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The Asynergies of Structural Disaster Risk Reduction Measures: Comparing Floods and Earthquakes

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Key Points:
- An improved understanding of asynergies between disaster risk reduction (DRR)measures is crucial for long-term sustainable development
- We define asynergies as the potential adverse effects of measures aimed to decrease the risk of one hazard on the risk of another hazard
- Asynergies of flood and earthquake DRR measures are assessed in a case study of Afghanistan

Supporting Information:
- Supporting Information S1

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Abstract

Traditionally, building-level disaster risk reduction (DRR) measures are aimed at a single natural hazard. However, in many countries the society faces the threat of multiple hazards. Building-level DRR measures that aim to decrease earthquake vulnerability can have opposing or conflicting effects on flood vulnerability, and vice versa. In a case study of Afghanistan, we calculate the risk of floods and earthquakes, in terms of average annual losses (AAL), in the current situation. Next, we develop two DRR scenarios, where building-level measures to reduce flood and earthquake risk are implemented. We use this to identify districts for which DRR measures of one hazard increase the risk of another hazard. We then also calculate the optimal situation between the two scenarios by, for each district, selecting the DRR scenario for which the AAL as a ratio of the total exposure is lowest. Finally, we assess the sensitivity of the total risk to each scenario. The optimal measure differs spatially throughout Afghanistan, but in most districts it is more beneficial to take flood DRR measures. However, in the districts where it is more beneficial to take earthquake measures, the reduction in risk is considerable (up to 40%, while flood DRR measures lead to a reduction in risk by 16% in individual districts). The introduction of asynergies between DRR measures in risk analyses allows policy-makers to spatially differentiate building codes and other building-level DRR measures to address the most prevalent risk while not compromising the risk resulting from other hazards.

Plain Language Summary

Our study aims to improve our understanding of potentially unwanted effects of measures that reduce the impacts of disasters across different hazards. Traditionally, those measures are aimed at decreasing the risk a building faces of a single hazard type despite their potential of having unwanted effects on other hazard types. For example, building on stilts is an often-used measure to decrease a building's flood vulnerability, however, it simultaneously increases a building's earthquake vulnerability. In this paper, we refer to these as asynergies. However, in many countries the built environment faces the threat of different hazard types. We define such potentially unwanted effects between measure as "asynergies." A case study of Afghanistan is presented in which the asynergies of flood and earthquake building-level measures are assessed. An improved understanding of these asynergies can help policy makers enforce measures that decrease the overall risk.

1. Introduction

Traditionally, building-level risk reduction measures aim to address the risk of a single hazard type, for instance, through building codes (Cutter et al., 2015; Daniell, 2015; Shreve & Kelman, 2014). However, many countries face the risk of multiple disasters (Cutter et al., 2015; De Ruiter et al., 2020). Floods and earthquakes are often the hazard types with the highest economic damages, especially in developing countries (Zorn, 2018), and their damages are likely to continue to increase in the future (Bilham, 2009; Cutter et al., 2015; Winsemius et al., 2016). The increase in the damages in the future is due to both a projected increase in the frequency of (climate-driven) hazards (in the case of floods), and also due to increasing exposure in vulnerable areas (Balica et al., 2015). This is expected to continue in the future, with projections estimating that the world's population will have doubled between 1950 and 2050, which requires the construction of an additional 1 billion housing units (Bilham, 2009). Moreover, social inequalities cause developing countries and the poor to suffer disproportionally from the impacts of natural hazards (Bacigalupe, 2019; Di Baldassarre et al., 2010; Hallegatte et al., 2018; Murnane et al., 2017; Winsemius et al., 2018) and their built environment is especially vulnerable to the impacts of natural hazards (Alexander, 2017; Balica et al., 2015). For these countries it is especially important to improve our understanding of the potential of disaster risk reduction (DRR) measures to reduce risk (Kreibich et al., 2015).

Risk is defined by the United Nations Office for Disaster Risk Reduction (UNDRR, 2016) as the probability of harmful consequences, or expected losses from interactions between hazards, exposure and vulnerable conditions. The body of literature on multi-(hazard) risk has been growing since the early nineties (Ciurean et al., 2018; De Ruiter et al., 2020; Gallina et al., 2016; Gill & Malamud, 2014; Kappes et al., 2012; Marzocchi et al., 2012; Scolobig et al., 2017; Tilloy et al. 2019; United Nations Environment Program 1992). Moreover, the general need for a shift from single to multirisk assessments has been widely recognized in international agreements, such as the Sendai Framework for Disaster Risk Reduction (UNDRR, 2015) and it was high on the agenda of the UNDRR Global Platform 2019 (UNDRR, 2019). The effectiveness of DRR measures could benefit from the advocated comprehensive systemic risk approach (Cutter et al., 2015; Peduzzi, 2019; Scolobig et al., 2017; UNDRR, 2020). This includes accounting for the different types of hazards that threaten an area, and the interactions and dynamics between different hazards and their DRR measures (e.g., Crosti et al., 2010; Mahmoud & Chulahwat, 2016; Zaghi et al., 2016). DRR measures can be aimed at the different components of risk and encompass both structural measures aimed at either improving disaster prevention or increasing adaptive capacity, and nonstructural measures such as planning, capacity, and awareness-building measures (Wisner et al., 2012). While this shows that DRR measures can be implemented during the different phases of the disaster risk management cycle, there is an increasingly forward-looking approach in addressing communities' risk to natural hazards (Peek et al., 2016). Financial aid from the international community used to focus on postdisaster recovery, but recently there has been a shift in focus also toward preparedness (Balica et al., 2015). This is for example demonstrated by the recent growing attention for the concept of Building Back Better (BBB) as a way of increasing disaster resilience during the postdisaster recovery phase (Ainuddin & Routray, 2012; Hallegatte et al., 2018; Lyons, 2009; Mannakkara & Wilkinson, 2014). Many of those BBB studies focus on critical infrastructures such as bridges (Ganesh Prasad & Banerjee, 2013; Mosqueda et al., 2007), wind turbines (Mardfekri & Gardoni, 2015), lifelines (Reed et al., 2016), schools (Nassirpour et al. 2018) and hospitals (Marasco et al. 2017), and some include residential buildings (Sharma et al., 2016).

