ENVIRONMENTAL RESEARCH
LETTERS

PERSPECTIVE • OPEN ACCESS

# Multiform flood risk in a rapidly changing world: what we do not do, what we should and why it matters

To cite this article: Andrew Kruczkiewicz *et al* 2022 *Environ. Res. Lett.* **17** 081001

ENVIRONMENTAL RESEARCH
LETTERS

CrossMark

OPEN ACCESS

RECEIVED
15 November 2021

REVISED
28 June 2022

ACCEPTED FOR PUBLICATION
6 July 2022

PUBLISHED
25 July 2022



PERSPECTIVE

# Multiform flood risk in a rapidly changing world: what we do not do, what we should and why it matters

Andrew Kruczkiewicz[1,2,3,*], Fabio Cian[4], Irene Monasterolo[5], Giuliano Di Baldassarre[6], Astrid Caldas[7], Moriah Royz[8], Margaret Glasscoe[10], Nicola Ranger[11] and Maarten van Aalst[1,2,3,9]

1 Faculty of Geo-information Science and Earth Observation, University of Twente , Enschede, The Netherlands
2 Columbia University, New York, United States of America
3 Red Cross Red Crescent Climate Centre, The Hague, The Netherlands
4 The World Bank Group , Washington, DC, United States of America
5 EDHEC-Risk Climate Impact Institute, EDHEC Business School, Nice, France
6 Google, Uppsala University, Uppsala, Sweden
7 Union of Concerned Scientists, NASA Marshall Space Flight Centeri, Cambridge, MA, United States of America
8 Google, Mountain View, CA, United States of America
9 University of Twente and Red Cross Red Crescent Climate Centre
10 University of Alabama in Huntsville, Huntsville, Alabama, United States of America
11 University of Oxford, Oxford, United Kingdom
* Author to whom any correspondence should be addressed.

E-mail: andrewk@iri.columbia.edu

Keywords: disaster risk, floods, climate policy, climate change, extreme events, flash floods, compound events

## 1. Introduction

On a global scale, recent environmental, public health, socioeconomic and political events have illuminated the interdependent nature of climate-related hazards. These types of interconnected events have been categorized in various ways, with the terms 'compound weather event', 'compound climate event' or simply 'compound event' now widely accepted [1]. With the increased acknowledgement of treating specific types of compound events as unique phenomena, both from hazard and impact perspectives, awareness of the need for type-specific development for each integrated risk assessment, anticipatory financial mechanisms and enhanced governance for disaster preparedness, anticipatory action and response, has followed [2, 3]. However, most of the attention on compound events is focused on primary physical hazard (e.g. heat waves) either colliding; (a) With a different primary physical hazard (e.g. volcanic eruptions, wildfires) or (b) With specific socioeconomic situations (e.g. armed conflicts, public health crises). This has left gaps in understanding the variety and complexity of compound event scenarios that are both occurring in the current climate [4], as well as those that are poised to increase and evolve due to unmitigated climate change [4–7], as highlighted within the IPCC AR6 and throughout the UNFCCC COP26 [8]. Examples of such types of compound events that demand more detailed attention include multiform flood events, with a specific need to assess risk of multiform floods across certain sectors, such as the financial, disaster management and humanitarian sectors.

We define a multiform flood event as occurring when the hazard and/or impact elements from one flood subtype interacts with another flood subtype or another hazard (figure 1). This includes scenarios where two floods of the same subtype (riverine, for example) occur nearby yet as separate events, but the extent of socioeconomic impact from both flood events reinforce one another.

The specification of flood subtypes is important because of their varying spatiotemporal dynamics, which lead to different kinds of direct and indirect impacts [4, 9]. Differences in direct impacts are likely to propagate across various areas of the macro-economy leading to both high sensitivities in where indirect impacts occur (e.g. non-linearities and spillover effects) and differences in speed of recovery [10]. Accurate characterization of multiform flood events is critical in estimating risk across sectors, in order to appropriately inform policy and practice. Doing so is now urgent as implementation of compound event risk assessment and risk reduction activities increase, and as multiform flood events remain particularly neglected within the disaster management, humanitarian and financial sector contexts.

