Climate Risk Management 46 (2024) 100671

Contents lists available at ScienceDirect

Climate Risk Management

journal homepage: www.elsevier.com/locate/crm

Key design considerations for flood risk pooling facilities at the sub-national level

Kamleshan Pillay *

School of Geography, Archaeology and Environmental Studies, University of Witwatersrand, 1 Jan Smuts Avenue, Braamfontein 2000, Johannesburg, South Africa

ARTICLE INFO

Keywords:
Adaptation Finance
Climate Risk
Flood
Risk Pooling
Sub-national Governments

ABSTRACT

Disaster or catastrophe risk pooling refers to the sharing of risk by entities facing common risk exposure to an individual hazard or set of hazards over a geographical area. Risk pooling members can gain risk diversification benefits such as lower premium costs while facilities based on parametric insurance policies are able to provide timely post-disaster payouts to members. The topic of sub-national catastrophe risk pools is relatively unexplored. Sub-national risk pools are advantageous as they can overcome politicised issues of compromised sovereignty and joint decision-making while enhancing insurance access for smaller, rural sub-national authorities. This research represents a starting point on design considerations for developing a sub-national flood risk pool (SNFRP). The operation of an SNFRP may result in greater spatial correlation. This may affect the financial stability of SNFRPs or diminish the risk diversification benefits over time. The balancing of fully risk-based pricing and affordability is also likely to be a significant challenge for SNFRPs, especially those operating in emerging and developing economies (EMDE). Means-based subsidies can overcome this challenge; however, donor access may be limited. In addition to donor partnerships, SNFRPs require engagements with reinsurers and national government actors to assist with risk transfer and seed capitalisation, respectively. In EMDEs, an SNFRP focused on response and relief will likely be based on parametric insurance policies. Issues such as index selection, geographical basis risk, and data and modelling needs must be carefully considered during the design of flood parametric insurance policies. Geographic basis risk may be amplified in an SNFRP operating at smaller spatial scales as flood events are not restricted to the administrative boundaries of sub-national authorities. Other issues that could influence the implementation of a sub-national facility include gaining political buy-in; access to reinsurance markets; and risk reduction incentivisation.

1. Introduction

Floods are one of the most common natural disasters globally, causing significant loss of life and destruction of property and infrastructure. Between 2000 and 2022, floods worldwide have culminated in economic losses equivalent to US$ 929 billion, representing 3852 floods (Centre for Research on the Epidemiology of Disasters (CRED), 2023). In recent years, floods have continued to drive global insured losses (Swiss Re, 2022a). In 2021, 31 % of global economic losses were attributed to floods, only 2 % less than

* Corresponding author at: School of Geography, Archaeology and Environmental Studies, University of Witwatersrand, 1 Jan Smuts Avenue, Braamfontein 2000, Johannesburg, South Africa.

E-mail address: pillay.kamleshan@gmail.com.

https://doi.org/10.1016/j.crm.2024.100671
Received 1 October 2023; Received in revised form 11 November 2024; Accepted 13 November 2024
Available online 15 November 2024

tropical cyclones (Swiss Re, 2022b). Despite large global economic losses from floods (US$ 82 bn in 2020), there continues to be a significant flood protection gap. Between 2011 and 2021, 82 % of global economic losses from flood events were uninsured (Swiss Re, 2022c).

Large-scale floods have had substantial impacts at the sub-national government level. Sub-national governments refer to all government administration units under the national government level such as provinces, municipalities and counties (Gutierrez, 2015). Kocornik-Mina et al. (2020) found that 53 large-scale floods affected 1800 cities in 40 countries over a five-year period. Rapid urban expansion (Devi et al., 2019), poor development planning practices (Echendu, 2021), and increased heavy rainfall and extreme weather events driven by climate change (Beshir and Song, 2021) have all resulted in greater vulnerability to floods at the local government level. Urban areas, many of which possess rivers, coastlines, or both, are centres for population growth (Adikari et al., 2010; Jongman, 2018). This has led to a greater asset concentration in urban areas, increasing risk exposure and the potential for higher economic losses from flood events (Hallegatte et al., 2013; Hanson et al., 2011). Beyond being a major driver of pluvial flooding, urban expansion has also resulted in negative changes to urban hydrological processes (Beshir and Song, 2021).

Sub-national governments may integrate risk transfer instruments into their disaster risk financing strategies to manage flood events (Surminski et al., 2022; Swacha-Lech and Gawin, 2022). Risk transfer instruments refer to financial mechanisms that allow for an entity to transfer its financial risk to another party. These risk transfer instruments are typically property insurance policies with flood coverage integrated into policies or available as an add-on (Organisation for Economic Co-operation and Development (OECD), 2016; Surminski and Oramas-Dorta, 2014); the use of property insurance policies in isolation can result in a financial gap for broader disaster relief and response activities. The issue of limited disaster relief budgets and the unavailability of flood insurance is more acute in sub-national governments in emerging market and developing economies (EMDE) (Gurenko, 2015). There are various other types of risk transfer instruments that can be used to manage flood risk. These include agricultural insurance (indemnity- or parametric-based); business interruption insurance; disaster microinsurance; government-sponsored catastrophe insurance; and risk pools (Climatewise, 2012; Cummins and Mahul, 2009). A full overview of different disaster risk transfer products is outlined in Climatewise (2012).

Risk pooling can be defined as an approach or form of risk management (Cronk and Aktipis, 2021). The approach allows a sufficiently large collective of aligned entities with common risk exposure to jointly pool their risk before accessing the insurance, reinsurance, or financial markets (Low et al., 2020). More simply, risk pooling allows for entities to pool premiums together, while sharing losses if payouts from insurance policies are triggered. This allows for financial impact on a single entity to be shared or distributed across all pooling entities. Risk pools do not reduce risk; rather, they spread risk efficiently over space and time (Broberg and Hovani-Bue, 2019). Aligned entities typically act through a joint institution and may include individuals, companies, governments, or government-affiliated entities (Balogun et al., 2021; Callen et al., 2015; Doucette, 2002; Low et al., 2020). Risk pools can be initiated at the sub-national level. Sub-national risk pools – which are sometimes referred to as intergovernmental risk pools, municipal risk pools or public entity risk pools – are not-for-profit risk pools where members are sub-national agencies or governments (Association of Government Risk Pools (AGRiP), 2014; Doucette, 2002; Rappaport, 2016; Serkin, 2016). At present, most sub-national risk pools are used to cover public assets (Frankel, 2021).

Disaster or catastrophe risk pooling refers to the sharing of risk by entities facing common risk exposure to an individual hazard or set of hazards over a geographical area (Balogun et al., 2021; Martinez-Diaz et al., 2019). Catastrophe risk pools may vary in terms of the sectors, hazards and loss types (relief or property) for which coverage is provided and the level or scale at which they operate (micro, meso or macro). The most prominent examples of catastrophe risk pools are the African Risk Capacity (ARC) and the Caribbean Catastrophe Risk Insurance Facility (CCRIF). The ARC is a specialised agency of the African Union and provides mainly drought insurance coverage for selected Member States, while the CCRIF provides immediate liquidity for covered Caribbean and Central American governments after natural disasters such as earthquakes and hurricanes (ARC, n.d.; CCRIF, 2015).

There are fewer examples of catastrophe risk pools operating at a sub-national level. Risk pooling provides several benefits for sub-national governments beyond lower insurance premiums for risk pool members. Other benefits include: access to reinsurance and financial markets at better terms; quick payout timelines for sub-national risk pools based on parametric insurance policies (index-based products where payouts are triggered by exceedances of a pre-specified index threshold); an enhanced understanding from policyholders on managing and mitigating their own risks; and, facilitating the shift away from ex-post to ex-ante disaster risk financing instruments, thereby improving access to predictable post-disaster funding flows (World Bank Group, 2017). More broadly, risk pools could provide greater access to coverage for uninsured or smaller sub-national governments (Cebotari and Youssef, 2020) while enhancing the attractiveness of risk pools in countries that have declined to participate in sovereign catastrophe risk pools. For example, several countries rejected joining the ARC as decision-making was not at the complete discretion of the participating country (Pillay, 2016; Tarazona et al., 2017). Within sub-national risk pooling schemes, the implementing country, through its sub-national governments, would gain all benefits, and the design of the risk pool would be guided solely by the implementing country. This negates any issues related to compromised sovereignty. Sub-national risk pools may also represent an innovative way for regional governments, particularly those in EMDEs, to extend coverage where insurance gaps exist, or markets are underdeveloped.

There are various ways in which risk pools may offer flood coverage. Risk pools may provide protection against floods (and other hazards) through standard property insurance offered to individuals and businesses such as the policies offered by the Algerian Catastrophe Risk Insurance Pool (Surminski and Oramas-Dorta, 2014). Similarly, Norway's Natural Perils Pool offers compulsory cover against natural perils (including floods) linked to fire insurance (Bull, 2018). The NFIP is also an example of a government-sponsored catastrophe insurance scheme that acts as a public sector risk pool; however, the programme is focused exclusively on flood risk (Chivers and Flores, 2002; Thomas and Leichenko, 2011). Sovereign catastrophe risk pools such as the Caribbean Catastrophe Risk Insurance Facility (CCRIF) provide coverage to countries to assist with immediate flood relief and response needs through excess rainfall parametric policies (Oerther, 2016). The Philippine City Disaster Insurance Pool (PCDIP) is an example of a sub-national risk pool and is currently under development (Asian Development Bank, 2018). The facility is similar in structure to sovereign catastrophe risk pools. Flood coverage under the facility is expected to be covered through typhoon parametric insurance policies (Asian Development Bank, 2018). Risk pools may also cover specific types of flooding. In 2023, the ARC launched a parametric product to provide coverage against fluvial (riverine) floods for member states (ARC, 2023).

This research focuses on the hypothetical case of a sub-national flood risk pool (SNFRP). To date, there are no operational SNFRPs. There are several barriers that may limit the development of SNFRPs. Regulatory frameworks may not allow for flood risk pools to be developed between sub-national governments, where the use of disaster risk insurance vehicles is limited to higher levels of government. Political barriers may restrict risk sharing as sub-national governments may be under the governance of other political parties. The scale of an SNFRP may cause increased spatial correlation of hazards and reduced risk diversity, which could compromise the financial stability of an SNFRP. SNFRPs require significant seed capital allocations, which may be challenging for sub-national governments if donor assistance is not available. Other challenges include: access to flood-related data and models; coordination between sub-national authorities; low-risk awareness and moral hazard issues; and, affordability.

A general structure of a sub-national risk pool is presented in Fig. 1. The application of interest for this publication is one in which an SNFRP provides immediate payouts to assist disaster response and relief efforts (including the reconstruction of essential public assets), similar to sovereign catastrophe risk pools that provide coverage for sudden onset hazards through parametric insurance policies. Design considerations are assessed in the context of flood risk; however, learnings from the research are likely to apply to any sub-national risk pool providing coverage against natural catastrophes. There are several design elements that must be considered prior to the inception of an SNFRP. This research focuses on risk diversification and spatial correlation of floods; risk layering; risk pricing; affordability and forms of premium support; and policy design. The importance of enabling factors such as the governance and partnership model, data availability, political buy-in and ownership, and institutional arrangements are acknowledged, but beyond the scope of this research.

