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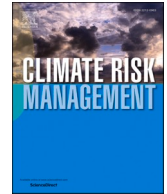
Towards drought impact-based forecasting in a multi-hazard context

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ABSTRACT

The lives and livelihoods of people around the world are increasingly threatened by climate-related risks as climate change increases the frequency and severity of high-impact weather. In turn, the risk of multiple hazards occurring simultaneously grows and compound impacts become more likely. The World Meteorological Organization (WMO) proposed the use of multi-hazard impact-based forecasting (IbF) to better anticipate and reduce the impacts of concurrent hazards, but as yet, there are few operational examples in the humanitarian sector.

Drought is particularly susceptible to multi-hazard influences. However, challenges encountered in the development of drought IbF systems – including poor understanding of compound impacts and specific hazard-focused mandates – raise important questions for the feasibility of multi-hazard IbF as envisioned by the WMO. With these challenges in mind, we propose an interim approach in which real-time assessment of dynamic vulnerability provides a context for drought-based IbF. The incorporation of dynamic vulnerability indicators account for the local effects of non-drought hazards, whilst the use of a drought-based system facilitates effective intervention. The proposed approach will improve our understanding of compound events, enhance adoption of IbF in the humanitarian sector, and better mitigate the impacts of concurrent hazards.

1. Introduction

Lives and livelihoods are increasingly threatened by climate-related risks as climate change increases the frequency and severity of high-impact weather (Seneviratne et al., 2012). Such risks threaten the UN's Sustainable Development Goals (UN General Assembly, 2015) and in recognition, a number of global agreements have established the need to enhance resilience to climate-related risks. The Sendai Framework for Disaster Risk Reduction aims to "*[p]revent new and reduce existing disaster risk through the implementation of… measures that prevent and reduce hazard exposure and vulnerability to disaster, increase preparedness for response and recovery, and thus strengthen resilience*" (UNDRR, 2015). The Paris Agreement also recognises the need to increase the ability of countries to deal with the impacts of climate change alongside measures to curb rising global temperatures (UNFCCC, 2015).

Both the Sendai Framework and Paris Agreement highlight the use of hydrometeorological forecasts to increase preparedness as a key step forward in climate-related risk reduction and adaptation. In response, a number of humanitarian organisations have developed early warning systems (EWS) utilising hydrometeorological forecasts to better anticipate specific hazards. Examples include, but are not limited to, the International Federation of the Red Cross' (IFRC) Early Action Protocols (https://media.ifrc.org/ifrc/fba/), the START Network's Disaster Risk Financing mechanisms (https://startnetwork.org/anticipation-and-risk-financing), and the Famine Early Warning System NETwork (https://fews.net/nuestro-trabajo).

Such EWS have improved preparedness for a number of independent hazards (e.g., for droughts *or* floods *or* cyclones). However, climate change increases the likelihood that multiple hazards will occur simultaneously. The concurrence of multiple hazards may alter vulnerabilities, change the magnitude of impacts, reverse development gains, and limit the efficacy of humanitarian interventions.

Acknowledging the importance of considering concurrent hazard impacts, in 2015, the World Meteorological Organization (WMO) proposed its *Guidelines on Multi-hazard Impact-based Forecast and Warning Services*. There are two key components to the WMO's guidelines:

Component 1. Impact-based forecasting (IbF)

The WMO identifies the "distinction between a general weather warning and an impact-based warning [a]s the inclusion of vulnerability of people, livelihoods and property". This definition is rooted in an understanding that impact is a function of the hydrometeorological hazard alongside the vulnerability and exposure of a concerned population (UNDRO, 1980), such that:

$$|\text{Potential impact } (x, t)| \equiv |\text{hazard } (x, t)| \cup |\text{vulnerability } (x, t)| \cup |\text{exposure } (x, t)| \tag{1}$$

In theory, focusing on what the weather will *do*, rather than what the weather will *be*, enables decision makers to plan and implement targeted preparatory actions to better reduce hazard impacts (Harrowsmith et al., 2020).