To fill this gap, we must start by defining the specific types of multiform flood events. Then awareness must be raised of the potential consequences of generalizing 'flood' within the development of new risk

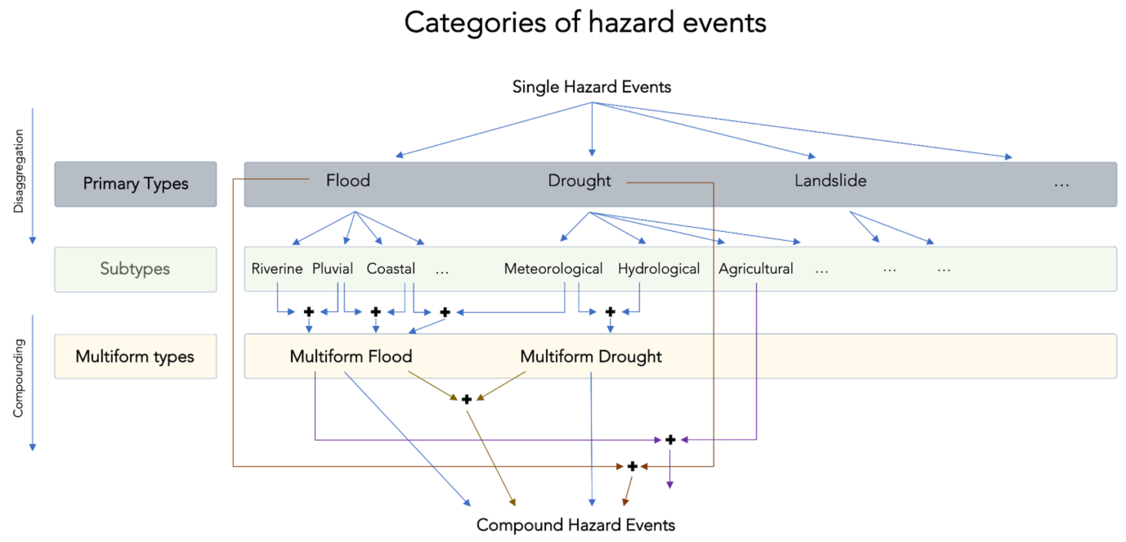


**Figure 1.** A method to categorize hazard events. A single hazard event is categorized as a primary type (e.g. flood or drought), which in turn can be disaggregated in subtypes (e.g. riverine flood or coastal flood). Different hazard events, if occurring within the same spatial and temporal domain, may form a compound event, such as a a flood and a drought, or subtype of those primary types, interacting within a specified area.

assessment frameworks and adaptation strategies, as doing so should be driven by reducing current and future multiform flood risk, in particular for the traditionally underserved and most vulnerable populations. Within the academic literature the definition and investigation of multiform flood events is in the early stages. The majority of work covers riverine and coastal subtypes [4, 11, 12], as well as co-occurrence of the same flood subtype, such as riverine and riverine [13]. While prioritizing these multiform flood types is understandable given their recent and projected impacts on livelihoods and economic activity [14, 15], many other types exist and are yet to be assessed.

In addition, measures aimed at reducing socioeconomic vulnerability to one type of hazard can influence the risk to others, contributing to the urgency for enhanced risk assessment methods for compound events, and particularly for floods, which are one of the most common hazards within compound events [16]. If we continue to fail in understanding multiform flood risk, programs intending to build resilience and reduce suffering can be misinformed.

For example, when Hurricane Florence approached North Carolina in 2018, populations on the Atlantic coast perceived the risk of coastal flood and evacuated inland, only to face risks of different (non-coastal) types of flood, inland riverine and pluvial flooding, which in this case were the flood types that led to significantly higher levels of loss of life and property damage compared to coastal [17].

Relative to multiform floods, gaps exist in each (a) Research on vulnerability and exposure; (b) Risk mitigation and resilience programs; (c) Understanding critical thresholds of intensity and spatiotemporal scales for various types to interact with each other in a meaningful way; and (d) Cascading and indirect impact assessment both local and distant to the occurrence of the event.

Our manuscript further describes these gaps through identifying challenges and potential consequences related to the oversimplification of disaster type representation in risk assessment and adaptation program design, focusing on non- or mis-assignment of flood type. We then present evidence-based transsectoral recommendations to enable joint efforts for more effective anticipatory action, risk reduction and resilience building for mitigating current and future impacts from multiform flood events.