1.1. Methodology

Considering the general absence of risk pooling facilities operating at the sub-national level, this paper uses the experience of sovereign and national level catastrophe risk pools as a basis to evaluate design considerations. This study applied the methodology of documentary analysis focusing on studies published in English between 1970 and 2023. The broad areas of literature collected included: (1.) general disaster risk financing approaches; (2.) risk transfer instruments that have been applied to manage disasters (including floods) with a focus on risk pools at all levels; (3.) risk pools or instruments with similar structures at the sub-national level covering general and disaster risks; (4.) risk pool components informing the design of a facility; and (5.) flood characteristics that influence the design and operations of a risk pool.

The start year of 1970 was considered sufficiently early to allow for literature focused on the application of risk pools in contexts beyond disasters to be detected. The cut-off date for literature was August 2023. Data sources included peer-reviewed literature and grey literature. Grey literature was restricted to data sources published by recognised institutions such as consultancies, governments, domestic and international non-governmental organisations, international financial institutions, mainstream media organisations, major risk pools, and risk transfer facilities.

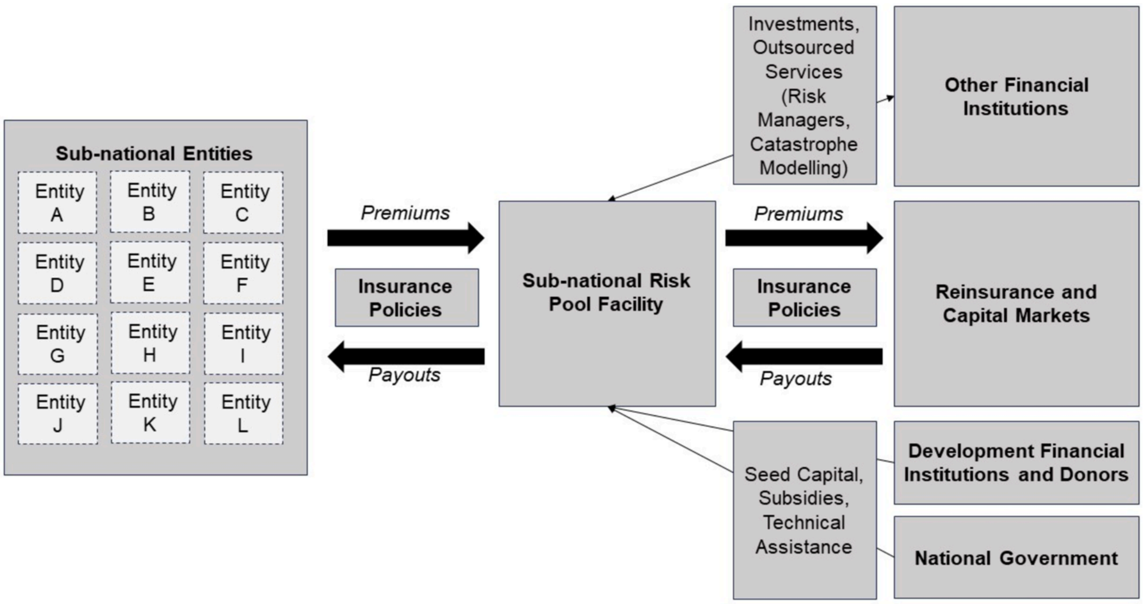

Fig. 1. The general structure of a sub-national risk pool (own representation).

Candidate literature was identified through keyword searches in search engines, snowball sampling based on the citations of publications, and the familiarity of the author on the topic of risk pooling. Regarding peer-reviewed candidate literature, search terms were entered into search engines such as Scopus and Web of Science. Grey literature searches were conducted in Google.

2. Risk diversification and spatial correlation of floods

Risk diversification is a foundational principle in risk pooling. Risk diversification refers to the spreading of exposure across different entities to reduce the overall risk exposure. Adequate risk diversification allows for risks to be spread across entities; this decreases the likelihood that large losses will be experienced by all members simultaneously (Cummins and Mahul, 2009; Mahul and Ghesquiere, 2010; Nguyen, 2013; Baum et al., 2018). Catastrophe risks typically possess two attributes that are problematic in a risk-transfer context. First, they are characterised by "fat-tailed" distributions. Fat-tailed distributions refer to probability distributions with higher probabilities of extreme outcomes. These distributions require insurers to charge higher premiums to manage potential large losses associated with high-severity, low-frequency events (Nguyen, 2013). Second, the losses of catastrophe risks may be spatially correlated (Kousky and Cooke, 2012); this refers to the extent to which a hazard that occurs in one region is related to another. Therefore, risks are not independent over space and time. The amplification of spatial correlation results in an increased probability of joint hazards occurring, potentially resulting in large losses that may compromise the financial stability of a risk pool (Baum et al., 2018; Kousky and Cooke, 2012; Nguyen, 2013). In addition to spatial correlation, risk diversification benefits in a risk pool will depend on factors such as the risk pool's geographic area (size), the number of risk pool members and the risk exposure profile of members (World Bank Group, 2017).

Spatial correlation is a significant concern in the context of flood hazards. This is well demonstrated by Berghuijs et al. (2019). The study found that the distance over which several rivers flooded simultaneously exceeded the size of individual drainage basins, with this trend varying regionally. In physical terms, spatial correlation is driven by the interactions between the space-time structure of rainfall (Singh, 1997; Smith et al., 1994), land surface properties that affect runoff generation (Blöschl and Sivapalan, 1997), river network topology and connectivity (Gupta et al., 1996), and channel-floodplain hydraulics (Turner-Gillespie et al., 2003). The downscaling of a sovereign risk pool to the sub-national level may exacerbate issues of spatial correlation. A reduction in the spatial area over which a flood hazard is evaluated may increase the effect of hydrological connectivity and interdependencies of flood drivers on the risk profiles of pooling entities (Brunner et al., 2019; Hochrainer and Mechler, 2011; Liu et al., 2018; Trigg et al., 2013).

SNFRPs may be more viable in countries with larger geographical extents such as Australia, the United States (U.S.), Canada, Russia, India, and China, as sub-national governments may also possess large spatial extents. This may increase the likelihood that the floods are completely contained within the administrative boundaries of sub-national governments acting as pooling entities. This reduces the potential for spatial correlation in an SNFRP.

Spatially correlated risks may be magnified in an SNFRP covering small geographical areas. In this case, the hazard area coverage as a proportion of the total risk pool area is larger than if the hazard had been covered under a sovereign risk pool or a large SNFRP. This increases the likelihood that large-scale events could affect several sub-national governments simultaneously. Consider the 2022 floods in Pakistan; in total, 1730 individuals lost their lives, total economic losses were approximately US$ 15.2 bn and 33 million people were affected (World Bank Group, 2022). The Sindh province was most affected, experiencing 70 % of the total damages and losses. Of Pakistan's 154 districts, 116 were affected to some degree by the floods (Sarkar, 2022). If an SNFRP operated at a district level, then it is probable that the financial stability of the risk pool could have been compromised. In this case, a sovereign catastrophe facility could be more viable. If flood risk had been covered by a sovereign catastrophe risk pool that included Pakistan as one of the countries, the financial stability of the risk pool could likely have been less affected by the hazard owing to the larger geographical area of the risk pool.

Several studies have noted that risk pools may still be able to deliver financial benefits under varying degrees of spatial correlation (Baum et al., 2018; Okhrin et al., 2013; World Bank Group, 2017). The issue of spatial correlation may be less relevant if SNFRPs possess a large number of members. The case of the CCRIF is notable. The CCRIF risk pool comprises 19 Caribbean and Central American countries that are in close proximity. Heinen and Strobl (2019) found that certain islands that were close to each other demonstrated strong positive spatial correlation (for example, Haiti, Dominican Republic, Jamaica, and Cuba); however, this was offset by negative spatial correlation between other pairs. Therefore, the pool as a whole possesses sufficient levels of risk diversification.

A consistent risk pool size in terms of its membership is essential to ensure adequate risk diversification (Pillay, 2016). Premium cost reduction benefits generally increase as new members join the risk pool, with benefits tapering off as the pool grows (World Bank Group, 2017). Maintaining a stable risk pool membership can be challenging as basis risk may compromise the long-term participation of members (See Section 6). This issue also affects the risk retention capacity of a risk pool (See Section 3.2). Risk retention capacity refers to the ability of a risk pool to hold and manage its financial risk internally instead of transferring its risk to insurance and financial markets.

The preceding paragraphs have discussed the issue of spatial correlation as a function of geographical size, location, and risk pool membership. However, the varying levels of risk exposure are acknowledged as a crucial determinant in determining risk independence. Risk independence refers to the assumption that the occurrence of a risk does not affect the probability of another risk occurring. Therefore, any evaluation of spatial correlation must account for contributing factors such as elevation, topography, land-use and land cover change, risk reduction and adaptation measures, and vulnerability variables.

3. Risk layering

Catastrophe risk pools at all levels are typically based on a layering approach to risk management (Fig. 2) (Warner et al., 2013; World Bank Group, 2017). Risk layering separates the management of natural disasters into different segments according to their frequency and severity (Mahul and Ghesquiere, 2010). Generally, disasters that occur more often (high frequency) but are less severe are financed by a combination of risk reduction, prevention and recovery, and risk retention measures as these approaches are usually more cost-effective (Warner et al., 2013). This represents the first risk layer. Less frequent and medium-severity disasters (Layer 2) are managed by a combination of risk retention and risk transfer approaches. Risk transfer instruments are mainly used to manage low-frequency, high-severity disasters (Layer 3), as risk retention instruments are inefficient in handling the magnitude of financial losses that may be incurred (Cummins and Mahul, 2009; Mahul and Ghesquiere, 2010). From a cost-effectiveness perspective, risk layering is envisioned to allow for cheaper sources of disaster finance to be used first while more expensive sources are used to manage larger disasters that are less frequent (Cummins and Mahul, 2009). In addition to cost-effectiveness considerations, the timing of financial support is a key factor in selecting risk retention and risk transfer instruments within disaster risk layering (Mahul and Ghesquiere, 2010).

Insurance policies offered by SNFRPs are envisioned to be a risk transfer option within layered disaster risk financing strategies of risk pool members. From the perspective of a risk pool, risk layering refers to the indirect support and incentivisation of risk reduction through insurance policies; the building of joint reserves from premium income and seed capitalisation (risk retention); and risk transfer to reinsurance and financial markets if risks are financially inefficient to retain.