Component 2. Multi-hazard EWS

The WMO guidelines reiterate the call for multi-hazard EWS initially proposed under the Sendai Framework. The multi-hazard approach recognises that hazards are not independent but interrelated, and when concurring, can cause impacts greater than the sum of their parts (WMO, 2018). In theory, multiple independent hazard-specific EWS (e.g. for droughts *or* floods *or* cyclones) are not considered multi-hazard EWS. Rather, a multi-hazard EWS should be a unified system simultaneously able to warn of multiple hazards, including biological, environmental, geological, hydrometeorological and technological hazards (UNDRR, 2015). By considering hazards simultaneously, the compounding impacts of concurrent hazards can be addressed more efficiently.

The WMO's guidelines do not however, define how multi-hazard IbF systems should operate. Combined with limited research into the impacts of compound events, this means that the challenge has been in translating the WMO guidelines into practice, and as yet, there are few operational multi-hazard IbF systems (although Building Information Platform Against Disaster, https://bipadportal.gov.np/, provides an exception). Further guidance on development and implantation of multi-hazard EWS would be valuable to progress towards multi-hazard IbF as envisioned by the WMO.

Drought presents a clear case for the multi-hazard approach. Because it is a slow-onset event, vulnerability to drought is susceptible to the influence of concurrent hazards and non-biophysical events, meaning multi-hazards must be considered if drought interventions are to be effectively targeted. Moreover, the intrinsic predictability and slow onset provides a timeframe in which early actions can be adapted in response to multi-hazard influences (Boult et al., 2020).

However, drought also presents a number of challenges for IbF (considered in detail below), which have seen drought IbF lagging behind that of other hazards (e.g., floods and cyclones) and will hinder progress towards the WMO's multi-hazard framework. Here, we draw on our collective experience in developing drought IbF programs in parts of Africa and Asia to outline these challenges. We propose an interim approach to drought IbF in a multi-hazard context, incorporating real-time judgement of dynamic vulnerabilities. Such an approach is feasible in the short-term because of the existence of real-time drought forecasting systems (e.g., FEWSNET Water Requirement Satisfaction Index, TAMSAT-ALERT soil moisture, AstroCast Vegetation Condition Index; (Barrett et al., 2020; Boult et al., 2020; Shukla et al., 2014)) and vulnerability monitoring operated by organisations such as the IFRC. We believe this approach will move us closer to the multi-hazard IbF systems envisioned by the WMO. Finally, we demonstrate how the approach might work in practice using Kenyan drought as a case-study.

2. Challenges for drought IbF

Below, we outline a number of challenges encountered during our experience of developing drought IbF. We believe these challenges hinder the inclusion of drought in WMO-proposed multi-hazard IbF.

2.1. Direct forecasting of drought impacts is difficult

The most common approach to IbF is direct prediction of humanitarian impact (e.g. food insecurity) by forecasting a hydrometeorological hazard, then translating the hazard into impact via a predefined functional relationship (Bachmair et al., 2017). However, establishing a functional relationship can be difficult for a number of reasons.

Firstly, during past events, humanitarian aid has mediated the worst impacts of drought (Delbiso et al., 2017), and development has weakened the link between drought hazards and impacts (Rocha & Soares, 2015). Further, sufficient impact data may be unavailable, as was the case for the START Network when trying to establish a functional relationship between heatwave severity and hospital admissions in Karachi, Pakistan: admission data were only available for 2015 (Chaudhry et al., 2015). Limitations in impact data therefore make it difficult to directly relate hazard severity to the magnitude of impacts. An alternative is to use humanitarian spending as a proxy for impact severity, but a number of reports have raised concerns that financial assessments are a poor reflection of humanitarian need (Georgieva et al., 2016; Swithern, 2018).

Further, the relationship between hazard severity and impact is mediated by vulnerability (Equation (1)). Non-linearities in the hazard-impact relationship may be explained by dynamic vulnerabilities, but as yet, we have a limited understanding of the factors that make individuals, communities or social groups vulnerable to drought.