### 1.1. Types of flood and interactions

The term ‘flood’, a ‘primary’ hazard type, includes various subtypes such as coastal, riverine, glacial lake outburst, dam-break and flash flood amongst others, each characterized by different impact profiles in space and time, thus requiring subtype-specific approaches to risk reduction, resilience and adaptation [17–19]. With climate change, the spatial and temporal distribution of flood risk, for all subtypes, continues to evolve. For some types of floods, such as single coastal or riverine events, the dynamics of both the hazard and risk elements are relatively well understood. In such cases, as well as for other single hazards, the range of potential impacts from climate change-driven shifts are also well described [20–22]. However, this is not the case for all flood subtypes, and events where flood subtypes interact with non-flood (including non-climate) hazards (figure 1). In short, understanding multiform flood event dynamics matters, particularly as these events are likely to become more deadly and have a wider reaching and longer lasting impact than single flood events [5].

As flood hazards combine, impact in some contexts is likely to be non-linear [23], creating tension in the systems that have only recently been designed for adaptation, such as those including elements of resilience, early warning and anticipatory action. Assessing social, economic and financial direct and indirect impact of multiform flood events are crucial steps to inform fiscal and financial policies and instruments in more comprehensive and cross-sectoral ways that accurately represent the full spectrum of their potential effects [24]. For example, flooding can be completely or partially positive, such as riverine floods that occur seasonally as expected, at a manageable magnitude. Such flood events can be beneficial to agricultural practices and can promote ecological health within the riparian zone [25, 26]. It is possible to have two flood subtypes interact with each other concurrently, such as a beneficial riverine flood which supports agriculture production, with a devastating flash flood that leads to transportation difficulties and demolition of crop harvest storage facilities.

Cost-benefit and cost-effectiveness analyses must be designed to capture not only the negative aspects, especially when such analyses can be used to inform prioritization (and de-prioritization) of anticipatory actions triggered by shifts in risk of a specific type of multiform event. For example, if expectations exist for a subtype of flood (such as riverine) to occur within a specific season and location, and if sufficient resilience processes are in place, then negative impacts should be few, in which case overall impact could be beneficial or neutral. Nevertheless, if for that same location and season the subtype of flood is atypical and/or unexpected, for example a flash flood driven by out-of-season extreme precipitation, the spatial and temporal distribution of adverse socioeconomic impact could be significantly greater and longer lasting, such as has been described in the context of flood impact as residual risk [27]. The differences in event evolution, including both hazard and impact, must be addressed to ensure the benefits and costs driven by floods are assigned to the correct locations and processes, at the appropriate timescales. This is indeed important for single flood type events, yet it is particularly important for multiform flood events, especially as complexity increases in the future due to socioeconomic and climate change and because the degree of nonlinearity of impacts from interacting multiform floods is largely unknown.

## 2. Rising risk of compound events involving floods

With more intense floods, and many with increasing duration and spatial extent [28], greater attention is needed to assess how compound events, including multiform flood events, have both changed over time and how they may evolve due to climate change [9, 29]. Multiform flood risk could potentially lead to tail risk, amplifying the magnitude and persistence of economic shocks [30], in turn leading to economic losses that negatively affect public financial stability by decreasing fiscal revenues and leading to increases in public debt particularly in conditions of pre-existing high stock of debt and limited or no economic growth. In addition, multiform flood risk could affect the financial stability of individual financial actors and of the financial system as a whole. Negative adjustments in the profitability of firms affected by multiform floods would lead to either an adjustment (downward) of the value of the financial contracts issued by such firms or their ability to repay outstanding loans, which would negatively affect the balance sheet of financial institutions who hold such securities [31].

Clear, actionable strategies to minimize multiform flood impacts have yet to emerge, as most risk assessment frameworks and adaptation programs continue to generalize flood risk. Neglecting multiform flood risk could introduce potentially avoidable levels of uncertainty into already complex systems, and may increase the chance of underestimating risk both locally and in locations geographically distant from an event through indirect ripple effects via interconnected financial systems [32]. Indeed, compound events of any type can lead to a structural change in the economy, and long-term implications cannot be simply deduced by the sum of single risks today, nor from future projections of single risks. When risks compound, they can generate prolonged out-of-equilibrium states of the economy and financial systems. For multiform floods, the understanding of these dynamics is in its infancy.

In recent years, decision makers in various sectors, including urban planning, humanitarian and finance, have been forced to react to types of flood events that have not previously occurred in their area of responsibility [33, 34]. For example, people living in areas that have experienced riverine and coastal floods have made choices to purchase insurance (or not), with those choices at least to some extent driven by their risk perception of those types of flood, only to have an unexpected type (such as a flash flood) cause harm. Policies related to pre-disaster anticipatory action have become prevalent in the humanitarian sector in recent years [35], however protocols for identifying where, when and to what extent early action should be taken before compound disasters, such as multiform flood events, are yet to be developed [3].