3.1. Risk reduction

Since risk pools do not reduce risk, risk pool members continue to implement risk reduction initiatives irrespective of coverage held from risk pools. Risk pools do not directly support risk reduction. However, they may indirectly incentivise risk reduction efforts through pricing benefits within the insurance policies they offer (Hudson et al., 2019). Risk reduction incentives may be dampened in risk pools that integrate subsidies to support the affordability of premiums (Vivid Economics et al., 2016). Therefore, SNFRPs must consider measures to avoid the effects of price distortion on risk reduction incentives. SNFRPs may require that donors place conditions on subsidy provisions requiring risk reduction to be undertaken for the duration of subsidy support (Scott et al., 2022; Vivid Economics et al., 2016). This is similar to the contingency planning required under the ARC that outlines how payouts are to be used (Scott et al., 2022). SNFRPs may co-ordinate with the national government on risk reduction and climate adaptation initiatives. This approach has been adopted in France by the Caisse Centrale Réassurance through its Catastrophes Naturelles scheme – a government-backed catastrophe insurance scheme (Kousky and French, 2023); however, studies continue to conclude that policyholders have insufficient incentives to undertake risk reduction (Poussin et al., 2013). A combined means-based voucher and risk reduction loan scheme could also be used to address this issue, as suggested by Kousky and Kunreuther (2014). Means-based vouchers are used to support the affordability of low-income policyholders, while the integration of a risk reduction loan product creates a financial stream for risk reduction implementation (Kousky et al., 2018). Hudson et al. (2016) noted the usefulness of supporting voucher and risk reduction

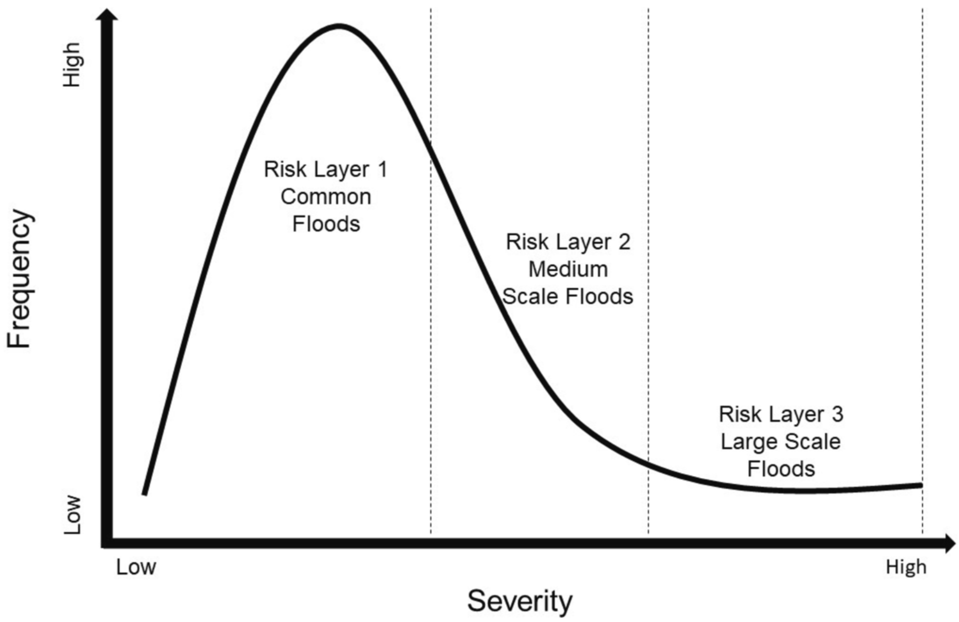

Fig. 2. Risk layering for flood hazards (adapted from (Warner et al., 2013)).

loan schemes by demonstrating that risk reduction benefits outweigh the costs of the voucher scheme over time. Hudson et al. (2016) suggest that a voucher scheme should be temporary such that the pricing incentive for risk reduction is maintained in the long term.

More broadly, SNFRPs can co-ordinate with risk pool members to ensure that risk reduction programmes are aligned to the objectives of the risk pool (Kousky and French, 2023). Risk reduction could also be supported through technical assistance and capacity building. For example, the CCRIF (in partnership) delivered capacity building to member states under their Economics of Climate Adaptation (ECA) programme (CCRIF, 2015; World Bank Group, 2017). The programme assisted member states in evaluating risk reduction and risk transfer options to determine the most cost-effective initiatives relative to their loss aversion potential (CCRIF, 2015; World Bank Group, 2017).

The use of parametric-based policies may limit the ability of SNFRPs to incentivise risk reduction. In comparison to indemnity-based insurance, the pricing structures of parametric insurance policies are not linked to the insured's behaviour, but rather, the payouts are based on hazard-related index thresholds (Organisation for Economic Co-operation and Development (OECD), 2016; Vivid Economics et al., 2016; World Bank Group, 2017, 2023a). The small size of payouts from SNFRPs based on parametric insurance policies relative to total damages may also limit the issue of disincentivised risk reduction (Vivid Economics et al., 2016). This is contingent on coverage limits being appropriately set to match the disaster relief needs of sub-national authorities. The integration of risk reduction into insurance pricing is challenging as there is a need for an accurate appraisal of risk exposure at the scale of the policyholder, as well as a comprehensive understanding of the risk reduction potential of the implemented measures. This issue is further complicated by the variety of risk reduction options, the lack of standardised assessment methods, and the situation-specific nature of their applications. Parametric insurance policies could stimulate risk reduction through the use of premium discounts or if payouts are used for risk reduction measures that avoid flood damages in the future.

The scale of risk reduction initiatives is an important consideration in an SNFRP. The integration of risk reduction measures at a larger spatial scale is dependent on the characteristics and maturity of initiatives. For example, consider the risk reduction potential of a mesoscale wetland rehabilitation initiative in terms of avoided flood losses and relief costs. In this case, the contribution of activities to system-level resilience over a sub-national scale may be time-consuming and technically challenging to appraise. In comparison, risk reduction measures such as levees and dikes, which are more established, have had long-term success in reducing flood risk, most notably in the Netherlands. The assessment of property-level disaster risk reduction may also be complex in the context of an SNFRP, as initiatives may vary by building type, building materials and location. Even if the benefit of property-level risk reduction initiatives is well-understood, their contribution to system-level resilience may be difficult to assess as it is not necessarily determined by the aggregate of property-level risk reduction benefits.

Risk reduction benefits are also difficult to assess for SNFRPs as initiatives may not be restricted to sub-national administrative boundaries. Extending the example of a wetland rehabilitation initiative, risk reduction benefits from wetland restoration in the upper catchment may deliver benefits for sub-national authorities that contain lower parts of the catchment. Certain risk reduction measures may be more easily integrated into an SNFRP than others. For example, policies limiting developments within the floodplain will likely result in reduced disaster response costs (Filatova, 2014).

Risk reduction measures should be coordinated by public sector actors within a larger flood risk management strategy. Flood risk reduction measures are typically public goods that require government investment. In practice, coordination between governments and insurers may be challenging as governments rely on insurers to provide coverage, while insurers rely on governments to provide protection through risk reduction initiatives. Insurers could include co-financing provisions within policies if risk reduction measures are able to directly benefit policyholders. Public-private partnerships have been used to jointly share responsibility and costs for flood risk reduction implementation.

3.2. Risk retention

Risk retention, as it relates to an SNFRP, refers to the joint reserves held by a facility. Joint reserves are derived from two primary sources: seed capital and premium payments from risk pool members (World Bank Group, 2017). Adequate joint reserves enhance a risk pool's financial efficiency, allowing the facility to cover first risk layers, especially within the early years of risk pool operations when claims capacity is yet to be built from premium income. This allows for less risk to be transferred to reinsurance and financial markets, enabling premium cost benefits for risk pool members (Ciullo et al., 2023). The benefits of adequate seed capital on premium cost reductions are noteworthy. An actuarial analysis conducted by the CCRIF for its planned expansion to Central American countries reported that the joint reserve capacity of the risk pool further enhanced premium cost reduction benefits. The study found that premium savings increased by up to 13 % within the CCRIF with joint reserves as opposed to jointly accessing reinsurance markets without capital reserves (World Bank Group, 2017).

Seed capital for SNFRPs is usually derived from two sources: donor concessional finance or national transfers. Using national transfers as seed capital would need to adhere to public finance legislation. Bilateral and multilateral sources have been the primary providers of donor-driven premium support for catastrophe risk pools at the sovereign level (Broberg and Hovani-Bue, 2019). Access to donor funds may be limited by fiduciary management capacity and capabilities, donor fund track records, and perceived political and policy instability (Junghans et al., 2016). Institutional partnerships can assist an SNFRP to overcome some of these issues. For example, under the CCRIF, risk management, financial planning and catastrophe modelling are provided by Evaluacíon De Riesgos Naturales (ERN) and other external partners (CCRIF, 2018).

The ability of an SNFRP to generate adequate joint reserve capacity from premium charges is influenced significantly by the risk pricing approach adopted and premium affordability challenges. These issues are discussed in Sections 4 and 5. In addition to these issues, SNFRPs must maintain a consistent or growing policy uptake over time. This ensures that premium inflows contribute to joint reserve capacity in a reliable manner. The discontinuation of cover can occur for a variety of reasons. A commonly cited reason is basis risk. Basis risk refers to the risk that the payout from a parametric insurance policy does not match the financial loss incurred by the policyholder. This was the experience of Malawi during the 2015/2016 season under the ARC (Scott et al., 2022) and the Solomon Islands under the pilot of the Pacific Catastrophe Risk Insurance Company (PCRIC), which withdrew from their respective risk pools (Nguyen, 2019). In the case of Malawi, the absence of a payout after the 2015/2016 rainy season resulted in negative public attention, leading to the withdrawal of the country from the ARC; Malawi has subsequently rejoined the ARC (Tarazona et al., 2017; Scott et al., 2022). An SNFRP can overcome this challenge by using multi-year policies (Organisation for Economic Co-operation and Development (OECD), 2016) or partial compensation to member states after a certain period in which no payouts occur. Basis risk concerns are expanded upon in Section 6.

3.3. Risk transfer

Risk that is deemed inefficient to hold by SNFRPs can be transferred to the reinsurance and capital markets (Charpentier, 2008). This tranche typically represents the largest share of risk, underwriting the higher layers of a risk pool's portfolio (Tesselaar et al., 2020). All sovereign catastrophe risk pool facilities have integrated risk transfer into their disaster risk financing strategies. As of 2017, the CCRIF possessed an annual joint reserve layer of US$ 25 million, with a further US$ 140 million passed onto reinsurance and capital markets for higher layers (World Bank Group, 2017). In a similar manner, the ARC allocated US$ 22.5 million and US$ 72.5 million for the same layers under its 2015/2016 policy year, respectively (World Bank Group, 2017). In 2012 and 2014, law changes allowed the NFIP to access these reinsurance and financial markets to manage high risk layers, enhancing the financial sustainability of the programme (Federal Emergency Management Agency (FEMA), 2023a; Linder-Baptie et al., 2022). In 2017, the NFIP secured its first reinsurance coverage of US$ 1.042 billion and a further US$ 1.2 billion in coverage through catastrophe bond issuances in 2018, 2019 and 2020 (Linder-Baptie et al., 2022).