Second, it is often difficult to distinguish the impacts of drought from those resulting due to other causes. For example, food insecurity is a common impact targeted by drought IbF programs, but food insecurity is a multi-hazard impact: it may arise as a result of a number of independent hazards (e.g., hailstorms, pests, flooding), due to the combined effects of concurrent hazards, or because of non-biophysical factors (e.g., conflict, high food prices). It can therefore be difficult to determine if people are hungry for the "right" reasons (i.e., due to drought).

Third, there can be a mismatch between the predicted element of the hazard (e.g., seasonal rainfall total) and elements which drive impact (e.g., false onsets, dry spells, sub-seasonal rainfall distribution). Inferring the expected impact of a forecast is therefore difficult: on one hand, "below-normal" seasonal rainfall may still produce a reasonable harvest if rain is well-distributed throughout the season, but "near-normal" rainfall could cause harvest failure if rain occurs on extreme rainfall days, leading to inundation and crop destruction.

Whilst there has been some success in establishing functional relationships between drought hazards and impacts in Europe (Blauhut et al., 2015; Stagge et al., 2015; Sutanto et al., 2019), these relationships are highly context-specific and cannot be extrapolated to new regions. Even machine learning approaches, which bypass the need to explicitly define functional relationships (Saeed et al., 2017), rely heavily on the accuracy of impact data. This means that in regions where accurate impact data is unavailable (often coinciding with those most vulnerable to climate-related hazards), it is extremely difficult to directly predict humanitarian impact for drought.

2.2. Predefined systems may neglect changing vulnerabilities

In designing IbF systems, there is a trade-off between the system being largely predefined (breaching of a predefined forecast threshold triggers pre-agreed actions) or requiring real-time decision making (whether to trigger and what actions to take).

Predefined systems "front-load" expert judgement such that trigger thresholds and early actions are agreed during system development based on an assessment of likely impacts as a function of static vulnerability (factors which change only slowly over time, e.g., livelihood zones, distance to roads and markets, poverty indices), and once the system is operational, there is limited scope for real-time subjectivity.

A number of humanitarian organisations, notably the IFRC, have opted for predefined systems due to the associated benefits. By avoiding real-time subjectivity, predefined systems: (1) remove emotional and political influences, improving transparency and accountability, and (2) eliminate costly delays associated with real-time decision making (e.g., reviews of the 2011–2012 Horn of Africa famine were critical of the tendency to defer judgement and "wait for certainty"; (Hillier & Dempsey, 2012)). Additionally, because trigger thresholds and actions are pre-agreed, rates of triggering and basis risk (false alarms and missed events) are known, and the costs of the program are acknowledged in advance.

The alternative is to incorporate real-time expert decision making. Real-time decisions can reduce basis risk and allow for the consideration of emerging drivers of vulnerability which were not initially included during system development. Exclusion of such drivers does not reflect the thoroughness of predefined system development, but rather acknowledges that it would be impossible to foresee all possible drivers of vulnerability and impact. The ability to adapt to dynamic vulnerabilities is particularly important for slow-onset hazards and those for which vulnerability is poorly understood, such as drought.

In practice, most operational systems include a safety net that allows for ex gratia payments and other actions if an event is missed by the IbF system. Even predefined systems will, moreover, flex in extreme circumstances. For instance, during the COVID-19 pandemic, a number of IFRC National Societies (NS) adapted existing Early Action Protocols (EAPs): the Bangladesh NS included COVID-19 as an additional factor in their vulnerability assessment and the Mozambique NS triggered their cyclone EAP before the predefined threshold was breached to account for the heightened socio-economic vulnerabilities caused by COVID-19 (Tozier de la

Poterie et al., 2021).

While IbF systems continue to be managed by international humanitarian organisations, the ability to flex triggers and actions will remain. However, as IbF programs are installed in national government, scope to flex IbF systems in response to dynamic vulnerabilities will be vital to avoid rendering predefined actions ineffective, overlooking vulnerable groups and risking the loss of confidence in drought EWS.