Several studies have advocated for an increased understanding of the complexities of multihazard risk DRR measures (Cutter et al., 2015; De Ruiter et al., 2020; Scolobig et al., 2017). However, the quantification and comparison of the effects of DRR measures aimed at reducing building-level vulnerability across different hazards, such as floods and earthquakes, is not common (Crosti et al., 2010; Gautam & Dong, 2018; Li et al., 2012). Hence, despite the recognized importance of increasing our understanding of the risk of different hazards, many loss studies and DRR measures continue to focus on a single hazard type (Chmutina et al., 2017; Cutter et al., 2015; Gall et al. 2011; Gardoni & LaFave, 2016; Kappes et al., 2012; Peduzzi, 2019). Moreover, besides the lack of scientific understanding, institutional barriers continue to jeopardize the design and implementation of DRR planning policies that account for different hazard types (Cutter et al., 2015; Scolobig et al., 2017).

While positively influencing the risk of one hazard, DRR measures can have adverse effects on the risk of another hazard type (Crosti et al., 2010; De Ruiter et al., 2020; Kennedy et al., 2008; Li et al., 2012), thereby increasing the vulnerability of the built environment, exacerbating impacts and potentially causing compound hazards (Chmutina et al., 2017; Scolobig et al., 2017). We refer to these negative impacts between hazards as the asynergy of a DRR measure. For example, wood-frame buildings tend to perform well underground shaking but are likely to sustain higher damages due to flooding than concrete buildings (Wood & Good, 2004). Lighter structures such as glass walls can reduce the impacts of earthquakes, while the potential damages from winds can increase (Li et al., 2012). Several studies have tried to understand the potential adverse effects of DRR measures on the risk from the same hazard type. For example, Di Baldassarre et al. (2018) created a framework to better understand the unintended effects of structural flood protection measures on flood risk. However, the authors do not consider the effects of structural flood protection measures on the risk from other hazard types. Chang et al. (2018) account for temporal changes in the building stock on the future risk of different hazards in Vancouver, but they do not include an assessment of cross-hazard effects. Some studies have compared the costs and benefits of different DRR measures tailored to different hazards (e.g., Hochrainer-Stigler et al., 2010; Li, 2010; Shreve & Kelman, 2014), but these studies do not account for asynergies between different measures. Few studies have discussed the design of buildings that can mitigate the risk of specific combinations of hazards. For example, the performance of wood-frame buildings under combined snow and earthquake loading (Y. Wang & Rosowsky, 2016) or the performance of structures during earthquakes and tsunamis (e.g., Fraser et al., 2013; Mück et al., 2013; Saatcioglu et al. 2006; Wood et al., 2004). Finally, some studies have assessed (a)synergies of DRR measures specifically aimed at critical infrastructure (Argyroudis et al., 2020; Fereshtehnejad & Shafieezadeh, 2018; Gardoni & LaFave, 2016; Moftakhari & AghaKouchak, 2019). Nonetheless, as a result of the common use of the single-hazard approach, the potential asynergies of structural, building-level DRR measures remain poorly understood (Di Baldassarre et al., 2018; Kull et al., 2013; Scolobig et al., 2017; Shreve et al., 2014).

Comparing the impacts of two (or more) different hazard types is challenging as it requires a standardized unit of measuring impacts (Kappes et al., 2012; Marzocchi et al., 2012). A commonly used metric in multi-risk studies is the average annual losses (AALs; Delmonaco et al., 2006). This has, for example, been applied in the EU Directive on multirisk mapping (Delmonaco et al., 2006) and in other studies comparing flood and earthquake risk (e.g., Murnane et al., 2017).

In this article, we assess the asynergies of structural, residential building-level DRR measures that are aimed at reducing the impacts of two independent hazards that threaten the same country. A case study of Afghanistan is used to quantify changing risk, expressed in terms of AAL (similar to Murnane et al. [2017]), due to asynergies between flood and earthquake building-level DRR measures. The asynergies are assessed by creating two DRR scenarios: in the first scenario, the structural, residential building-level DRR measures are designed to decrease the impacts of fluvial flooding and in the second scenario they are designed to decrease the impacts of earthquakes. Due to its location in a tectonically active area and its steep slopes in headwaters and lack of vegetation, Afghanistan is extremely prone to both floods and earthquakes (World Bank, 2018). Historically, flooding is the most frequently occurring hazard type in the country, while earthquakes are the most damaging hazard in terms of fatalities (Ranghieri et al., 2017; World Bank, 2018). There is only very limited data available about Afghanistan's current and future disaster risk as a result of the ongoing conflict (World Bank, 2018). The country is therefore often either excluded from global risk assessments or poorly modeled due to data availability challenges (e.g., Peduzzi et al., 2009). The World Bank (2018) conducted a country risk profile assessing Afghanistan's risk to the most damaging hazards (i.e., floods, earthquakes, droughts, landslides, and avalanches). This paper builds on that study by the World Bank. Due to the limited data availability, we use information from neighboring countries on the behavior of regionally common building material types under floods and earthquakes. It is important to note that this study does not aim to provide a comprehensive loss estimates for flood and earthquake risk in Afghanistan, nor does it focus on changes in vulnerability to one hazard as a result of damages caused by another hazard. Rather, we aim to assess how the risk of one hazard is affected by implementing structural DRR measures aimed at reducing the impacts of another hazard. Therefore, the two DRR scenarios are designed such that each mimics a complete upgrade of the residential built environment. While a complete upgrade of the built environment may appear unrealistic, it is used to demonstrate the concept of asynergies and the need to account for them in multihazard risk assessments. We believe that increasing awareness among practitioners of the concept of asynergies is of high importance to create a more sustainable design of structural DRR measures.