During prolonged periods with large losses, reinsurers raise their rates. The lack of affordable reinsurance leads to insurers (risk pools) retaining more risk, ultimately passing on these risks (and costs) to their consumers (risk pool members). The projected increase in extreme weather events driven by climate change is a well-documented concern by insurers and reinsurers (Charpentier, 2008; Monti, 2009; Tesselaar et al., 2020). This increase has prompted reinsurers to place more conditions on insurers. For example, reinsurers may require insurers to include named perils as opposed to providing comprehensive coverage against all catastrophes – open perils (Reuters, 2023). Therefore, it is not only reinsurance rates that are increasing but also coverage within reinsurance policies that is decreasing. Regarding flood risk, Tesselaar et al. (2020) demonstrated that the rising costs and higher variability of flood events under future climate change scenarios are likely to cause greater volatility in reinsurance markets resulting in higher premiums.

In some cases, volatility has resulted in insurers withdrawing coverage completely. For example, large property insurers in the U.S. have withdrawn coverage in Florida and California due to increased losses from wildfires, floods and hurricanes (Rivelli, 2023). It is unclear how an SNFRP would manage uninsurability concerns in the future. One possible avenue could be the approach of the Flood Re and French Catastrophes Naturelles insurance scheme where the national government provides national guarantees if solvency challenges arise (Tesselaar et al., 2020). In addition to reinsurance, SNFRPs may also access the financial markets through insurance-linked securities (ILS). ILS instruments such as catastrophe swaps and bonds are useful in providing risk pools with additional claims capacity during hard reinsurance cycles. They are also less sensitive to large catastrophes in comparison to reinsurance while assisting risk pools in avoiding reinsurance credit risk challenges (Charpentier, 2008). However, sub-national authorities may be less familiar with insurance-linked securities, especially in EMDEs.

4. Risk pricing

The selected pricing approach critically important in determining the long-term financial stability of an SNFRP. Pricing approaches may exist across a spectrum from one that is fully risk-based (FRB) to a solidarity-based (SB) model (Hudson et al., 2019; Kousky and French, 2023; Poussin et al., 2013; Surminski, 2018). FRB pricing refers to the case when the price of catastrophe risk (in this case, flood risk) is based solely on the underlying risk faced by risk pool members. In comparison, an approach based entirely on solidarity entails the provision of mandatory disaster risk coverage irrespective of the individual risk exposure of units. This allows for low-cost premiums to be charged at a fixed rate (cross-subsidisation across risk groups).

The use of FRB approaches is likely to depend on its political feasibility, affordability concerns, the maturity of flood insurance markets and whether coverage is available from public or private insurers (Surminski, 2018). In mature private insurance markets, flood risk insurance offered by private insurers is likely to be risk-based as cross-subsidisation may attract high-risk policyholders, making coverage unsustainable in the long term. In contrast, flood insurance schemes in certain EU countries such as France, Belgium and Spain, intend on maintaining risk sharing amongst policyholders.

In EMDEs, FRB approaches are not likely to be politically feasible owing to affordability concerns (Surminski, 2018); therefore, pricing approaches typically involve some degree of subsidisation. For example, policies underwritten by the ARC, CCRIF and PCRIC are partially risk-based (PRB) with external means-based subsidies to support affordability. In contrast, the solidarity approach has been adopted in France, Spain, and New Zealand. In these schemes, disaster coverage is integrated into standard property insurance policies allowing for cross-subsidisation (Kousky and French, 2023; Organisation for Economic Co-operation and Development (OECD), 2016; World Bank Group, 2017). In the context of an SNFRP, the adoption of a pricing approach must consider: (1.) the long-term solvency of the facility, (2.) the affordability of premiums for sub-national authorities, (3.) the influence of pricing on risk pool membership, and (4.) incentives to undertake risk reduction and climate adaptation by risk pool members.

The choice of pricing approach is not straightforward. The justification of FRB pricing to facilitate actuarial soundness must be assessed critically. Premium rates are actuarially sound if they “represent the expected value of all future costs associated with the sale of each flood insurance policy” (Bingham et al., 2006, p. 12). Risk-based pricing is often used as a proxy for actuarially sound premiums (McAneney et al., 2016). However, from a solvency perspective, an SNFRP may be actuarially sound if it possesses sufficient capital reserves and reinsurance capacity to meet its statutory obligations even if the pool does not charge risk-reflective premiums (McAneney et al., 2016).

The potential impact of PRB pricing on the financial stability of an SNFRP is well demonstrated by the NFIP. The NFIP, created in 1968 by the U.S. Congress, offers flood insurance to property owners, renters, and businesses (FEMA, 2023b). Solvency challenges in the NFIP stem from historical decisions by Congress to set total revenue from premium charges below an actuarially sound level (Bingham et al., 2006). Premium rates were set to maintain total revenues to the ‘historical average loss year’ (which was less than the expected true long-term average) (Bingham et al., 2006, p. 10). This allowed for increased market penetration of the NFIP and lower premium prices. However, it also resulted in the programme not possessing sufficient reserves to manage large losses, as was the case for Hurricane Katrina in 2005 (Bingham et al., 2006). Hurricane Katrina resulted in NFIP claims close to US $ 17 billion forcing the programme to borrow from the U.S. Treasury (Insurance Information Institute (III), 2023). More recently, Hurricane Harvey (2017) and Superstorm Sandy (2012) have continued to leave the NFIP in debt (Insurance Information Institute (III), 2023). As of November 2022, the National Flood Insurance Program’s (NFIP) debt stood at $20.5 billion (FEMA, 2022).

PRB or SB pricing is often used to address concerns of affordability by allowing low-risk policyholders to subsidise high-risk ones. In the NFIP, this has been accomplished by utilising discounts, subsidies, and cross-subsidies (McNulty et al., 2011). Regarding pricing, between 15 and 20 % of all NFIP policyholders were explicitly subsidised; this resulted in savings of between 60 and 65 % on the premium costs for high-risk policyholders (Brannon and Blask, 2017). Despite these pricing benefits, subsidies can cause perverse effects. In the NFIP, subsidies are not based on need; therefore, their uniform implementation creates pricing benefits for individuals who can pay full-risk premium rates. Compromising actuarial fairness is usually undertaken with the assumption that the pricing benefits will accrue to “poorer” entities. This is well noted by Ben-Shahar and Logue (2015, p. 596) who state: “To the extent that high-income owners of beachfront property are the primary beneficiaries of [the NFIP], and to the extent that the cross-subsidy is disproportionately funded by the less affluent inland-residing taxpayers and policyholders, it represents a regressive form of redistribution.” Therefore, subsidisation efforts cannot assume that risk differences will be arbitrary while more broadly, affordability cannot be used as a proxy for distributive justice (Ben-Shahar and Logue, 2015). The Federal Emergency Management Agency has developed a new rating system (Risk Ratings 2.0) to address the issue of actuarially unsound premiums within the NFIP (Kousky and French, 2023). Despite this initiative and the statutory limits on annual premium rate increases, affordability concerns remain. Most commentators note the need for means-based subsidies to support the full implementation of risk-based premiums (Government Accountability Office (GAO), 2017, 2016; Horn, 2023; Kousky and French, 2023).

PRB or SB pricing may not be possible in an SNFRP. Since sub-national authorities may be under the leadership of different political parties, the endorsement of cross-subsidisation to assist entities with less financial capacity is less likely. PRB or SB approaches may be endorsed if sub-national authorities are able to acknowledge *and* accept that the payouts from the SNFRP still provide public benefits (disaster relief efforts and the resumption of public service delivery), irrespective of where they accrue. If affordability is a concern for SNFRP members, external subsidies from outside the risk pool can be used. This ensures that insurance pricing is separate. Premium support issues will be elaborated upon in Section 5.

PRB or SB pricing may also deter participation in an SNFRP. Participation in SNFRPs could be made mandatory by higher levels of government. Legislated participation in risk pools is not uncommon. For example, in the U.S., participation in workers’ compensation pools is mandatory for most employers in every state except for Texas ((National Association of Insurance Commissioner (NAIC), 2022). Under the Catastrophes Naturelles scheme, a mandatory natural catastrophe premium is added to the properties and vehicle insurance contracts (Poussin et al., 2013), irrespective of their exposure to flooding – no risk pricing. This, in addition to the high penetration of insurance in metropolitan France (close to 100 %), contributes to maintaining a stable risk pool size (Charpentier et al., 2022). The public benefit nature of SNFRPs could support the argument for mandatory participation and its legislation from higher levels of government. PRB and SB approaches may also diminish the ability of insurance premiums to incentivise risk reduction and climate adaptation (Vivid Economics et al., 2016) − Section 3.1.

The use of PRB and FRB may be limited by the availability of accurate flood risk maps and the underlying data for its generation. This has historically been a concern for the NFIP. Flood risk maps may also include climate change projections. It is doubtful that insurers will use long-term climate projections in their pricing models as policies are typically priced one year ahead. However, flood risk maps that integrate climate change considerations may be better placed to assess the financial stability of flood insurance schemes in the long term. In addition, they may provide timeframes for when flood risk reduction measures should be implemented and areas that may be uninsurable in the future. Issues with the availability of flood-related data are likely to be acute in EMDEs, with sources heavily biased towards European and North American regions.

5. Affordability and forms of premium support

Premium financing has been noted as one of the most significant challenges in sovereign catastrophe risk pools. Premium cost reductions of 52, 45 to 50, and 50 % have been provided to member states under the ARC, CCRIF and PCRIC’s pilot, respectively (ARC, n.d.; Linnerooth-Bayer et al., 2012; Mahul and Cook, 2014). Even though risk pools may be able to deliver premium cost reductions, premium financing and affordability remain well-documented concerns. There has been a degree of subsidisation within all three major sovereign catastrophe risk pools. Under the pilot of the PCRIC, the Marshall Islands, Samoa, Tonga, and Vanuatu received partial premium support while Senegal and Haiti received similar support under the ARC and CCRIF, respectively (World Bank Group, 2017). Subsidies may be offered in various forms. They may be targeted or universal: Targeted subsidies are offered based on certain criteria such as income levels or location, or through self-identification; universal subsidies are offered to all risk pool members (Vivid Economics et al., 2016). Subsidies can be offered to sub-national authorities on a fixed level, as a percentage of a premium level or as a cap to avoid premium charges over a certain level (Vivid Economics et al., 2016).

As outlined in Section 4, SNFRPs in EMDEs are likely to adopt PRB pricing. PRB pricing may incorporate the use of means-based subsidies that are external to the risk pool or cross subsidisation between risk pool members. Section 5 will focus on the influence of premium affordability on the increased uptake of insurance coverage – price elasticity of flood coverage against the backdrop of an SNFRP; the need for premium support; and the form of subsidies that maximises premium cost reductions. The issue of access to donor funds is noted but not discussed in greater detail.

5.1. Does price influence demand?

The primary aim of premium subsidies is to improve the affordability and access to insurance policies. Therefore, the first question influencing the provision of subsidies is whether their use can increase the demand and uptake of insurance coverage – is affordability a barrier to the uptake of insurance policies? The assessment of price elasticity can be challenging and may vary by the scale and nature of the flood insurance product. For example, natural disaster coverage in Norway is bundled with fire insurance and mandatory for all property insurance lines (Bull, 2018). In this case, price elasticity is difficult to assess as disaster coverage is bundled and mandatory.