As the interconnectivity of impacts from compound events increases over time, there is greater importance for the development of policy responses for risk reduction and resilience to sufficiently capture the range of potential impact not only for long term climate change, but also over other periods of time in the future, such as interannual timescales and specific decades [36, 37]. The current suite of risk assessment tools and methods falls short of what is needed for society to understand and react to compound events. We are now faced with an opportunity to ensure that future efforts more accurately assess compound event risk. We must improve existing approaches before the additive climate change-driven uncertainties, on top of the inherent complexity of compound events, are deemed too significant to overcome. In doing so, we have the responsibility to clearly state what subtypes of floods, and if multiform floods, are excluded and/or captured in risk assessment.

## 3. Improving multiform flood risk assessment and policy development

With climate change, multiform flood events will become a more significant contributor towards the magnitude, geographic specificity, onset, and duration of systemic risk build-up, adding urgency to further analyses of these relationships. Currently, when including flood as a hazard within compound event risk assessments and policy responses, disaggregation by subtype does not always occur. Given the vast diversity of disaster subtypes, in terms of direct and indirect impacts within and across sectors, failure to represent them individually will lead to incomplete assessment of risk. Subsequently, this will promote insufficient preparedness and ineffective policy response, potentially eroding recent gains in sustainable development, climate change adaptation and mitigation strategies. In the financial sector, for instance, steps have been taken to assess investors' exposures to climate risks as financial authorities have developed climate change mitigation scenarios for financial risk assessment, produced by large-scale process-based integrated assessment models (IAM). However, these models currently do not capture multiform flood event risk, and doing so must be normalized. In particular, process-based IAMs used to provide climate mitigation scenarios (e.g. the Network for Greening the Financial System (NGFS) scenarios, based on sectors' output trajectories), do not consider acute physical risk [10]. This is a main limitation to our understanding of the impact of different types of flood risks on the feasibility of the transition trajectories, and the public and private investments needed to build resilience to such risks [38].

While considering the inherent uncertainty, it is important to strengthen the representation of multiform risk scenarios to inform the parameterization of IAMs. Doing so is fundamental to correctly assessing their economic and financial impacts, identifying their entry points in the economy, as well as their direct and indirect impacts [30]. Some families of models allow us to assess non-linearities and persistence of losses, emerging from agents' interactions in the economy and finance [39]. These results, in turn, can be elaborated into stress test models to assess the largest losses for investors conditioned to climate scenarios assessing the resilience of investors' balance sheets, and implications for financial stability.

Generalizing flood type may be perceived as a way to simplify risk assessment and adaptation methods, however some types of 'simplification', such as aggregating event reports of various or unknown flood subtypes into a single category of 'flood', can introduce unintended error through mis-representation (over and under) of risk of a specific subtype. While in certain locations misrepresentation of subtype risk could be low, this is likely to be the case only in areas where there is risk of one, and only one, subtype of flood. However, even in the areas where current climatic and socioeconomic conditions lead to one, and only one, subtype occurring, it is possible that both future flood risk of a different subtype may be present, and other subtypes of floods may have occurred in the past (which could influence the subtype assignment of historical flood records of events labeled only as 'flood') [40].

Concerted efforts should be made to normalize analysis and communication of the costs of generalizing flood subtype, as impacts of doing so already exist. For example, in the computation of flood loss ratios for infrastructure, the relevance of predictors will vary based on flood type [41]. In addition, when exploring economic consequences of floods a lack of subtype specificity can lead to significantly different results especially when the intended spatial unit of analysis is at the local or community level [42]. Lack of disaggregation could promote incorrect prioritization of resources, which can lead to continued disproportionate disaster impact on traditionally underserved populations. As a consequence, the development of disaster risk reduction and humanitarian policy involving floods could be ill-posed and at increased risk of unintended or unperceived consequences [43]. Similarly, in the macroeconomic and financial sectors, the interaction between economic and financial agents with their risk perception and decision making can lead to nonlinearities that amplify an event's direct shock (both locally and across large spatial scales) before, during and after. These too have not yet been quantitatively assessed for most compound event scenarios, including multiform floods [38].