We first discuss several key potential asynergies of building level DRR measures for floods and earthquakes tailored to decreasing the risk of one hazard on the risk of the other hazard and use this to develop two the DRR scenarios. Next, we assess the current risk of floods and earthquakes separately using the World Bank's (2018) building inventory of Afghanistan. Then, we calculate the asynergies of the earthquake and flood DRR scenarios. Subsequently, we use the results of these two scenarios to calculate the optimal situation. To single out the potential asynergies of DRR measures, we assume stable hazard conditions and exposure in terms of the total number of buildings and their location. Finally, we discuss our findings and provide recommendations for future research.

2. Asynergies of Building-Level DRR Measures

In developing countries, a house is generally the most valuable asset owned by people but the residential building stock often also accounts for the largest share of the total damages as a result of a disaster (Ahmed, 2011). A study by UNHCS (2009) found that at that time, 40% of the global population lived in earthen buildings, with 50% of the population in developing countries living in earthen dwellings (Kenny, 2012). In Afghanistan, walls of residential buildings are commonly made out of adobe and clay bricks and foundations (if present) are shallow. The majority of residential buildings have one or two storeys (53% of the residential houses in urban areas and 95% in rural areas have one storey, and 40% and 5% of the buildings in urban areas have two storeys, respectively; World Bank, 2018). Moreover, buildings are not subject to a unified or enforced building code and building elements generally lack proper connections (Haziq & Kiyotaka, 2017; Maheri et al., 2005). In our case study of Afghanistan, we focus on the asynergies of common structural, building-level flood and earthquake DRR measures. In this section we present an extensive literature review (Table 1) of common building and structural construction practices in developing countries and their asynergies on flood and earthquake risk, based on which we develop two DRR scenarios for the case study (Section 3).

The Global Earthquake Model's building taxonomy tool for multi-hazard exposure (GED4ALL) provides a uniform classification system that categorizes exposed assets to natural hazards (Silva et al., 2018). Its taxonomy includes building attributes such as exterior wall material, foundation type, height and elevation of the ground floor. The literature recognizes the following common approaches aimed at increasing the structural resilience of buildings to fluvial flood damages: elevating buildings, elevating door and window openings, creating floodable buildings, and improving the structure and material of the walls, foundation, and frame (Das & Mukhopadhyay, 2018; Mebarki et al., 2012; Nassirpour et al., 2018). Another common distinction is made between wet and dry proofing, where the former focuses on minimizing the damages when floodwaters do enter a building (floodable) and the latter is defined as measures preventing floodwaters from entering the building such as the use of low-permeable materials or building on stilts (De Ruig et al., 2019; Kreibich et al., 2015) (shown in Table 1 under "other building practices"). Structural DRR measures may vary based on design flood or earthquake magnitudes. In recent years, probabilistic risk analyses are increasingly used to determine structural building design's ability to withstand different seismic magnitudes and to revise seismic building codes accordingly (Daniell 2015; Ellingwood, 2001). Similarly, building-level flood DRR measures are often designed based on base flood elevation (BFE; Freeman & Kunreuther, 2002). It is important to note that earthquake risk assessments more commonly account for the vulnerability posed by such building attributes compared to flood risk assessments (De Ruiter et al., 2017; Douglas, 2007). Based on the characteristics of residential buildings in Afghanistan, we focus on wall material and building height related DRR measures.

2.1. Wall Material

The material of a building is an important determinant its physical vulnerability to damage by a flood or earthquake. Table 1 highlights four commonly used building materials in developing countries or informal urbanized areas (i.e., earthen-structures, wood frames, bamboo, and masonry), the first three of which are commonly used in rural areas of less-developed countries (Castillo et al., 2011). The use of soil makes the buildings very prone to both flood (Siddique & Schwarz, 2012) and earthquake damages (Holliday et al., 2012). In a study of Pakistan, it was found that 82% of the damaged houses during the 2010 floods were made of a form of mud (Shah et al., 2013). To decrease flood vulnerability, the authors suggest changes such as: elevating the house, eliminating openings in the wall, increasing the wall thickness, and using soil with sand and clay (Shah et al., 2013). In a study of earthquake community resilience in Pakistan's Baluchistan province, Ainuddin et al. (2012) found that 50% of the building stock is comprised of adobe houses. During the 2005 and 2008 earthquakes, it was shown that the adobe buildings are especially vulnerable to damages and complete failure compared to the other building types. In another study in Pakistan, Siddique and Schwarz (2012) discuss how brick masonry buildings are likely to perform poorly during an earthquake, while the same building type increases flood resilience. In studies after the 2003 Bam earthquake in Iran, it was found that the vast majority of the damaged buildings were one to two storey buildings and made out of adobe (Maheri et al., 2005; Manafpour, 2008). Adding bamboo to adobe to increase a building's earthquake

Table 1
Examples of Common Building Practices in Developing Countries and Their Asynergies on Flood and Earthquake Risk

