risk change: a complexity perspective (Elsevier).

14. Klijn, F., Kreibich, H., de Moel, H., and Penning-Rowsell, E. (2015). Adaptive flood risk management planning based on a comprehensive flood risk conceptualisation. Mitig Adapt Strateg Glob Change *20*, 845–864. https://doi.org/10.1007/s11027-015-9638-z.

15. Elmer, F., Hoymann, J., Düthmann, D., Vorogushyn, S., and Kreibich, H. (2012). Drivers of flood risk change in residential areas. Nat. Hazards Earth Syst. Sci. *12*, 1641–1657. https://doi.org/10.5194/nhess-12-1641-2012.

16. Priest, S.J., Suykens, C., Van Rijswick, H.F.M.W., Schellenberger, T., Goytia, S., Kundzewicz, Z.W., van Doorn-Hoekveld, W.J., Beyers, J.-C., and Homewood, S. (2016). The European Union approach to flood risk management and improving societal resilience: lessons from the implementation of the Floods

Directive in six European countries. ECOLOGY AND SOCIETY *21*. https://doi.org/10.5751/ES-08913-210450.

17. Rauter, M., Thaler, T., Attems, M.-S., and Fuchs, S. (2019). Obligation or Innovation: Can the EU Floods Directive Be Seen as a Tipping Point Towards More Resilient Flood Risk Management? A Case Study from Vorarlberg, Austria. Sustainability *11*, 5505. https://doi.org/10.3390/su11195505.

18. Sairam, N., Schröter, K., Lüdtke, S., Merz, B., and Kreibich, H. (2019). Quantifying Flood Vulnerability Reduction via Private Precaution. Earth's Future *7*, 235–249. https://doi.org/10.1029/2018EF000994.

19. Dillenardt, L., Hudson, P., and Thieken, A.H. (2022). Urban pluvial flood adaptation: Results of a household survey across four German municipalities. J Flood Risk Management *15*, e12748. https://doi.org/10.1111/jfr3.12748.

20. Attems, M., Thaler, T., Genovese, E., and Fuchs, S. (2020). Implementation of property-level flood risk adaptation (PLFRA) measures: Choices and decisions. WIREs Water *7*, e1404. https://doi.org/10.1002/wat2.1404.

21. Holub, M., Suda, J., and Fuchs, S. (2012). Mountain hazards: reducing vulnerability by adapted building design. Environ Earth Sci *66*, 1853–1870. https://doi.org/10.1007/s12665-011-1410-4.

22. Knighton, J., Buchanan, B., Guzman, C., Elliott, R., White, E., and Rahm, B. (2020). Predicting flood insurance claims with hydrologic and socioeconomic demographics via machine learning: Exploring the roles of topography, minority populations, and political dissimilarity. Journal of Environmental Management *272*, 111051. https://doi.org/10.1016/j.jenvman.2020.111051.

23. de Ruiter, M.C., and van Loon, A.F. (2022). The challenges of dynamic vulnerability and how to assess it. iScience *25*, 104720. https://doi.org/10.1016/j.isci.2022.104720.

24. Naylor, A., Ford, J., Pearce, T., and Van Alstine, J. (2020). Conceptualizing Climate Vulnerability in Complex Adaptive Systems. One Earth *2*, 444–454. https://doi.org/10.1016/j.oneear.2020.04.011.

Acknowledgements

Venturing into uncharted territory is always an adventurous journey. It is with deep gratitude that I look back on four exciting and educational years. I would like to express my sincere thanks to all those who supported and motivated me during the PhD journey.

First of all, I would like to thank Margreth Keiler and Andreas Zischg for their competent supervision of my PhD, many (crazy) ideas and valuable support during this time. Thank you for the numerous discussions and insightful feedback. Even when there were challenging moments with a brain full of color, I always found an open ear and helpful words. I am very impressed with the way you share your knowledge and enthusiasm for the field. I am very grateful that I have been able to benefit from this over the past few years and let myself be infected. I will always try to work with at least as much enthusiasm for the subject.

I would also like to thank the Oeschger Centre for Climate Change Research and the Mobiliar Insurance Company. The Mobiliar Lab for Natural Risks is a joint research initiative and provides the opportunity to write a dissertation that bridges the gap between science and practice.

Special thanks also go to the team members of the Mobiliar Lab, especially my office colleagues Lukas and Markus. We had many discussions during this time, be it about technical issues or other concerns and challenges. I would also like to thank the hydrology and geomorphology groups for valuable and interesting discussions, inputs, coffee and lunch breaks. Additionally, I would like to thank the coupled human-landscape systems group at the University of Innsbruck for the warm welcome and discussions online and in person.

Last but not least, I would like to thank my family and friends who have supported and motivated me in various ways. My special thanks go to my parents and my partner. Your endless love and support has given me strength, courage and endurance.

Erklärung

gemäss Art. 18 PromR Phil.-nat. 2019

Name/Vorname:

Matrikelnummer:

Studiengang:

Bachelor ☐ Master ☐ Dissertation ☐

Titel der Arbeit:

LeiterIn der Arbeit:

Ich erkläre hiermit, dass ich diese Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen benutzt habe. Alle Stellen, die wörtlich oder sinngemäss aus Quellen entnommen wurden, habe ich als solche gekennzeichnet. Mir ist bekannt, dass andernfalls der Senat gemäss Artikel 36 Absatz 1 Buchstabe r des Gesetzes über die Universität vom 5. September 1996 und Artikel 69 des Universitätsstatuts vom 7. Juni 2011 zum Entzug des Doktortitels berechtigt ist. Für die Zwecke der Begutachtung und der Überprüfung der Einhaltung der Selbständigkeitserklärung bzw. der Reglemente betreffend Plagiate erteile ich der Universität Bern das Recht, die dazu erforderlichen Personendaten zu bearbeiten und Nutzungshandlungen vorzunehmen, insbesondere die Doktorarbeit zu vervielfältigen und dauerhaft in einer Datenbank zu speichern sowie diese zur Überprüfung von Arbeiten Dritter zu verwenden oder hierzu zur Verfügung zu stellen.

Ort/Datum

Unterschrift