## 4. Recommendations to the research, scientific, and policy making communities: an agenda for taking action on multiform flood risk

New standards for climate risk management in and across sectors must account for climate change-induced spatiotemporal shifts in risks for all types of single and compound event scenarios. To ensure the dynamics are integrated appropriately into risk assessment frameworks and policy development, the magnitude, geographic distribution and temporal

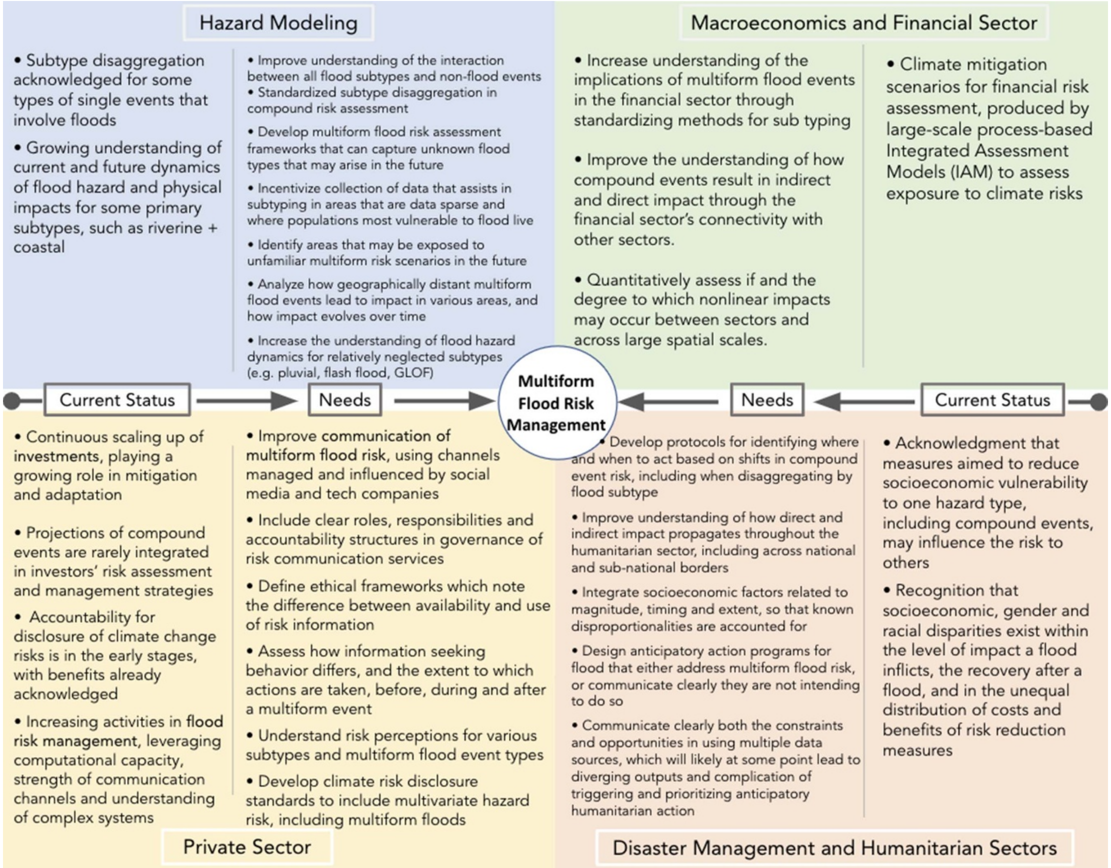


**Figure 2.** Towards multiform flood risk management; a summary of the current status and the needs for four sectors: hazard modelling, macroeconomics and financial sector, disaster management and the humanitarian sectors, and the private sector.

extent of direct and indirect impacts of multiform disaster types, such as multiform floods, must be better understood (figure 2).

The first steps towards more comprehensive risk assessment and risk management that includes multiform floods must first address trans-disciplinary knowledge gaps:

(a) Frequency, extent and intensity of disaster types and subtypes, and potential shifts in risk for single subtype and multiform events to occur, and overlap, in a given geographic area of interest, for given periods of time now and in the future;
(b) Intensity and duration of direct and especially indirect or cascading impacts of types and subtypes of floods on various physical and socioeconomic systems;
(c) The differences in the degree of macroeconomic interconnectedness and complexity related to impacts, which can amplify climate risks via reverberation in financial networks.