Building construction practices	Decreases earthquake risk	Asynergies flood risk	Decreases flood risk	Asynergies earthquake risk	References (country/region of case study)
Material related building DRR practices					
Wood-frames	Able to resist earthquakes due to their flexibility, typically perform better than concrete frames during ground shaking.	(1) Potential of structural failure in relation to flood velocity and depth (2) Building can float due to lightweightness and buoyancy*, however this is highly dependent on whether flood waters have entered the building			Becker et al., 2010 (North-America); Holliday et al., 2012 (Nicaragua); Wood et al., 2004 (Pacific Northwest)[1]
Earthen structures (e.g., adobe)	When mixed with bamboo, earthquake resistance can be increased	Highly vulnerable mainly due to undermining of the foundation, erosion and damages to due collapsing of roof	When building a house on an embankment, flood risk can be decreasedMixing adobe with concrete can increase the resistance of walls to standing water	Highly vulnerable due to heaviness, walls separate at the corners and shear cracks develop across the walls	Ainuddin et al., 2012 (Pakistan); Hochrainer-Stigler et al., 2010 (India); Holliday and Kang 2012 (Nicaragua); San Bartolomé et al., 2013 (Peru); Shah et al., 2013 (Pakistan)
Bamboo	Building can sway due to not being fixed to the ground		Building can float due to lightweight and buoyancy*		Das and Mukhopadhyay 2018 (India)
Masonry		Masonry buildings ability to withstand flood damages mainly depends on hydrostatic loading (long-time standing water), flow velocity, the quality of the brick (e.g., the porosity) and (the height of) openings such as windows	Low-porosity brick and reinforced masonry tend to be able to withstand flood damages	Relatively poor performance due to low ductility and high lateral stiffness. It does depend on the infill configuration of the masonry infilled reinforced concrete frame, where bare frames have the highest vulnerability compared to partially and fully infilled reinforced concrete frames	Castillo et al., 2011 (Venezuela); Hughes, 1982 (South Asia); Kennedy et al., 2008 (Indonesia); Murty et al. 2006 (India); Saatcioglu et al., 2006 (Indonesia); Wang et al., 2018 (NA)
Height related building DRR practices					
Dry-proofing using stilts			Raising house above base flood elevation decreases likelihood of damages	Upper storeys have a higher stiffness than the ground storey, causing an inverted pendulum swing.[1] Damage to the ground storey leads to building collapse	Bramley et al., 2002 (UK); De Graaf et al., 2012 (EU); Mebarki et al., 2012 (France); Murty, 2005 (India); De Ruig et al., 2019 (LA, USA); Sakijege et al., 2014 (Tanzania and Indonesia)[1]

Table 1
Continued

Building construction practices	Decreases earthquake risk	Asynergies flood risk	Decreases flood risk	Asynergies earthquake risk	References (country/ region of case study)
Compact urban development (increasing urban density)		(uncontrolled) urbanization often takes place in flood plains. Also often leads to more impervious areas	More urbanized areas are more likely to have urban drainage systemsThe use of multistorey apartment buildings decreases the number of exposed households	Multistorey apartment buildings can also suffer from the weak-storey effect	Brody et al., 2014 (USA); Chang et al., 2018 (Canada); Lee and Brody, 2018 (South Korea); Löwe et al., 2017 (Australia)[1]
Improve plinth and/or foundation	Improved seismic force resistance		The use of less-permeable material has showed mixed results in decreasing flood risk		Ahmed, 2011 (developing countries including Bangladesh, Vietnam, Indonesia, Peru); Fatemi et al., 2020 (Bangladesh)

DRR, disaster risk reduction.
*Buoyancy can cause a building to drift from its foundation. Previous studies have shown that buildings will float when the flood depth reaches approximately three-quarters of the building height (Becker et al., 2010). [1]Where limited information specific to developing countries' building practices was available, information from nondeveloping countries has been included.

reinforcement has shown promising results (Das & Mukhopadhyay, 2018). However, this option is limited to areas with access to bamboo. Wood-framed houses are light, and when tied together well they are able to resist earthquake damage due to their flexibility (Holliday & Kang, 2012). However, as shown in Table 1, the use of wood creates a flood asynergy: studies have shown that high flow velocity increases the risk of flood damages to wooden buildings, especially in the case of flash floods (Becker et al., 2010). In contrast to wood-frame buildings, earthen structures tend to be heavy, causing even small accelerations to lead to high seismic forces, increasing the chance of damages (Holliday & Kang, 2012). The use of low-permeability materials up to BFE to decrease flood risk has showed mixed results in two studies in Bangladesh. In a UNDP-funded project, plinths of houses in Bangladesh traditionally made from earthen materials were covered with cement-based soil, showing promising results (Ahmed, 2011). While a more recent study showed that houses built using more durable, low-permeability materials nonetheless suffered severely from flood damages (Fatemi et al., 2020).

2.2. Building Height

Next, building on stilts is often considered to be the most effective measure to decrease flood damages (Bramley & Bowker, 2002; Sakijege et al., 2014). However, as shown in Table 1, building on stilts compromises a building's sturdiness as it contributes to an inverse pendulum swing during earthquakes, increasing the risk of earthquake damages (Murty, 2005). This was demonstrated in case studies of India, Turkey, Taiwan, and Algeria, by the collapse of a significant number of these types of buildings during different earthquakes (Murty, 2005). In a study of India, Hochrainer-Stigler et al. (2019) found that raising the plinth by building om embankments is cost effective for new houses but not for the improvement of existing houses. Buildings in earthquake prone areas could benefit from such an increased sturdiness of building foundations (Ahmed, 2011).

An important issue to note is that of people's limited understanding of novel construction practices (Kennedy et al., 2008). Haziq and Kiyotaka (2017) found that the lack of construction knowledge and disaster awareness contribute to the high impacts of disasters in Afghanistan. For Tanzania and Indonesia, Sakijege et al. (2014) found that one of the main issues is the limited involvement of experts, often due to their costliness, and the lack of maintenance of previously implemented adaptation strategies. Moreover, both case study communities would resort to using construction materials that were thought of as flood resistant (soil bricks with cement mortar and sand with cement blocks), however they are all deemed by FEMA as vulnerable to (prolonged) floods (Sakijege et al., 2014). Despite the common use of adobe especially in developing countries, Holliday et al. (2016) found that engineering properties of construction materials such as concrete remain far more studied and far better understood than the engineering properties of earthen buildings, despite the fact that these earthen materials have been used for buildings far longer.

From our review, it appears that the knowledge of building practices is largely fragmented based on a single hazard paradigm (hazard silos) and most discussions of asynergies of building-level DRR practices in developing countries between different hazard types in the literature have concentrated on local case-studies.