### 2.3. Practical considerations for multi-hazard IbF

As per the WMO guidelines, true multi-hazard IbF should simultaneously and explicitly forecast the interrelated impacts of multiple hazards (World Meteorological Organisation, 2015). Whilst the design and functionality of such systems remain unclear, our experience in drought IbF raises a number of points to consider.

We have already outlined how limitations associated with impact data make it difficult to characterise the functional relationship between drought and its impacts. True multi-hazards IbF requires that functional relationships are defined for multiple hazards and multiple impacts simultaneously, whilst also accounting for potential cumulative, cascading, or attenuating effects of concurrent hazards. Fundamentally, our current limited understanding of compound events makes this proposition unrealistic.

Even if a true WMO-envisioned multi-hazard system is developed, functionality must be maintained to allow the individual impacts of a distinct hazard to be identified. For instance, even where hazards share an impact (e.g., both drought and hailstorms may cause food insecurity), the mechanisms by which these hazards cause impacts differ, and therefore require different interventions (e.g., there would be no use in distributing drought-tolerant seeds in anticipation of a hailstorm).

Such functionality will also be important for humanitarian and disaster management organisations which focus on (or are mandated to manage) only a subset of hazards (e.g., Kenya's National Drought Management Authority) or a subset of impacts (e.g., the World Food Program focuses on food insecurity). Whilst organisational focus doesn't prevent organisations considering multi-hazards, it can mean that an organisation lacks the relevant resources or expertise to incorporate and act on multi-hazard warnings and may face donor issues if doing so.

If ignored, the combination of these factors risks multi-hazard IbF being ineffective. Without scope to accommodate dynamic vulnerabilities, actions cannot be effectively targeted or may prove ineffective. Moreover, if the complex relationships linking multi-hazards to multi-impacts obscure attribution of particular impacts to particular hazards, hazard-focused organisations may be limited by their institutional mandate and thus unable to act.
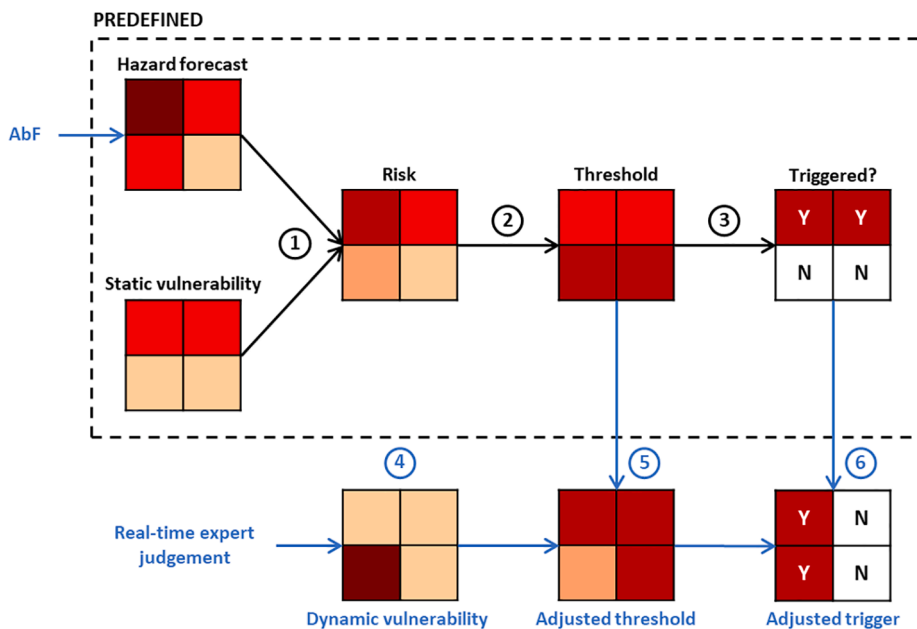
Fig. 1. A hybrid framework for multi-hazard IbF. Refer to the main text for a definition of numbers. Black arrows and numbers: components common across predefined humanitarian IbF systems. Blue arrows and numbers: real-time components. Grids represent spatially varying values. Darker reds indicate higher values of risk, vulnerability, and thresholds. In this example, despite only low to moderate risk in the southwest square, increased dynamic vulnerability lowers the threshold for action, resulting in triggering. Meanwhile, reduced vulnerability in the northern squares elevates trigger thresholds, so the northeast square no longer triggers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. An interim approach

The challenges outlined above do not negate the importance of the multi-hazard approach but do require significant consideration before effective multi-hazard IbF, as envisaged by the WMO, can be realised. Thus, there is an opportunity for an interim approach which contextualises drought amongst concurrent hazards.