To address the above-mentioned knowledge gaps, we propose the following actions:

(a) Improve modeling and characterization of multiform flood risks to better inform new approaches and technologies, especially those that decrease socioeconomic disparities in flood impacts. This should include the integration of local and expert knowledge on flood subtype definition and description of impact [44].
(b) Understand the degree to which outputs of macroeconomic models will differ when using different flood subtypes and their related variables as input parameters. In particular, the duration and spatial coverage of floods, if incorrectly integrated into models, could lead to both over- and underestimation of impact from compound events involving floods.
(c) Address the weaknesses in compound risk assessment related to floods, stressing the need for both systematic approaches to multiform risk assessment, and engagement with various sectors including information technology, media, health, financial and energy, from the early stages of development of multiform risk assessment methods.
(d) Incentivize the disclosure of the type and substype of events that are (and are not) included within risk assessment, hazard modelling and scenario development. Disclosures should also include statements demonstrating the degree to which there is confidence in the accuracy of their

representation. This will ensure expectations are clear in terms of what type of events will be captured, may possibly be captured, and will be excluded in risk models, promoting increased transparency and trust in the models themselves and subsequently in disaster risk reduction and climate risk management strategies.

(e) Leverage Earth observation data to characterize multiform flood risk. Lack of widely acceptable definitions of flood subtype and multiform flood risk presents opportunities for use of data from satellites and other forms of remote sensing. Satellite data can also support response and recovery related to multiform flood events and damage assessment. Progress has been made for use of EO within anticipatory action for floods [45], but consideration has been limited to primary flood types.

(f) Improve the assessment of the economic and financial implications of multiform flood risk, to ensure consideration of the non-linearity of losses, their persistence, and tail risk effects. To this aim, the development of macroeconomic models that endogenously represent financial actors and their decision making (including risk assessment), and their feedback on investment and policy decisions, would allow to overcome the challenges of current macroeconomic models, which are not able to capture the characteristics of multiform risks, leading to an underestimation of socio-economic and financial losses. In this regard, Stock-Flow Consistent behavioral models, such as the EIRIN model [30, 39] represent a step forward in this direction.

(g) Additional research must be prioritized on complex and rare multiform event occurrences—even for the multiform flood event types that have not yet been recorded or represented in traditional historical records of disasters. Indeed, what is considered a rare and/or complex multiform flood event in one area could have occurred in the past, however given lack of specificity in disaster reporting, their distribution and impact profiles are unclear.

## 5. Conclusion

We argue that while there are ongoing efforts in compound risk assessment, they remain almost exclusively focused on compounding of primary disaster types—especially when considering disaster risk management, financial, macroeconomic and humanitarian contexts. These efforts leave room for improvementin highlighting the core differences around subtypes of events, particularly floods, which from an impact profile perspective, can be as different as primary types. The COVID-19 pandemic reminded us that compound events can and will occur, further increasing demand for compound risk assessments, as well as for efforts to tailor them to specific sectors and spatiotemporal contexts. However, strategies are needed that allow us to anticipate impacts across short- and longer-term climate change-induced multiform flood risk scenarios.

Multiform flood events are among the many climate hazards that must be appropriately defined to avoid misrepresentation of risk in a variety of modeling and assessment efforts, especially as social and economic transformational demands to avoid the worst impacts of climate change are highlighted in global reports such as the IPCC AR6, The May 2022 G7 Foreign Ministers' Statement on Strengthening Anticipatory Action in Humanitarian Assistance and The United States Bipartisan Infrastructure Bill. For example, anticipatory action program development must acknowledge that even within the context of a single event, such as a tropical cyclone, different types of floods can occur, at various time and geographic scales (with some overlapping and some not). Further, risk communication must be enhanced with multiform flood risk in mind, so that early warning messaging capturing the spatiotemporal evolution of various flood subtypes can be clearly disseminated, at appropriate lead times, to the right populations. Lastly, as other compound event types evolve, the process of moving towards flood-type specific risk assessment can inform progress towards disaggregate risk of other disaster types. Doing so is of increased importance as more sophisticated global economic models and strategies for mitigating compound risks emerge, and as climate change leads to a future with growing risk from currently known and unknown disaster types and subtypes.

## Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

## Acknowledgment

This research was funded by the National Aeronautics and Space Administration, Grant No. 80NSSC18K0342.