3. Methods

Figure 1a shows a flow diagram summarizing the methods used to calculate flood and earthquake risk, asynergies of the two DRR scenarios and the optimal scenario. To assess the asynergies of flood and earthquake DRR measures in Afghanistan, we calculate the AAL of both hazards under current conditions and in two DRR scenarios (Figure 1a). The AAL is calculated at the grid level (90 × 90 m), with building areas (from district-level database) of different building types distributed over urban and rural grid cells. In each DRR scenario, the building stock is adjusted to reflect either decreased flood or decreased earthquake vulnerability. These DRR scenarios are designed based on the findings of Section 2. Subsequently, the asynergies of each scenario and the optimal situation per district are calculated. This section follows the methods flow diagram. We first discuss the data obtained and the methods used to assess the AAL of floods and earthquakes for Afghanistan. Next, we discuss the two DRR scenarios used to assess the asynergies of flood versus earthquake DRR measures and the assessment of the optimal scenario.

3.1. Calculating Risk

To estimate risk in terms of AAL for each hazard, we combine information on the hazard, exposure, and vulnerability, as described below. In brief, we use hazard and exposure data obtained by the World Bank (2018) (hereafter referred to as WB-data), while the flood vulnerability component builds on previous work by Englhardt et al. (2019) and the earthquake vulnerability component uses the approach discussed by Haldar et al. (2013). The AAL is calculated at a 90 × 90 m cell level; the same spatial resolution as those used for the inundation maps.

3.1.1. Hazard

For the flood hazard component, we used simulated inundation maps for fluvial floods with a 90 × 90 m resolution, as created by the World Bank for their Afghanistan country risk profile for 8 different return periods (i.e., 5, 10, 20, 50, 100, 250, 500, and 1,000 years; World Bank, 2018). The earthquake hazard maps were obtained through the World Bank (2018) Afghanistan multirisk profile, which were modeled following Daniell (2014). The hazard maps were derived for various spectral accelerations (from 0 to 2s), at 10, 50, 100, 250, 500, 1,000 and 2,500-year return periods using CRISIS2007 which is part of CAPRA (World Bank, 2018). Figure 2 shows the flood map for the 500-year return period of the Kabul and Nangarhar provinces and the earthquake ground motion for the 500-year return period as an example. We refer to the supplementary material for more details on the hazard maps.

3.1.2. Exposure

Both the earthquake and flood risk assessments use exposure data of residential buildings (excluding multiuse buildings) that were obtained through the World Bank (2018) by local partners and in collaboration with UNDP's National Risk and Vulnerability Assessment (Central Statistics Organization, 2014). For each of the 409 districts, the exposure data consist of the size of the building surface area (building footprint in square meter) classified by (i) 31 wall materials, (ii) the number of stories (1–6), and (iii) land use class (i.e., urban or rural). In addition, for each class the US$ value of buildings per square meter is provided. The wall material types (Table S1) are categorized using common model building types (MBT) based on the Indian MBT (Haldar et al., 2013), PAGER (Jaiswal & Wald, 2008), PSI method (R. Spence et al., 2008), descriptions of Afghan (Szabo & Barfield, 1991) and Pakistani architecture (Maqsood & Schwarz, 2008). Examples of