An assessment of price elasticity at a sovereign or sub-national scale is challenging. This is owing to political and fiscal constraints that influence a determination of premium affordability and the uptake of policies. As highlighted by Surminski et al. (2022), despite the economic rationale for insurance, anticipatory measures may offer limited political benefits for sub-national governments as compared to more tangible and visible services (for example, the establishment of a clinic in a rural area, or enhanced sanitation and water provisions). This sentiment may be dependent on the timing and scale of disasters. McAneney et al. (2016) suggest that the political debate on affordability (among other issues) tends to fluctuate depending on the sequence of losses and the length of periods between large-scale events. The reluctance to pay for coverage may also stem from a reliance on donor and relief aid (Linnerooth-Bayer et al., 2005) or intergovernmental transfers from national government actors that are available post-disaster (Pillay, 2016). This reliance may be magnified in sub-national authorities in EMDEs where competing demands could be more urgent. Other factors influencing the decision to take up insurance include the timing of budget cycles, understanding the benefits associated with disaster coverage, and the complexity of disaster risk management approaches.

Subsidies can be useful for increasing or maintaining the size of an SNFRP. Anecdotal evidence suggests that an increase in the price of policies offered by SNFRPs could result in reduced participation and policy uptake. For example, 61 % of CCRIF members stated that they would discontinue their policies if they were financially constrained (CCRIF, 2015). Four countries with PCRIC's pilot cited that they would be unable to participate without premium subsidies (Martinez-Diaz et al., 2019). Once-off subsidy support can also entice SNFRP participants to integrate premiums into their budget processes. For example, after receiving a subsidy from Japan in its first year under the ARC, Senegal mainstreamed premium costs into their budget planning for the following years (Scott et al., 2022). It is important to note that full premium subsidies do not always guarantee policy uptake. For example, Mozambique declined participation under the ARC despite being offered a 100 % premium subsidy; Scott et al. (2022) stated that Mozambique's declined participation was due to concerns with the underlying risk model.

At a household level, the price elasticity of flood insurance is difficult to assess owing to the mandatory purchase requirements of certain products, as is the case in several EU countries (Kousky, 2017). Browne and Hoyt (2000) found that income levels and price were influential in determining decisions to purchase flood insurance at a household level. However, other studies have found flood insurance to be price-inelastic (Atreya et al., 2015; Kriesel and Landry, 2004; Landry and Jahan-Parvar, 2011).

5.2. Need for premium support by sub-national authorities

The revenue generation capacity of sub-national governments may be limited. For example, higher value taxes, such as those for fuel and income, usually flow into national budgets (Pillay and Pillay, 2018). Sub-national inflows are limited to national transfers and funds from property rates and service charges (Pillay and Pillay, 2018). In EMDEs, the service delivery mandate and strained internal budgets of sub-national authorities make it unlikely that entities will be able to finance insurance premiums entirely; partial subsidies could entice sub-national governments to finance the remaining shortfall. Since the unaffordability or willingness to pay for insurance is difficult to define for sub-national authorities, it is difficult to determine whether the trade-offs or opportunity costs of insurance premiums are justified in comparison to essential budget allocations (for example, health and social services) (Surminski, 2018). Furthermore, unallocated budget allocations or positive cash balances of sub-national authorities are not necessarily indicators of wasted expenditure. Sub-national governments may require flexibility in responding to urgent needs requiring reallocations.

5.3. Form of premium support

A critical question regarding premium support is the most impactful form of subsidy such that premium cost reductions are maximised. Premium subsidies from concessional sources may be direct or indirect (Vivid Economics et al., 2016; World Bank Group, 2017). Direct premium subsidies are focused on the demand side and refer to financial assistance to support the partial or whole premium costs of risk pool participants. In comparison, indirect premium subsidies support the supply side, allowing the risk pool to offer lower premiums. Indirect premium subsidies could include the provision of seed capital or the payment of reinsurance premiums.

Donor decision-making in the form of premium support (direct or indirect) is challenging and risk pool-specific. In a hypothetical analysis conducted by the World Bank Group (2017), the cost-effectiveness of indirect subsidies used for seed capital instead of direct subsidies depends on whether premium savings from seed capital are above or below a threshold relative to the net present value of the direct subsidy volume. The threshold of premium savings attained by retaining risk depends on the reinsurance cycle's state and the capital reserves relative to total premium volume (World Bank Group, 2017). The trade-offs between direct subsidies and capital injections were also investigated by Vivid Economics et al. (2016); the study also notes that the assumptions of any assessment are likely to change the relative cost-effectiveness of each option. In addition, the study broadly finds that the direct premium subsidies, donor capitalisation and reinsurance payments are likely to have the most impact on the premium costs for risk pool members.

Concessional support for risk pool capitalisation may only be effective to a certain level (Scott et al., 2022). For example, the ARC is considered overcapitalised (Vivid Economics et al., 2016). Therefore, additional donor flows could yield less premium cost reductions than direct premium subsidies. This issue is also circular. Donor funds for capitalisation are likely to be needed if the risk pool grows; however, this is contingent on the availability of premium subsidies. Other criteria that may influence the decision-making of donors and the subsidy form for recipients include: the stage of risk pool development; the current levels of subsidisation and capitalisation; the demand for insurance policies; and, expected capital and premium support in the future (Scott et al., 2022).

5.4. *Phasing of premium support*

Subsidies may be offered for a limited period, on a sliding scale with the intention of being phased out, or on a continuous basis (Vivid Economics et al., 2016). Irrespective of the form of subsidy support, a key concern associated with its provision is the potential reliance of schemes on donor support; this may compromise the stability of an SNFRP once subsidy programmes end. Kousky and Shabman (2015) found that the uptake of NFIP policies across most U.S. states declined after the passing of the Biggert-Waters Flood Insurance Reform Act of 2012, which reduced premium subsidies. Certain subsidies were reinstated through the passing of the Homeowner Flood Insurance Affordability Act of 2014; this was enabled by efforts from communities lobbying across 35 states (Organisation for Economic Co-operation and Development (OECD), 2016). This demonstrates that once subsidies are offered, they are challenging to eliminate.

Long-term premium support may be the only option for the participation of certain countries. For example, Haiti has received premium subsidies continuously under the CCRIF (Artemis, 2018; Caribbean Development Bank (CDB), 2014; Martinez-Diaz et al., 2019; World Bank Group, 2017). The country's significant catastrophe risk exposure and fiscal circumstances meant that the country would not have been able to participate in the CCRIF without premium support (World Bank Group, 2017).

Premium subsidies through donors are not available in perpetuity. Therefore, avoiding donor reliance while facilitating financial independence is a crucial component in developing an SNFRP. To avoid donor reliance, premium subsidies could be offered using a sliding scale that gradually phases out the percentage commitment. For example, under the ARC, a subsidy schedule of 75 % is recommended for year one, with the subsidy decreasing by 25 % per year until premiums are fully risk-based (Vivid Economics et al., 2016). This approach is advantageous as it allows for subsidy support to be planned over time, ensuring for a smooth transition if subsidy programmes end.

6. Policy design

A critical decision during the development of an SNFRP is the form of policies to be administered to members. Policies may be parametric- or indemnity-based. The most critical issue influencing this decision is the overarching purpose and focus areas of the SNFRP. A facility may aim to: (1.) correct market failures in the property and asset insurance market for natural catastrophe coverage; (2.) provide immediate liquidity to support responses to natural catastrophes; or, (3.) provide general coverage for municipal assets that includes coverage of catastrophe risks. Both parametric- and indemnity-based insurance policies can be used to address these objectives. The choice of policy type is not straightforward and is also influenced by several factors such as: the type of coverage required; the speed of payout; the regulatory environment; and transaction costs. Given the SNFRP application of interest in this research as a provider of immediate liquidity to support post-disaster relief and the ability of SNFRPs to provide coverage in EMDEs with underdeveloped indemnity insurance markets, parametric insurance policies are preferred.

Indemnity-based policies reimburse the insured for actual losses incurred, while parametric insurance covers payouts according to pre-defined parameters (Organisation for Economic Co-operation and Development (OECD), 2016; Vivid Economics et al., 2016; World Bank Group, 2017, 2023a). In parametric insurance policies, payouts are commensurate to the severity of the flood event; however, the payout size is not intended to provide comprehensive coverage of all disaster losses experienced (World Bank Group, 2023a). Parametric insurance products are more flexible (Swiss Re, 2022d). This allows for contracts to be tailored to the specific index and needs of the policyholder. Under the CCRIF's excess rainfall policies, governments can use their payouts for various purposes (CCRIF, 2019). This includes, but is not limited to: humanitarian aid for affected individuals; repairs to essential infrastructure such as stormwater networks, water treatment facilities, roads and other transport networks; managing external debt commitments; and government salaries (CCRIF, 2019). Within standard property insurance policies, flood coverage is typically limited to direct damages (property damage and building contents) (Organisation for Economic Co-operation and Development (OECD), 2016).

As direct service providers to individuals, sub-national governments at the local level are often the first responders to flood events (Chen, 2020; Crow and Albright, 2019). Despite this status, internal disaster management budgets of sub-national governments are often insufficient to manage the financial costs of large-scale floods, especially in EMDEs (Gurenko, 2015). Strained budgets in sub-national governments may also limit their ability to reprioritise internal funds during or immediately after a disaster. International aid and earmarked emergency funds from higher levels of government may be available (Chen, 2020; Soetanto et al., 2020); however, these financial transfers are often slow in reaching lower levels of government (Kelkar et al., 2006).

Parametric insurance policies can facilitate quick payouts as they are based on a pre-agreed payment structure based on an event's index value, with payouts being triggered once the threshold has been exceeded (CCRIF, 2015; Pillay, 2016; Swiss Re, 2022d; World Bank Group, 2023a). The benefit of timely post-disaster financial support is well-illustrated by Haiti's CCRIF payout after an earthquake in January 2010. The US$ 7.5 million payout was the first set of funds received when compared to other pledges (international and regional) (CCRIF, 2010). Under the CCRIF, PCRIC and ARC – all of which are based on parametric insurance policies – payouts have been made between 3 to 14 days once a threshold has been exceeded (World Bank Group, 2017). In comparison, payouts from indemnity-based insurance policies are based on post-disaster loss adjustment assessments. These assessments can be time-consuming (often between months to years after a disaster), complex and administratively intensive (Sengupta and Kousky, 2023). Parametric insurance policies may generate administrative savings over time (Pillay, 2016). The initial capital requirements for hazard monitoring systems and data and modelling needs to develop index-payout relationships may be costly; however, these costs are usually donor subsidised.

Basis risk can occur in both types of policies; however, it is a greater concern in parametric insurance policies (Swiss Re, 2022d). Basis risk refers to the case when triggered payouts do not match the policyholder's financial loss (Margan, 2021). Basis risk arises from the imperfect alignment between the payout index, trigger event and the severity of the hazard (Figueiredo et al., 2018). Basis risk may also result from geographical variations between the location of the index measurement and the loss experienced – geographical basis risk (World Bank Group, 2023b). This is a notable issue in rainfall indices owing to the spatial rainfall effect (Norris et al., 2023). Geographical basis risk is problematic as SNFRP members exist spatially over a landscape. This results in difficulty in aligning index measurements, flood occurrences and the administrative boundaries of policyholders (sub-national governments) (Tellman et al., 2022). Geographical basis risk may be exacerbated in the case of SNFRPs with small spatial extents or ones composed of entities with smaller geographical extents. Geographical basis risk challenges in excess rainfall policies may necessitate a greater density of rainfall stations over an area, satellite precipitation products, or both (Courty et al., 2018).