We propose a hybrid framework, building on a predefined system and incorporating real-time judgement of dynamic vulnerability to capture multi-hazard influences. Not only will this allow existing drought IbF systems to account for multi-hazards, but we believe that the understanding of compound impacts gained will support progress towards WMO-style multi-hazard IbF systems.

The framework is summarised in Fig. 1. A baseline predefined drought IbF system is retained:

1) A hydrometeorological forecast indicating the likelihood of drought occurring is combined with a predefined assessment of static vulnerability to determine risk. Where static vulnerability is higher (Fig. 1: northern squares), trigger thresholds are lower.
2) Risk is compared to agreed-upon thresholds for action.
3) If risk is greater than or equal to the threshold, early action is triggered to mitigate the worst impacts of drought.

We then propose a number of components to account for dynamic vulnerabilities caused by concurrent hazards:

4) Expert judgement is utilised to determine dynamic vulnerabilities. For instance, conflict, pest outbreaks, or recent hydrometeorological events, may act to increase vulnerability to drought in the affected location.
5) In locations where vulnerability is elevated (Fig. 1: southwest square), the predefined forecast threshold ("danger level") is relaxed in order to trigger for less severe droughts. This acknowledges that those with elevated vulnerabilities require support even if drought is only slight. In regions where dynamic vulnerability is lower (Fig. 1: northern squares), the predefined forecast threshold may be raised, to avoid the perception of false alarms if a less severe drought does not have significant impact on food security (the trigger threshold for northern squares is elevated to reflect reduced vulnerability). Balancing of lower thresholds for vulnerable regions against higher thresholds for less vulnerable regions reduces the need for 'safety nets', enabling more accurate anticipation of donor costs.
6) If risk exceeds the adjusted thresholds, early actions are triggered. Early actions may need to be adapted to account for multi-hazards.

Practically, we recommend a number of steps to implement drought IbF in a multi-hazard context:

3.1. Follow the action-based forecasting (AbF) approach to identify suitable hazard forecasts

In focusing on directly forecasting drought impact, identifying the most suitable hazard forecast has been hindered by the lack of accurate impact data. An alternative approach, action-based forecasting (AbF), was proposed to identify suitable flood forecasts (Coughlan De Perez et al., 2016). AbF focuses on early actions. For each action, local stakeholders define the lead time required to implement the action and the willingness of stakeholders to act in vain. This provides criteria against which to verify, and choose, hazard forecasts in lieu of observational impact data.

3.2. Incorporate dynamic vulnerability as a means to account for multi-hazards

Whilst static vulnerability assessments within existing drought IbF systems allows for broad-scale spatial targeting of at-risk people, consideration of dynamic vulnerability allows the system to additionally address prevailing conditions, thus accounting for multi-hazard influences.

3.3. Utilise real-time expert judgement to assess dynamic vulnerability

Given that no comprehensive framework for assessing vulnerability exists (Adger, 2006; Cardona, 2004; Cardona et al., 2012), that real-time vulnerability data is difficult to monitor in an automated manner (although see (Enenkel et al., 2020) for a potential way forward), and that the number of factors potentially influencing vulnerability is vast and therefore unrealistic to incorporate in system development, it makes sense to allow for subjectivity in the real-time expert judgement of dynamic vulnerability.

We envision a process by which experts are brought together as a technical working group (TWG) during a predefined window ahead of key seasons (e.g., the rainy season). "Experts" should represent a broad range of viewpoints, have good contextual knowledge of the region, possess diverse expertise, and include relevant at-risk groups (Harris et al., 2021; Klassen, 2021). TWGs assess additional forecast information, monitoring data and anecdotal evidence to identify conditions which are currently, or may soon, increase the vulnerability of particular localities or groups, or could reduce the effectiveness of pre-agreed actions.