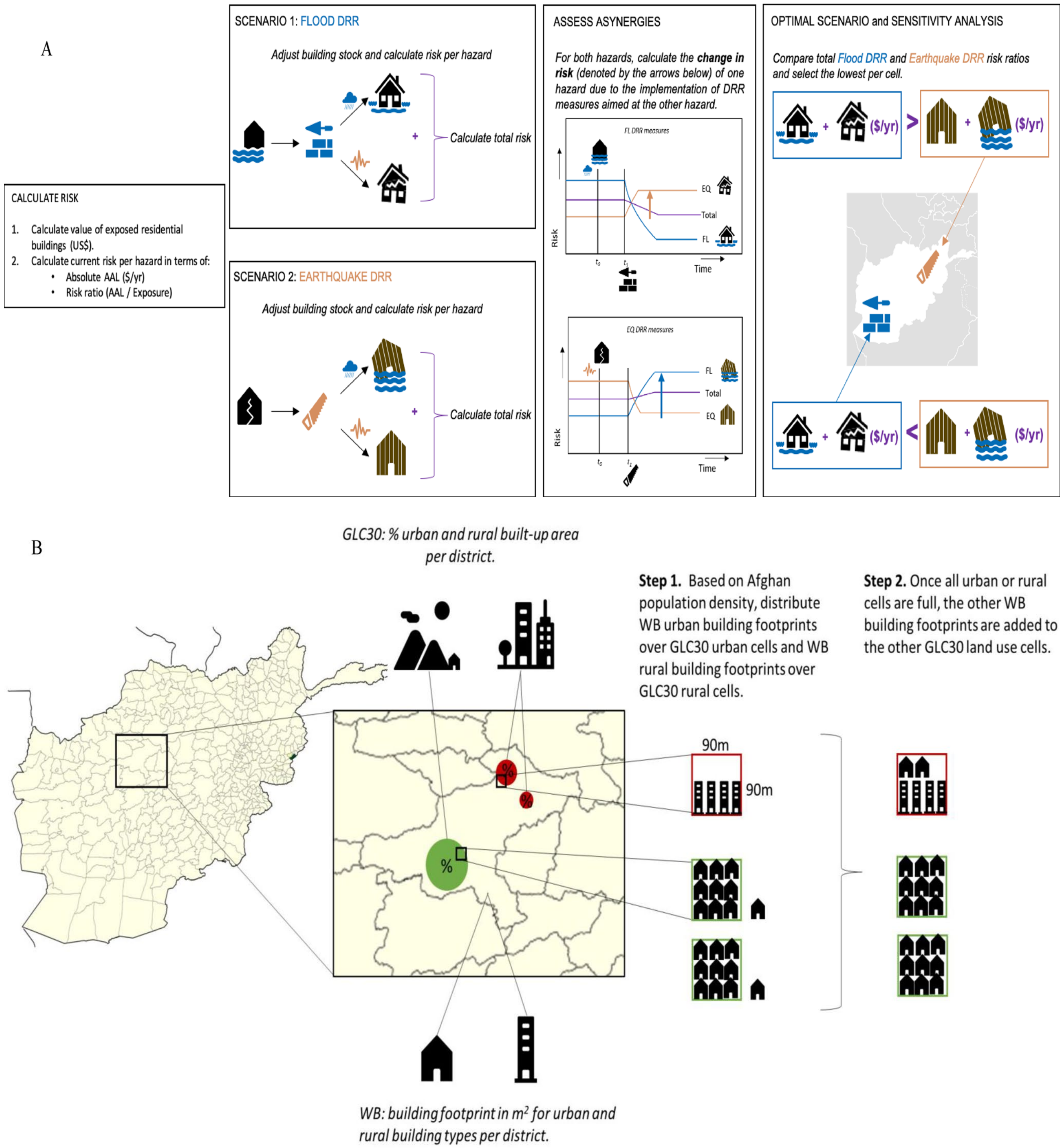

Figure 1. Flow diagram of methods. (a) Starting from the left, we first calculate the flood and earthquake risk in terms of absolute and relative AAL. Next, we design two DRR scenarios and use those to assess the asynergies (after a disaster caused by a particular hazard, DRR measures are tailored to reducing the risk of that hazard), and finally we calculate the optimal scenario per district. (b) Detailed flow diagram of the exposure methods shows that for each district, we have the building footprint in square meters for all urban and rural building types. The GLC30 urban and rural built up area raster is resampled from 30 × 30 to 90 × 90 m cells. Next, the WB, district-level building inventory data is distributed over the cells based on their class (urban buildings types are allocated to urban built up cells and rural building footprints are allocated to rural cells; step 1). When the cells of one class is full before all building footprints of that class are distributed, they are added to the cells of the other class (step 2). We always only have districts of which the cells of one class are filled, allowing us to allocate the remaining building footprint to cells of the other class. Source icons: UNOCHA (2012 and 2018). AAL, average annual loss; DRR, disaster risk reduction; WB, World Bank.

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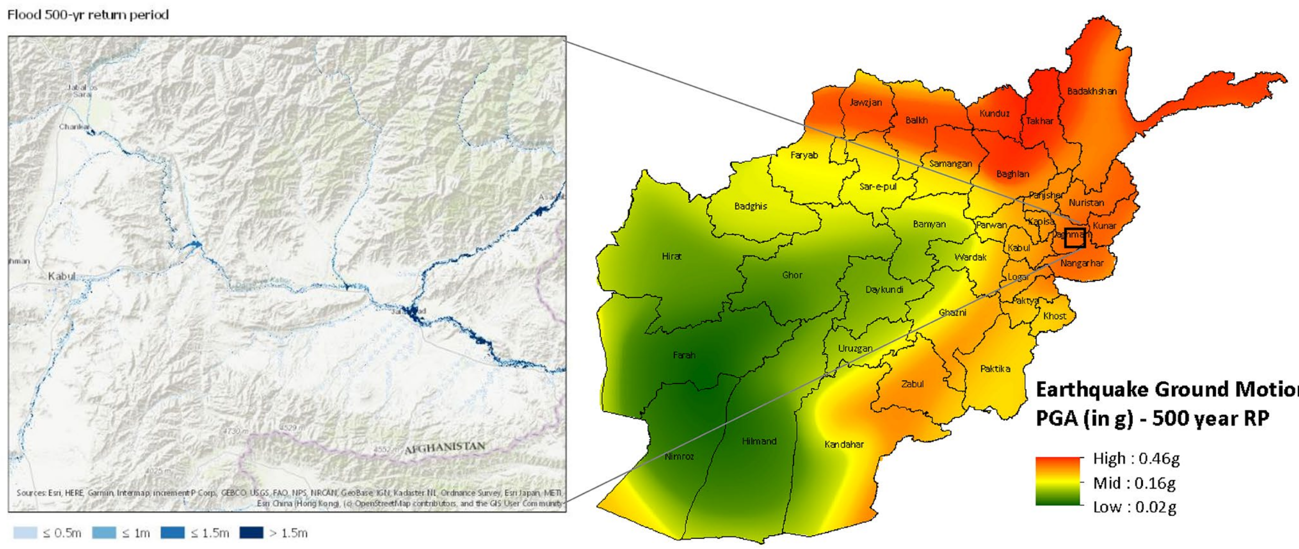

Figure 2. Example hazard maps for floods (left—an insert of the 500-year return period for the provinces of Kabul and Nangarhar) and earthquakes (right—500-year RP Earthquake ground motion—the Peak Ground Acceleration [PGA]).

common Afghan building typologies are shown in Figure 3. In total, the database consists of 594,930 urban and 2,592,062 rural residential buildings (Table S2 contains a breakdown of the number of residential buildings per province and their value).

For the flood and earthquake risk assessments, these buildings (at district level) need to be distributed over 90 × 90 m cells (i.e., downscaling). Unfortunately, in Afghanistan there are very few data available about the exact locations of buildings. For example, the Global Human Settlement (GHS) Layer (Corbane et al., 2019), shows a low agreement with satellite observations in arid regions, such as Afghanistan, where open soil surfaces and scattered vegetation results in a high false alarm rate (Klotz et al. 2016). As an example, we found that 38 of the 409 districts have no built-up area depicted at all in the GHS. Other datasets, such as OpenStreetMap are very sparsely populated in Afghanistan (Barrington-Leigh & Millard-Ball, 2017).

Figure 3. Examples of common building typologies in Afghanistan. AM, AL, and AC are adobe buildings, MM, ML, and MC are unreinforced masonry buildings, RC1, RC2, RC3 are reinforced concrete buildings and ST1, ST2, and ST3 are steal frame buildings. Source: World Bank (2018). The building type codes and their descriptions are shown in Table S1.

Therefore, we use land cover data of GlobeLand30 (GLC30) from 2010, which does have a high agreement with land cover types observed in satellite imagery (Chen et al. 2017), including in arid regions (Jokar Arsanjani et al., 2016). We refer to Chen et al. (2017) for an extensive review of the use of GLC30 data.