The selection of flood-related indices within parametric policies may also be problematic. Indices, sometimes referred to as parameters, are defined as "objective measures that are correlated to a specific risk and ultimately to a financial loss" (Swiss Re, 2023, para. 16). In general, rainfall and inundation-related (flood depth, inundation duration, or inundation area) indices are most commonly used. Flood drivers such as extreme rainfall may be used as indices; however, these indices are only able to partially explain flood damages (Spekkers et al., 2012). This is also a problem with inundation variables as flood depth cannot explain complex property damage (Kreibich et al., 2009; Lazzarin et al., 2022). This issue is further complicated in the context of an SNFRP focused on relief; in this case, indices would also need to be linked to relief costs incurred.

The modelling and data requirements to assess flood-related indices are typically resource-intensive and complex (Norris et al., 2023). Inundation-related indices such as flood depth may require the use of hydrodynamic models (Thomas et al., 2023; Vecere et al., 2021). These approaches may necessitate input data at a high spatial resolution such as Light Detection and Ranging (LIDAR) digital elevation datasets (Thomas et al., 2023). Satellite imagery may also be used to detect inundation extents; however, these techniques may be limited by (1.) the type of sensor – optical sensors as opposed to microwave (Synthetic Aperture Radar (SAR)) sensors are not able to provide imagery of suitable quality in cloudy weather (Anusha and Bharathi, 2020); (2.) the spatial resolution of imagery – inundation detection in urban environments is limited owing to higher property densities (Courty et al., 2018; Yang et al., 2022); and, (3.) the temporal resolution of imagery – longer revisit time of satellites may result in small or flash floods being missed (Yang et al., 2022).

Generally, modelling and data requirements are more intensive for flood parametric policies than indemnity-based property insurance policies with flood coverage. Indemnity-based property policies may also use similar techniques adopted within parametric insurance policies such as flood inundation depth maps with different return periods across an area. However, these model outputs are generally static in nature. Detecting indices in near-real-time is necessary within parametric insurance policies as events are continuously assessed to determine if a payout is triggered (Norris et al., 2023). A comprehensive analysis of factors influencing the design of flood parametric insurance policies is beyond the scope of this research. These design considerations are investigated in a forthcoming publication – See (Pillay, 2023).

Other advantages associated with parametric insurance policies include: enhanced transparency; avoided concerns of moral hazard and adverse selection; and the provision of coverage for risks that are difficult to model (Sengupta and Kousky, 2023; Swiss Re, 2022d). It is important to note that standard indemnity- and parametric-based insurance are not mutually exclusive; that is, SNFRP members can hold property and asset insurance policies offered by other parties in addition to parametric policies underwritten by the SNFRP. Regarding payout timeliness, all post-disaster financing needs are not required at the same time (Mahul and Ghesquiere, 2010). Owing to the flexible and quick nature of payouts, an SNFRP focused on flood relief and response activities could be based on parametric insurance policies, while indemnity-based property and asset insurance policies should be used if comprehensive flood protection for public assets is required, and the speed of payout is not a primary concern.

7. Conclusion

This research represents a starting point on considerations for developing a sub-national flood risk pooling facility (SNFRP). In conclusion, an SNFRP managing flood risks must consider the following:

- The scaling down of a risk pool to a smaller geographic area at the sub-national level could influence the geographic area of a hazard and its occurrence over several sub-national authorities, while increasing the potential interconnectivity between natural landscape features. This may increase the spatial correlation of flood events affecting the risk diversification benefits over time. The evaluation of spatial correlation at the sub-national level may also be limited by more granular data and modelling requirements;
- An SNFRP should develop a layered disaster risk financing strategy to ensure financial efficiency. A layered disaster risk financing strategy from the perspective of the SNFRP must integrate strategies to support and incentivise risk reduction indirectly; build joint reserves from premium income and access funding for seed capitalisation efforts; and transfer risk to reinsurance and capital markets that is inefficient to hold. This may necessitate partnerships and engagement with reinsurance companies (including brokers), national government and donors on issues of seed capitalisation; donor subsidy support; reinsurance access; uninsurability concerns driven by climate change; and alignment with risk reduction and climate adaptation programmes;
- An SNFRP focused on relief is likely to be based on parametric policies. The design of parametric policies must carefully consider the flood-related index to be used, noting concerns of geographical basis risk. Geographic basis risk may be amplified in an SNFRP operating smaller spatial scales as flood events are not restricted to the administrative boundaries of sub-national authorities. Data partnerships are crucial, especially for facilities based in EMDEs; and
- Balancing FRB pricing and affordability represents a significant challenge for SNFRPs, especially those operating in EMDEs. The limited revenue generation capacity of sub-national authorities compared to the national level may necessitate PRB pricing (means-based subsidies) to enhance premium affordability. The form of premium support required (direct or indirect) will depend on the specific characteristics of the SNFRP. From anecdotal evidence, premium subsidies can ensure greater participation in SNFRPs. However, their design must consider safeguards to reduce charity hazard and price distortions that may affect risk reduction and climate adaptation implementation.

Despite the comprehensive set of design considerations outlined by this research, the most significant factor influencing the inception of a sub-national flood risk pool is securing political buy-in. Political buy-in is essential to ensure political party co-ordination. In addition, it can assist in promoting budgeting that prioritises disaster insurance and seed capital while subsidising certain risk pool members to enhance affordability. Their co-operation results in reduced donor reliance; a constant risk pool membership; and, the maintenance of coverage irrespective of election cycles.

CRediT authorship contribution statement

Kamleshan Pillay: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: [Kamleshan Pillay reports financial support was provided by International Development Research Centre.].

Acknowledgements

This work was supported by the International Development Research Centre (IDRC) [Grant no. 108620-001] through the Municipal Risk Pooling program.

Data availability

No data was used for the research described in the article.

References

Adikari, Y., Osti, R., Noro, T., 2010. Flood-related disaster vulnerability: an impending crisis of megacities in Asia: Flood vulnerability in Asian megacities. Journal of Flood Risk Management 3, 185–191. https://doi.org/10.1111/j.1753-318X.2010.01068.x.

Federal Emergency Management Agency (FEMA), 2023a. National Flood Insurance Program's reinsurance program [WWW Document]. National Flood Insurance Program's reinsurance program. URL https://www.fema.gov/flood-insurance/work-with-nfip/reinsurance (accessed 6.16.23).

Anusha, N., Bharathi, B., 2020. Flood detection and flood mapping using multi-temporal synthetic aperture radar and optical data. The Egyptian Journal of Remote Sensing and Space Science 23, 207–219. https://doi.org/10.1016/j.ejrs.2019.01.001.

ARC, 2023. African Risk Capacity launches the first flood risk Insurance product in Africa. URL https://www.arc.int/news/african-risk-capacity-launches-first-flood-risk-insurance-product-africa (accessed 7.16.23).

ARC, n.d. Sovereign disaster risk solutions: A project of the African Union.

Artemis, 2018. Haiti to get Caribbean Development Bank support for CCRIF premiums. URL https://www.artemis.bm/news/haiti-to-get-caribbean-development-bank-support-for-ccrif-premiums/ (accessed 7.26.23).

Asian Development Bank, 2018. Philippine City Disaster Insurance Pool: Pool rationale and design. Asian Development Bank, Manila, Philippines. .

Association of Government Risk Pools (AGRiP), 2014. Pr toolkit for public entity pools. Association of Government Risk Pools, Southfield, United States.

Atreya, A., Ferreira, S., Michel-Kerjan, E., 2015. What drives households to buy flood insurance? New evidence from Georgia. Ecological Economics 117, 153–161. https://doi.org/10.1016/j.ecolecon.2015.06.024.

Balogun, K., Vyas, S., Wagner, S., Soenke, K., 2021. Managing floods: Developing a risk pooling framework (Discussion Paper). Munich Climate Insurance Initiative, Germany.

Baum, R., Characklis, G.W., Serre, M.L., 2018. Effects of geographic diversification on risk pooling to mitigate drought-related financial losses for water utilities. Water Resources Research 54, 2561–2579. https://doi.org/10.1002/2017WR021468.

Ben-Shahar, O., Logue, K.D., 2015. Under the weather: Government insurance and the regulation of climate risks. SSRN Journal. https://doi.org/10.2139/ssrn.2549320.

Berghuijs, W.R., Allen, S.T., Harrigan, S., Kirchner, J.W., 2019. Growing spatial scales of synchronous river flooding in Europe. Geophys. Res. Lett. 46, 1423–1428. https://doi.org/10.1029/2018GL081883.

Beshir, A.A., Song, J., 2021. Urbanization and its impact on flood hazard: the case of Addis Ababa, Ethiopia. Nat Hazards 109, 1167–1190. https://doi.org/10.1007/s11069-021-04873-9.

Bingham, K., Charron, M., Kirschener, G., Messick, R., Sabade, S., 2006. The role of actuarial soundness in the National Flood Insurance Program. Deloitte Consulting LLP, Hartford, United States.

Blöschl, G., Sivapalan, M., 1997. Process controls on regional flood frequency: Coefficient of variation and basin scale. Water Resour. Res. 33, 2967–2980. https://doi.org/10.1029/97WR00568.

Brannon, I., Blask, A., 2017. Reforming the National Insurance Program: Towards private insurance (No. 817). CATO Institute, Washington D.C.

Broberg, M., Hovani-Bue, E., 2019. Disaster risk reduction through risk pooling: The case of hazard risk pooling schemes, in: Samuel, K.L.H., Aronsson-Storrier, M., Bookmiller, K.N. (Eds.), The Cambridge Handbook of Disaster Risk Reduction and International Law. Cambridge University Press, pp. 257–274. Doi: 10.1017/9781108564540.015.

Browne, M.J., Hoyt, R.E., 2000. The demand for flood insurance: Empirical evidence. Journal of Risk and Uncertainty 20, 291–306. https://doi.org/10.1023/A:1007823631497.

Brunner, M.I., Hingray, B., Zappa, M., Favre, A., 2019. Future trends in the interdependence between flood peaks and volumes: Hydro-climatological drivers and uncertainty. Water Resources Research 55, 4745–4759. https://doi.org/10.1029/2019WR024701.

Bull, H.J., 2018. Natural damage insurance: The Norwegian model. Scandinavian Studies in Law 64, 46–55.

Callen, M., Imbs, J., Mauro, P., 2015. Pooling risk among countries. Journal of International Economics 96, 88–99. https://doi.org/10.1016/j.jinteco.2015.01.006.

Caribbean Development Bank (CDB), 2014. Support for Haiti to meet commitment to Caribbean Catastrophe Risk Insurance Facility (CCRIF) for the 2014-2015 hurricane season. Caribbean Development Bank (CDB), Barbados.