## ORCID iDs

Andrew Kruczkiewicz https://orcid.org/0000-0002-2425-7308
Maarten van Aalst https://orcid.org/0000-0003-0319-5627

## References

[1] Zscheischler J et al 2020 A typology of compound weather and climate events Nat. Rev. Earth Environ. 1 333–47
[2] Fiedler T, Pitman A J, Mackenzie K, Wood N, Jakob C and Perkins-Kirkpatrick S E 2021 Business risk and the

emergence of climate analytics *Nat. Clim. Change* **11** 87–94

[3] Kruczkiewicz A, Klopp J, Fisher J, Mason S, McClain S, Sheekh N M, Moss R, Parks R M and Braneon C 2021 Opinion: compound risks and complex emergencies require new approaches to preparedness *Proc. Natl Acad. Sci.* **118** e2106795118

[4] Couasnon A, Eilander D, Muis S, Veldkamp T I, Haigh I D, Wahl T, Winsemius H C and Ward P J 2020 Measuring compound flood potential from river discharge and storm surge extremes at the global scale *Nat. Hazards Earth Syst. Sci.* **20** 489–504

[5] Zscheischler J *et al* 2018 Future climate risk from compound events *Nat. Clim. Change* **8** 469–77

[6] Ranger N, Mahul O and Monasterolo I 2021 Managing the financial risks of climate change and pandemics. What we know (and don't know) *One Earth* **4** 1375–85

[7] Wahl T, Jain S, Bender J, Meyers S D and Luther M E 2015 Increasing risk of compound flooding from storm surge and rainfall for major US cities *Nat. Clim. Change* **5** 1093–7

[8] IPCC 2021 Climate change 2021: the physical science basis *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed V Masson-Delmotte *et al* (Cambridge: Cambridge University Press)

[9] Raymond C *et al* 2020 Understanding and managing connected extreme events *Nat. Clim. Change* **10** 611–21

[10] Ranger N, Mahul O and Monasterolo I 2022 Assessing financial risks from physical climate shock: a framework for scenario generation *Equitable Growth, Finance & Institutions Insight* (Washington, DC: World Bank)

[11] Dykstra S L and Dzwonkowski B 2021 The role of intensifying precipitation on coastal river flooding and compound river-storm surge events, Northeast Gulf of Mexico *Water Resour. Res.* **57** e2020WR029363

[12] Fang J, Wahl T, Fang J, Sun X, Kong F and Liu M 2021 Compound flood potential from storm surge and heavy precipitation in coastal China: dependence, drivers, and impacts *Hydrol. Earth Syst. Sci.* **25** 4403–16

[13] Berghuijs W R, Allen S T, Harrigan S and Kirchner J W 2019 Growing spatial scales of synchronous river flooding in Europe *Geophys. Res. Lett.* **46** 1423–8

[14] Merz B *et al* 2021 Causes, impacts and patterns of disastrous river floods *Nat. Rev. Earth Environ.* **2** 592–609

[15] Ghanbari M, Arabi M, Kao S C, Obeysekera J and Sweet W 2021 Climate change and changes in compound coastal-riverine flooding hazard along the US coasts *Earth's Future* **9** e2021EF002055

[16] Arns A, Wahl T, Wolff C, Vafeidis A T, Haigh I D, Woodworth P, Niehüser S and Jensen J 2020 Non-linear interaction modulates global extreme sea levels, coastal flood exposure, and impacts *Nat. Commun.* **11** 1–9

[17] Paul S, Ghebreyesus D and Sharif H O 2019 Brief communication: analysis of the fatalities and socio-economic impacts caused by Hurricane Florence *Geosciences* **9** 58

[18] Thieken A H, Mohor G S, Kreibich H and Müller M 2022 Compound flood events: different pathways–different impacts–different coping options? *Nat. Hazards Earth Syst. Sci. Discuss.* **22** 165–85

[19] Petrucci O 2022 Factors leading to the occurrence of flood fatalities: a systematic review of research papers published between 2010 and 2020 *Nat. Hazards Earth Syst. Sci.* **22** 71–83

[20] Nicholls R J, Lincke D, Hinkel J, Brown S, Vafeidis A T, Meyssignac B, Hanson S E, Merkens J L and Fang J 2021 A global analysis of subsidence, relative sea-level change and coastal flood exposure *Nat. Clim. Change* **11** 338–42

[21] Ridder N N *et al* 2020 Global hotspots for the occurrence of compound events *Nat. Commun.* **11** 1–10

[22] Khanam M, Sofia G, Koukoula M, Lazin R, Nikolopoulos E I, Shen X and Anagnostou E N 2021 Impact of compound flood event on coastal critical infrastructures considering current and future climate *Nat. Hazards Earth Syst. Sci.* **21** 587–605