Figure 1b shows a flow diagram of the exposure methods. GLC30 comprises of 10 land cover types at a 30 × 30 m cell-size level, including cultivated land and artificial surfaces, which we resample using nearest-neighbor resampling to the resolution (90 × 90 m) and projection of the flood maps. Unfortunately, the definition of urban and rural areas in the WB-data (based on local expert knowledge) is different from the definition of artificial surfaces and cultivated lands in the GLC30 data (based on remote sensing techniques). In extreme cases, a district comprises only of urban built-up area according to the WB-data, whereas GLC30 shows cultivated land use (e.g., Kabul district), or there is only rural population according to the WB-data, whereas GLC30 data clearly shows urban centers. Therefore, we first determine the total area (i.e., urban and rural) from the WB-data and distribute this built-up area over the artificial and cultivated land from the GLC30 data, while considering the average Afghan built-up density difference between urban and rural areas. The urban built-up area depicted in the WB-data is first allocated to the artificial surfaces cells, while the rural built-up area depicted is first allocated to the cultivated areas. If the artificial surfaces in a district are filled, the remaining urban buildings are allocated to the cultivated land cells in that district. Vice versa, if the cultivated land in a district is filled, the rural buildings are allocated to the artificial surfaces cells.

Finally, many (global) flood risk models tend to overestimate risk due to the coarse resolution of the hazard maps (Ward et al. 2015) in combination with the low quality of large-scale exposure data (Klotz et al., 2016). When looking closely at the 5-year flood zone map in comparison with the exposure data, it appeared that many people would be living in the riverbed, while in reality they would be living just next to it. More importantly, as in most arid to semi-arid countries, Afghanistan's rivers are for the most part ephemeral (Ahlers et al., 2014). Some studies suggest that for those ephemeral rivers in arid regions bankfull discharges are found at longer return periods (5–8 years; De Jalón, 2003; Ward et al, 2016). Ward et al. (2016) argue that the flood volume associated with 2-year return period discharge is defined in a purely statistical matter based on annual time-series of annual maximum flood volumes. As such it does not refer to the 2-year flood volume. Finally, according to FLOPROS the flood protection standard for Afghanistan ranges from 2 to 5 years (Scussolini et al., 2016). Therefore, no building area was distributed to cells (artificial surface or cultivated land) inside the 5-year flood zone. Due to the exclusion of the 5-year flood zone in the exposure component, we expect the AAL to be lower than in global flood risk assessments, which do not account for this. Note that the same exposure (with no building area in the 5-year flood zone) was used for the earthquake risk assessment, such that the comparison is consistent.

3.1.3. Vulnerability

Flood and earthquake vulnerability are commonly quantified using vulnerability curves that link a hazard factor (e.g., inundation or ground shaking) to damage potential (De Ruiter et al., 2017). For floods, this damage potential is often referred to as the damage factor (i.e., the percentage of the building damaged) and spans from zero (no damage) to one (maximum damage; Huizinga et al., 2017) and for earthquakes as the damage ratio (i.e., the ratio of the repair cost of the building to construction cost; Daniell, 2014). While earthquake vulnerability curves tend to be designed based on building materials, flood vulnerability curves are commonly designed based on aggregated land-use classes (e.g., residential, commercial, industrial), which do not account for heterogeneity of the building stock (De Ruiter et al., 2017; Englhardt et al., 2019). To the best of our knowledge, there exist no flood and earthquake building-material based vulnerability curves specific to the Afghanistan building stock. Therefore, for both hazards, curves have been based on existing curves of similar building types and adjusted to local building characteristics based on expert judgment. For both hazard types, the building classes are grouped based on their respective vulnerability characteristics as shown in Table S1 with their respective vulnerability curves shown in Figure S1. The maximum damage values were obtained through the World Bank (2018) as shown in S4 for each of the 31 building classes. It should be noted that due to the way in which buildings are designed and constructed there are many uncertainties in estimating Afghan building vulnerabilities (World Bank, 2018). We refer to the supplementary material (Figure S1) for a detailed description of the flood and earthquake vulnerability curves.

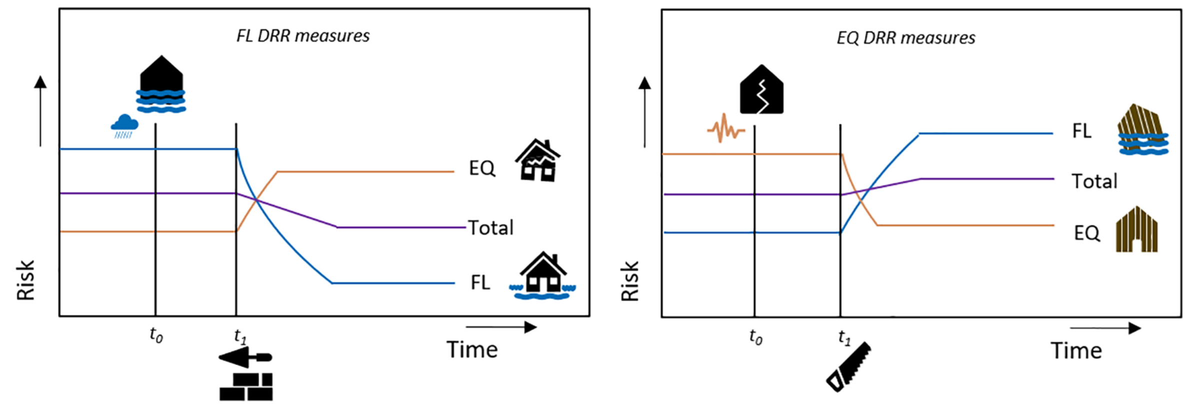

Figure 4. Conceptual representation of asynergies of DRR measures. The left panel shows how after a flood event at t0 flood DRR measures for buildings are implemented at t1. While these measures cause a decrease in flood risk, they increase the risk of earthquakes: an asynergy of flood DRR measures. The right panel shows the same in an earthquake scenario. The figure also depicts the two scenarios used to assess the asynergies: flood proofing by upgrading adobe buildings to brick buildings and earthquake proofing by upgrading adobe buildings using wood (Section 3.4). Source icons: UNOCHA (2012 and 2018). DRR, disaster risk reduction.