CCRIF, 2010. CCRIF: Application of risk analysis and modelling in the insurance sector.

CCRIF, 2015. CCRIF strategic plan 2015 - 2018. CCRIF, Cayman Islands.

CCRIF, 2018. CCRIF strategic plan 2018 - 2021. CCRIF, Cayman Islands.

CCRIF, 2019. Use of CCRIF payouts (2007 - 2018). The Caribbean Catastrophe Risk Insurance Facility SPC, Cayman Islands.

Cebotari, A., Youssef, K., 2020. Natural disaster insurance for sovereigns: Issues, challenges and optimality. IMF Working Papers 2020, 1. Doi: 10.5089/9781513525891.001.

Centre for Research on the Epidemiology of Disasters (CRED), 2023. The International Disaster Database.

Charpentier, A., 2008. Insurability of climate risks. Geneva Pap Risk Insur Issues Pract 33, 91–109. https://doi.org/10.1057/palgrave.gpp.2510155.

Charpentier, A., Barry, L., James, M.R., 2022. Insurance against natural catastrophes: balancing actuarial fairness and social solidarity. Geneva Pap Risk Insur Issues Pract 47, 50–78. https://doi.org/10.1057/s41288-021-00233-7.

Chen, G., 2020. Assessing the financial impact of natural disasters on local governments. Public Budgeting & Finance 40, 22–44. https://doi.org/10.1111/pbaf.12245.

Chivers, J., Flores, N., 2002. Market failure in information: The National Flood Insurance Program. Land Economics 78, 515–521.

Ciullo, A., Strobl, E., Meiler, S., Martius, O., Bresch, D.N., 2023. Increasing countries' financial resilience through global catastrophe risk pooling. Nat Commun 14, 922. https://doi.org/10.1038/s41467-023-36539-4.

Climatewise, 2012. Compendium of disaster risk transfer initiatives in the developing world.

Courty, L., Rico-Ramirez, M., Pedrozo-Acuña, A., 2018. The significance of the spatial variability of rainfall on the numerical simulation of urban floods. Water 10, 207. https://doi.org/10.3390/w10020207.

Cronk, L., Aktipis, A., 2021. Design principles for risk-pooling systems. Nat Hum Behav 5, 825–833. https://doi.org/10.1038/s41562-021-01121-9.

Crow, D.A., Albright, E.A., 2019. Intergovernmental relationships after disaster: state and local government learning during flood recovery in Colorado. Journal of Environmental Policy & Planning 21, 257–274. https://doi.org/10.1080/1523908X.2019.1623660.

Cummins, J.D., Mahul, O., 2009. Catastrophe risk financing in developing countries: Principles for public intervention. The World Bank, Washington D.C.

Devi, N.N., Sridharan, B., Kuiry, S.N., 2019. Impact of urban sprawl on future flooding in Chennai city, India. Journal of Hydrology 574, 486–496. https://doi.org/10.1016/j.jhydrol.2019.04.041.

Doucette, J.E., 2002. Wading in the pool: Interlocal cooperation in municipal insurance and the state regulation of public entity risk sharing pools—A survey. Connecticut Insurance Law Journal 8, 533–689.

Echendu, A.J., 2021. Relationship between urban planning and flooding in Port Harcourt city, Nigeria; insights from planning professionals. J Flood Risk Management 14. https://doi.org/10.1111/jfr3.12693.

Vivid Economics, Surminski Consulting, Calland Consulting, 2016. Understanding the role of publicly funded premium subsidies in disaster risk insurance in developing countries. United Kingdom.

FEMA, 2022. The watermark. Federal Emergency Management Agency (FEMA), Washington D.C.

FEMA, 2023b. Flood insurance. URL https://www.fema.gov/flood-insurance (accessed 6.26.23).

Figueiredo, R., Martina, M.L.V., Stephenson, D.B., Youngman, B.D., 2018. A probabilistic paradigm for the parametric insurance of natural hazards: A probabilistic paradigm for parametric insurance. Risk Analysis 38, 2400–2414. https://doi.org/10.1111/risa.13122.

Filatova, T., 2014. Market-based instruments for flood risk management: A review of theory, practice and perspectives for climate adaptation policy. Environmental Science & Policy 37, 227–242. https://doi.org/10.1016/j.envsci.2013.09.005.

Frankel, N., 2021. Municipal risk pools 101. URL https://www.benchmarkanalytics.com/blog/municipal-risk-pools-101/ (accessed 7.16.23).

Government Accountability Office (GAO), 2016. National Flood Insurance Program: Options for Providing Affordability Assistance. United States Government Accountability Office, Washington D.C.

Government Accountability Office (GAO), 2017. Comprehensive reform could improve solvency and enhance resilience. United States Government Accountability Office, Washington D.C.

Gupta, V.K., Castro, S.L., Over, T.M., 1996. On scaling exponents of spatial peak flows from rainfall and river network geometry. Journal of Hydrology 187, 81–104. https://doi.org/10.1016/S0022-1694(96)03088-0.

Gurenko, E.N., 2015. Climate change and Insurance, 1st ed. Routledge. Doi: 10.4324/9781849775960.

Gutierrez, A.H., 2015. What are we talking about when we talk about "subnational" governments? URL https://blogs.worldbank.org/governance/what-are-we-talking-about-when-we-talk-about-subnational-governments (accessed 7.13.23).

Hallegatte, S., Green, C., Nicholls, R.J., Corfee-Morlot, J., 2013. Future flood losses in major coastal cities. Nature Clim Change 3, 802–806. https://doi.org/10.1038/nclimate1979.

Hanson, S., Nicholls, R., Ranger, N., Hallegatte, S., Corfee-Morlot, J., Herweijer, C., Chateau, J., 2011. A global ranking of port cities with high exposure to climate extremes. Climatic Change 104, 89–111. https://doi.org/10.1007/s10584-010-9977-4.

Heinen, A., Strobl, E., 2019. Insuring Against Hurricanes: What is to be gained for Caribbean Islands to join a cross-country insurance scheme? Presented at the Annual Monetary Studies Conference, Annual Monetary Studies Conference, Port-of-Spain, Trinidad, Trinidad and Tobago, pp. 1–34.

Hochrainer, S., Mechler, R., 2011. Natural disaster risk in Asian megacities. Cities 28, 53–61. https://doi.org/10.1016/j.cities.2010.09.001.

Horn, P.H., 2023. Options for making the National Flood Insurance Program more affordable. Congressional Research Service, Washington D.C.

Hudson, P., Botzen, W.J.W., Feyen, L., Aerts, J.C.J.H., 2016. Incentivising flood risk adaptation through risk based insurance premiums: Trade-offs between affordability and risk reduction. Ecological Economics 125, 1–13. https://doi.org/10.1016/j.ecolecon.2016.01.015.

Hudson, P., Botzen, W.J.W., Aerts, J.C.J.H., 2019. Flood insurance arrangements in the European Union for future flood risk under climate and socioeconomic change. Global Environmental Change 58, 101966. https://doi.org/10.1016/j.gloenvcha.2019.101966.

Insurance Information Institute (III), 2023. Top 10 most significant flood events by National Flood Insurance Program payouts [WWW Document]. URL (accessed 6.16.23).

Jongman, B., 2018. Effective adaptation to rising flood risk. Nat Commun 9, 1986. https://doi.org/10.1038/s41467-018-04396-1.

Junghans, L., Eckstein, D., Kreft, S., Syberg, M., Weischer, L., 2016. Going to town: How the Green Climate Fund can support a paradigm shift in cities. Germanwatch e.V, Bonn.

Kelkar, U., James, C.R., Kumar, R., 2006. The Indian insurance industry and climate change: exposure, opportunities and strategies ahead. Climate Policy 6, 658–671. https://doi.org/10.1080/14693062.2006.9685631.

Kocornik-Mina, A., McDermott, T.K.J., Michaels, G., Rauch, F., 2020. Flooded cities. American Economic Journal: Applied Economics 12, 35–66. https://doi.org/10.1257/app.20170066.

Kousky, C., 2017. Financing flood losses: A discussion of the National Flood Insurance Program. Resources for the Future, Washington D.C.

Kousky, C., Shabman, L., 2015. A proposed design for community flood insurance. Resources for the Future, Washington D.C.

Kousky, C., Cooke, R., 2012. Explaining the failure to insure catastrophic risks. Geneva Pap Risk Insur Issues Pract 37, 206–227. https://doi.org/10.1057/gpp.2012.14.

Kousky, C., French, K., 2023. Inclusive insurance for climate-related disasters: A Roadmap for the United States. Ceres, Boston.

Kousky, C., Kunreuther, H., 2014. Addressing affordability in the National Flood Insurance Program. J. of Extr. Even. 01, 1450001. https://doi.org/10.1142/S2345737614500018.

Kousky, C., Michel-Kerjan, O., Raschky, P.A., 2018. Does federal disaster assistance crowd out flood insurance. Journal of Environmental Economics and Management. 87, 150–164. https://doi.org/10.1016/j.jeem.2017.05.010.

Kreibich, H., Piroth, K., Seifert, I., Maiwald, H., Kunert, U., Schwarz, J., Merz, B., Thieken, A.H., 2009. Is flow velocity a significant parameter in flood damage modelling? Nat. Hazards Earth Syst. Sci. 9, 1679–1692. https://doi.org/10.5194/nhess-9-1679-2009.

Kriesel, W., Landry, C., 2004. Participation in the National Flood Insurance Program: An empirical analysis for coastal properties. J of Risk & Insurance 71, 405–420. https://doi.org/10.1111/j.0022-4367.2004.00096.x.

Landry, C.E., Jahan-Parvar, M.R., 2011. Flood insurance coverage in the coastal zone. Journal of Risk and Insurance 78, 361–388. https://doi.org/10.1111/j.1539-6975.2010.01380.x.

Lazzarin, T., Viero, D.P., Molinari, D., Ballio, F., Defina, A., 2022. Flood damage functions based on a single physics- and data-based impact parameter that jointly accounts for water depth and velocity. Journal of Hydrology 607, 127485. https://doi.org/10.1016/j.jhydrol.2022.127485.

Linder-Baptie, Z., Epstein, J., Kousky, C., 2022. The National Flood Insurance Program: A primer. University of Pennsylvania, Philadelphia, United States, Wharton Risk Center.

Linnerooth-Bayer, J., Mechler, R., Pflug, G., 2005. Refocusing disaster aid. Science 309, 1044–1046. https://doi.org/10.1126/science.1116783.

Linnerooth-Bayer, J., Hochrainer-Stigler, S., Mechler, R., 2012. Mechanisms for financing the costs of disasters. Government Office for Science, London, United Kingdom.

Liu, Z., Cheng, L., Hao, Z., Li, J., Thorstensen, A., Gao, H., 2018. A framework for exploring joint effects of conditional factors on compound floods. Water Resour. Res. 54, 2681–2696. https://doi.org/10.1002/2017WR021662.