[23] Xiao Z, Yang Z, Wang T, Sun N, Wigmosta M and Judi D 2021 Characterizing the non-linear interactions between tide, storm surge, and river flow in the delaware bay estuary, United States *Front. Mar. Sci.* **8** 715557

[24] Battiston S, Monasterolo I, Riahi K and van Ruijven B J 2021 Accounting for finance is key for climate mitigation pathways *Science* **372** 918–20

[25] Lotsch A, Dick W and Manuamorn O P 2010 Assessment of innovative approaches for flood risk management and financing in agriculture (available at: https://openknowledge.worldbank.org/handle/10986/27577)

[26] Olokeogun O S, Ayanlade A and Popoola O O 2020 Assessment of riparian zone dynamics and its flood-related implications in Eleyele area of Ibadan, Nigeria *Environ. Syst. Res.* **9** 1–11

[27] Eisenberg D 2021 The need to consider residual risk *Nat. Clim. Change* **11** 803–4

[28] Najibi N and Devineni N 2018 Recent trends in the frequency and duration of global floods *Earth Syst. Dyn.* **9** 757–83

[29] Phillips C A *et al* 2020 Compound climate risks in the COVID-19 pandemic *Nat. Clim. Change* **10** 586–8

[30] Dunz N, Mazzocchetti A, Monasterolo I, Essenfelder A and Raberto M 2021 Compounding COVID-19 and climate risks: the interplay of banks' lending and government's policy in the shock recovery *J. Bank. Finance* **133** 106303

[31] Bressan G, Duranovic A, Monasterolo I and Battiston S 2022 Asset-level climate physical risk assessment and cascading financial losses (available at: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4062275)

[32] Naqvi A and Monasterolo I 2021 Assessing the cascading impacts of natural disasters in a multi-layer behavioral network framework *Sci. Rep.* **11** 1–14

[33] Szönyi M, Laurien F, Keating A and McQuistan C 2020 Flood resilience measurement for communities: using online data collection (available at: http://repo.floodalliance.net/jspui/bitstream/44111/3842/1/FRMC-Using%20online%20data%20collection.pdf)

[34] Hemmati M, Kornhuber K and Kruczkiewicz A 2022 Enhanced urban adaptation efforts needed to counter rising extreme rainfall risks *npj Urban Sustain.* **2** 1–5

[35] Pache A *et al* 2022 Stepping up support to the UN and humanitarian partners for anticipatory action *WMO Bull.* **71** 46–51

[36] Simpson N P *et al* 2021 A framework for complex climate change risk assessment *One Earth* **4** 489–501

[37] Kiem A S, Franks S W and Kuczera G 2003 Multi-decadal variability of flood risk *Geophys. Res. Lett.* **30** 7–1

[38] Jafino B A, Hallegatte S and Rozenberg J 2021 Focusing on differences across scenarios could lead to bad adaptation policy advice *Nat. Clim. Change* **11** 394–6

[39] Gourdel R, Monasterolo I, Dunz N, Mazzocchetti A and Parisi L 2022 The double materiality of climate physical and transition risks in the euro area *European Central Bank Working Paper Series* No. 2665

[40] Kruczkiewicz A, Bucherie A, Ayala F, Hultquist C, Vergara H, Mason S, Bazo J and De Sherbinin A 2021 Development of a flash flood confidence index from disaster reports and geophysical susceptibility *Remote Sens.* **13** 2764

[41] Mohor G S, Hudson P and Thieken A H 2020 A comparison of factors driving flood losses in households affected by different flood types *Water Resour. Res.* **56** e2019WR025943

[42] Botzen W W, Deschenes O and Sanders M 2020 The economic impacts of natural disasters: a review

of models and empirical studies *Rev. Environ. Econ. Policy* **14** 25–43

[43] Diaz D and Moore F 2017 Quantifying the economic risks of climate change *Nat. Clim. Change* **7** 774–82

[44] Bucherie A, Hultquist C, Adamo S, Neely C, Ayala F, Bazo J and Kruczkiewicz A 2022 A comparison of social vulnerability indices specific to flooding in Ecuador: principal component analysis (PCA) and expert knowledge *Int. J. Disaster Risk Reduct.* **73** 102897

[45] Nauman C, Anderson E, de Perez E C, Kruczkiewicz A, McClain S, Markert A, Griffin R and Suarez P 2021 Perspectives on flood forecast-based early action and opportunities for Earth observations *J. Appl. Remote Sens.* **15** 032002