The inclusion of real-time judgement may slow decision making, requires commitment from experts and increases the risk that conflicting interests influence decisions. However, incorporating TWG meetings into existing inter-institutional activities (see section 4) may mediate time commitments, and including a diverse range of experts should counter any one person's conflict of interests. Moreover, the baseline predefined system prevents delay and provides a safety-net against the risk that experts wrongly choose not to adjust trigger thresholds.

In practice, the degree to which dynamic vulnerabilities are incorporated will depend on institutional capacities and information available, ranging from the sole use of the baseline predefined system considering only static vulnerability, through to the TWGs described above. Adjustments to trigger thresholds are likely to be ad-hoc in the first instance, but with good record keeping (adjustments, actions, outcomes), early experience may inform later adjustments.

3.4. Allow for flexibility in IbF systems to address multi-hazards

The inclusion of real-time expert judgement of dynamic vulnerability necessitates IbF systems which are flexible, not automated, in order to (1) adjust danger-level thresholds in response to heightened vulnerability, (2) amend early actions to account for other hazards, and (3) ensure finances are available to support amendments (Tozier de la Poterie et al., 2021). The need for flexibility must be accommodated as IbF systems are installed in national government infrastructure.

4. Demonstration case study: Kenyan drought

The Kenya Red Cross Society (KRCS) are currently developing an EAP to mitigate the primary impacts of drought (water scarcity, reduced crop yield, and lack of pasture) and trigger financing through the IFRC's Disaster Relief Emergency Fund (https://www.anticipation-hub.org/experience/financing/fba-by-the-dref). We now demonstrate how the development and operation of KRCS's system would look under our proposed framework.

Firstly, a TWG assembled by KRCS would employ AbF to select forecasts and define triggers. Starting with a list of drought early actions, stakeholders would assess the lead time required, and the willingness to act in vain, for each action. Against this information, the TWG could compare a range of drought forecasts (e.g., Standardised Precipitation Index forecasts from Kenya Meteorological Department, Vegetation Condition Index forecasts from the Regional Centre for Mapping of Resources for Development, TAMSAT-ALERT soil moisture forecasts) and select those which best meet the criteria defined by stakeholders. Forecasts, triggers, and actions would be outlined in the EAP, forming the predefined "baseline" IbF system.

Operationally, KRCS would consult the TWG before each growing season to assess dynamic vulnerabilities. In recent years, experts may have identified locusts, COVID-19, conflict, and flooding as drivers of heightened vulnerability to drought. Practically, experts could utilise dynamic vulnerability assessments from established activities, including the Kenya Food Security Steering Group's short- and long-rains assessments, FEWSNET's food security outlook, the National Drought Management Authority's drought phase classification, the Food Security and Nutrition Working Group's locust briefings, the Conflict Early Warning and Response Mechanism's conflict information. KRCS would then adjust danger-level thresholds in light of dynamic vulnerabilities. The EAP would subsequently run as standard through the season, with forecasts monitored for any breach of adjusted thresholds.

5. Conclusion

As the potential for concurrent hazards grows, it is crucial to prioritise a multi-hazard focus. Whilst the WMO lays out a vision for multi-hazard IbF systems, there remain a number of challenges to overcome before such systems can incorporate drought hazards. Our proposed approach provides an interim solution to drought IbF in a multi-hazard context, and whilst the focus here has been on drought, this approach could equally be applied to other hazards as a means to incorporate multi-hazard influences in the near-term.

The inclusion of real-time judgement introduces questions around transparency, but importantly allows for the inclusion of dynamic vulnerabilities to address multi-hazard influences. Moreover, there is a case for "learning by doing", and we hope that our approach to multi-hazard IbF will improve our understanding of compound events in the long-term, paving the way towards true multi-hazard IbF as envisioned by the WMO, whilst better mitigating the impacts of concurrent hazards in the near-term.

Declaration of Competing Interest

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

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