Low, P.L., Fowler, G., Antich, R., Ranger, N., 2020. Fact sheet 6: Pooling and mutual options for public assets insurance. Southeast Asia Disaster Risk Insurance Facility, Singapore.

Mahul, O., Ghesquiere, F., 2010. Financial protection of the state against natural disasters: a primer, Policy Research Working Papers. The World Bank. Doi: 10.1596/1813-9450-5429.

Mahul, O., Cook, S., 2014. The Pacific Disaster Risk Financing and Insurance Program. World Bank Group, Washington D.C.

Margan, S.K., 2021. Overcoming basis risk in parametric insurance. Bimaquest 21, 31–39.

Martinez-Diaz, L., Snider, L., McClamrock, J., 2019. The future of disaster risk pooling for developing countries: Where do we go from here? (Working Paper). World Resources Institute.

McAneney, J., McAneney, D., Musulin, R., Walker, G., Crompton, R., 2016. Government-sponsored natural disaster insurance pools: A view from down-under. International Journal of Disaster Risk Reduction 15, 1–9. https://doi.org/10.1016/j.ijdrr.2015.11.004.

McNulty, M.W., Karson, A., Jensen, J., Henderson, K., 2011. Reforming the National Flood Insurance Program: An evaluation of policy alternatives. Keybridge. Research.

Monti, A., 2009. Climate change and weather-related disasters: What role for insurance, reinsurance and financial Sectors? Hastings West Northwest J. of Envtl. L. & Pol'y 15, 151–172.

National Association of Insurance Commissioner (NAIC), 2022. Worker's Compensation Insurance [WWW Document]. URL https://content.naic.org/cipr-topics/workers-compensation-insurance (accessed 6.17.23).

Nguyen, T., 2013. Insurability of catastrophe risks and government participation in insurance solutions (Background). United Nations Office for Disaster Risk Reduction, Geneva, Switzerland.

Nguyen, C.N., 2019. Economics of disaster recovery and earthquake insurance: Five essays on New Zealand. Victoria University of Wellington, Wellington, New Zealand.

Norris, A., Fraser, S., Dolk, M.M., Mahul, O., 2023. Flood risk modeling to support risk transfer: Challenges and opportunities in data-scarce contexts. World Bank Group, Washington D.C.

Oerther, D.B., 2016. From disaster to development: Finance provides a platform to empower technology for resilience to climate change. Procedia Engineering 159, 267–271. https://doi.org/10.1016/j.proeng.2016.08.173.

Okhrin, O., Odening, M., Xu, W., 2013. Systemic weather risk and crop insurance: The case of China. Journal of Risk and Insurance 80, 351–372. https://doi.org/10.1111/j.1539-6975.2012.01476.x.

Organisation for Economic Co-operation and Development (OECD), 2016. Financial management of flood risk. Organisation for Economic Co-operation and Development (OECD), Paris, France.

Pillay, K., Pillay, S., 2018. Financing climate adaptation and resilience in South African cities. In: South African State of City Finances. South African Cities Network, Johannesburg, South Africa, pp. 187–204.

Pillay, K., 2016. Climate risk management: opportunities and challenges for risk pooling (Small States Digest No. 2016/02), Small States Digest. Doi: 10.14217/5jln4p72226b-en.

Poussin, J.K., Botzen, W.J.W., Aerts, J.C.J.H., 2013. Stimulating flood damage mitigation through insurance: an assessment of the French CatNat system. Environmental Hazards 12, 258–277. https://doi.org/10.1080/17477891.2013.832650.

Rappaport, J., 2016. How private insurers regulate public police. SSRN Journal. https://doi.org/10.2139/ssrn.2733783.

Re, S., 2022a. Floods and storms drive global insured catastrophe losses of USD 38 billion in first half of 2022. Swiss Re Institute estimates, Swiss Re, Switzerland.

Re, S., 2022b. Natural catastrophes in 2021: the floodgates are open. Swiss Re.

Swiss Re, 2022c. Floods and storms drive global insured catastrophe losses of USD 38 billion in first half of 2022. URL https://www.swissre.com/press-release/Floods-and-storms-drive-global-insured-catastrophe-losses-of-USD-38-billion-in-first-half-of-2022-Swiss-Re-Institute-estimates/4d31d695-e49f-4168-85bc-2a5944313b05 (accessed 7.16.23).

Swiss Re, 2022d. 10 myths about parametric insurance. URL https://corporatesolutions.swissre.com/insights/knowledge/10_myths_about_parametric_insurance.html (accessed 7.23.23).

Swiss Re, 2023. What is parametric insurance? [WWW Document]. URL https://corporatesolutions.swissre.com/insights/knowledge/what_is_parametric_insurance.html (accessed 7.16.23).

Reuters, 2023. South African catastrophes, power woes signal end of cheap insurance. Engineering News. URL https://www.reuters.com/world/africa/south-african-catastrophes-power-woes-signal-end-cheap-insurance-2023-03-30/ (accessed 7.16.23).

Rivelli, E., 2023. Homeowners insurance companies abandon California and Florida — what to do if your state is also at risk. Homeowners insurance companies abandon California and Florida — what to do if your state is also at risk. URL https://www.sfgate.com/personal-finance/article/homeowners-insurance-climate-change-18163539.php (accessed 6.16.23).

Sarkar, S., 2022. Pakistan floods pose serious health challenges. BMJ o2141. https://doi.org/10.1136/bmj.o2141.

Scott, Z., Panwar, V., Weingärtner, L., Wilkinson, E., 2022. The political economy of premium subsidies: searching for better impact and design. Overseas Development Institute, London.

Sengupta, R., Kousky, C., 2023. Parametric insurance for insurance. University of Pennsylvania, Philadelphia, Pennsylvania.

Serkin, C., 2016. Insuring takings claims. Northwestern University Law Review 111, 1–66.

Singh, V.P., 1997. Effect of spatial and temporal variability in rainfall and watershed characteristics on stream flow hydrograph. Hydrol. Process. 11, 1649–1669. Doi: 10.1002/(SICI)1099-1085(19971015)11:12<1649::AID-HYP495>3.0.CO;2-1.

Smith, J.A., Bradley, A.A., Baeck, M.L., 1994. The space-time structure of extreme storm rainfall in the southern plains. J. Appl. Meteor. 33, 1402–1417. Doi: 10.1175/1520-0450(1994)033<1402:TSSOES>2.0.CO;2.

Soetanto, R., Hermawan, F., Milne, A., Hatmoko, J.U.D., As'ad, S., He, C., 2020. Developing sustainable arrangements for "proactive" disaster risk financing in Java, Indonesia. IJDRBE 11, 435–451. .

Spekkers, M.H., Ten Veldhuis, J.A.E., Kok, M., Clemens, F.H.L.R., 2012. Correlations between rainfall data and insurance damage data on pluvial flooding in the Netherlands. In: Presented at the 10th International Conference on Hydroinformatics, pp. 1–9.

Surminski, S., 2018. Fit for purpose and fit for the future? An evaluation of the UK's new flood reinsurance pool. Risk Management and Insurance Review 21, 33–72. https://doi.org/10.1111/rmir.12093.

Surminski, S., Oramas-Dorta, D., 2014. Flood insurance schemes and climate adaptation in developing countries. International Journal of Disaster Risk Reduction 7, 154–164. https://doi.org/10.1016/j.ijdrr.2013.10.005.

Surminski, S., Barnes, J., Vincent, K., 2022. Can insurance catalyse government planning on climate? Emergent evidence from Sub-Saharan Africa. World Development 153, 105830. https://doi.org/10.1016/j.worlddev.2022.105830.

Swacha-Lech, M.A., Gawin, M., 2022. Why don't local governments buy catastrophe insurance? Biased Decision-Makers. h 56, 149–168. https://doi.org/10.17951/h.2022.56.3.149-168.

Tarazona, M., Scott, Z., Simon, C., McConnell, J., Gettliffe, E., Murnane, R., Villanueva, P.S., Le Quesne, F., Perera, A., 2017. Independent evaluation of the African Risk Capacity (ARC). Oxford Policy Management and Itad, Oxford, United Kingdom.

Tellman, B., Lall, U., Islam, A.K.M.S., Bhuyan, M.A., 2022. Regional index insurance using satellite-based fractional flooded Area. Earth's Future 10. https://doi.org/10.1029/2021EF002418.

Tesselaar, M., Botzen, W.J.W., Aerts, J.C.J.H., 2020. Impacts of climate change and remote natural catastrophes on EU flood insurance markets: An analysis of soft and hard reinsurance markets for flood coverage. Atmosphere 11, 146. https://doi.org/10.3390/atmos11020146.

Thomas, A., Leichenko, R., 2011. Adaptation through insurance: lessons from the NFIP. International Journal of Climate Change Strategies and Management 3, 250–263. https://doi.org/10.1108/17568691111153401.

Thomas, M., Tellman, E., Osgood, D.E., DeVries, B., Islam, A.S., Steckler, M.S., Goodman, M., Billah, M., 2023. A framework to assess remote sensing algorithms for satellite-based flood index insurance. IEEE J. Sel. Top. Appl. Earth Observations Remote Sensing 16, 2589–2604. https://doi.org/10.1109/JSTARS.2023.3244098.

Trigg, M.A., Michaelides, K., Neal, J.C., Bates, P.D., 2013. Surface water connectivity dynamics of a large-scale extreme flood. Journal of Hydrology 505, 138–149. https://doi.org/10.1016/j.jhydrol.2013.09.035.

Turner-Gillespie, D.F., Smith, J.A., Bates, P.D., 2003. Attenuating reaches and the regional flood response of an urbanizing drainage basin. Advances in Water Resources 26, 673–684. https://doi.org/10.1016/S0309-1708(03)00017-4.

Vecere, A., Martina, M., Monteiro, R., Galasso, C., 2021. Satellite precipitation–based extreme event detection for flood index insurance. International Journal of Disaster Risk Reduction 55, 102108. https://doi.org/10.1016/j.ijdrr.2021.102108.

Warner, K., Yuzva, K., Zissener, M., Gille, S., Voss, J., Wanczeck, S., 2013. Innovative Insurance Solutions for Climate Change: How to Integrate Climate Risk Insurance into a Comprehensive Climate Risk Management Approach, No. 12. United Nations University Institute for Environment and Human Security (UNU-EHS), Bonn.

World Bank Group, 2017. Sovereign climate and disaster risk pooling. World Bank Group, Washington D.C.

World Bank Group, 2022. Pakistan floods 2022: Post-disaster needs assessment. World Bank Group, Washington D.C.

World Bank Group, 2023b. What is basis risk? [WWW Document]. URL https://www.indexinsuranceforum.org/faq/what-basis-risk (accessed 7.16.23).

World Bank Group, 2023a. Parametric insurance for disaster response. World Bank Group, Washington D.C.

Yang, Q., Shen, X., Yang, F., Anagnostou, E.N., He, K., Mo, C., Seyyedi, H., Kettner, A.J., Zhang, Q., 2022. Predicting flood property insurance claims over CONUS, fusing big earth observation data. Bulletin of the American Meteorological Society 103, E791–E809. https://doi.org/10.1175/BAMS-D-21-0082.1.