3.1.4. Calculating the AAL

Finally, risk is assessed by calculating the AAL for each hazard at cell level. In order to make the comparison between both hazards fair, we only consider exposure in the flood zones as it is not necessary to consider flood risk when designing buildings outside this zone, while the earthquake risk is not as geographically limited.

3.1.4.1. Flood AAL

For floods, we calculate the AAL (in US$) as follows: per return period, for each 90 × 90 m cell, the vulnerability ratio for each building is determined from the respective vulnerability curve and inundation depth. The vulnerability ratio is then multiplied by the maximum damage value for each building type (Table S3). The AAL is calculated by plotting the inverse return period and associated damages and taking the integral under the risk (probability-damage) curve (Ward et al. 2013).

3.1.4.2. Earthquake AAL

For earthquakes, the open source CAPRA model is modified to model the earthquake AAL (Cardona, Ordaz, & Reinoso, 2012; World Bank, 2018). First, the CRISIS2007 software is used to create event sets for different annual return periods (Mousavi et al., 2014; Ordaz et al., 2013). In CAPRA, the CRISIS2007 output (the PGA maps) is combined with the fragility functions and overlaid with the exposure to calculate deterministic and event-set probabilistic risk following Daniell (2014). The losses (AAL in US$) are calculated at a 1-km grid cell by summing the AALs for each return period, per building type for rural and urban residential buildings. For the comparison with floods, the AALs are then downscaled to 90 × 90 m raster cells per building class by redistributing them.

3.2. Designing the DRR Scenarios

Figure 4 shows a schematic representation of the asynergies for both scenarios (as part of the method's flow diagram of Figure 1). To assess the asynergies between flood and earthquake DRR measures in Afghanistan, we designed two DRR scenarios based on the review of Section 2. Table 1 shows that a common practice of addressing a building's earthquake resilience is by upgrading adobe buildings to wood frames and a common practice of increasing a building's flood resilience is by upgrading adobe buildings to masonry. Therefore, the two DRR scenarios are as follows:

- In the increased flood resilience scenario (Flood DRR scenario), the building stock was adjusted to make it less vulnerable to floods. Here, we assumed that all adobe building types (i.e., AL, AC, AM, MM, INF,

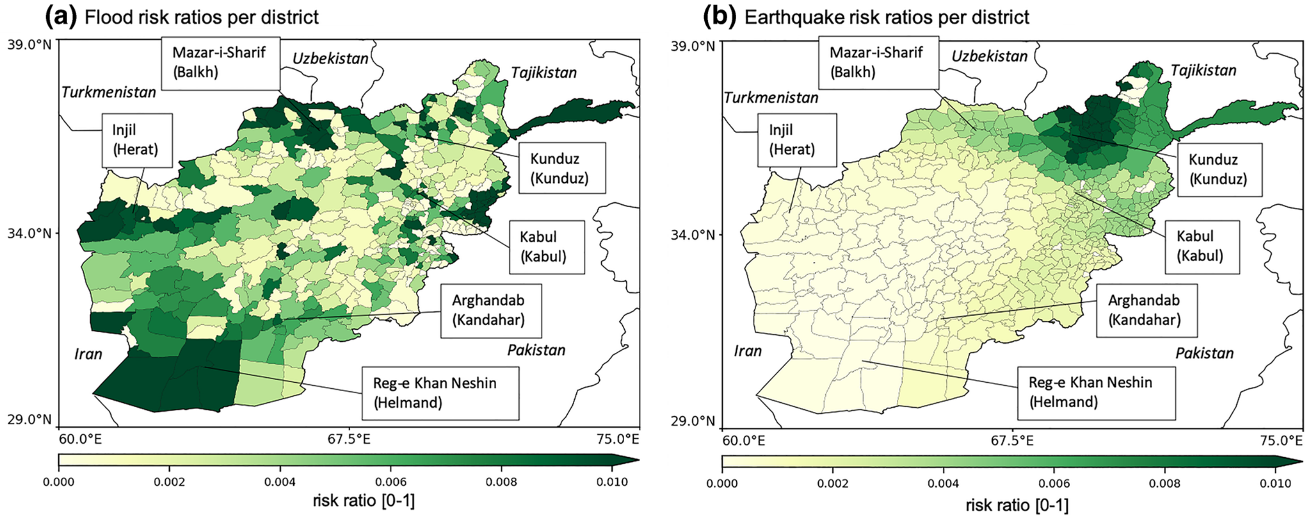

Figure 5. Current flood (a) and earthquake (b) risk ratios per district (with in brackets the province) combined for all return periods, urban and rural, and all building material vulnerability classes. We refer to Figure S3 for the absolute AAL values per district and per hazard. This and all subsequent maps use the Equirectangular projection of the WGS84 geographic coordinate system. The *x*- and *y*-axis of all maps show the long- and latitudes in degrees. AAL, average annual loss.

DJ, M2, ML, MCL, MCM) in the flood zone are upgraded to brick masonry buildings (the MEL building type)

- In the increased earthquake resilience scenario (Earthquake DRR scenario), the building stock was adjusted to be less vulnerable to earthquakes. This was simulated by adjusting the same adobe building types to wood buildings (the W1 building type) for all buildings in the flood zones

It is important to note that while upgrading the entire building stock is not a realistic DRR measure, it is used to demonstrate the impacts of asynergies between different DRR measures on risk.

3.3. Assessing Asynergies

To assess the asynergies per district, we first calculate the AAL relative to the value of exposure per cell (the risk ratio) for both floods and earthquakes in both DRR scenarios. It is important to assess the AALs as a ratio of the building stock value, to correct for the increase in the value of the exposure due to the improved buildings that have higher maximum damage values (e.g., the maximum damage per square meter residential footprint of an urban one-storey AM building is $44/m^2, while that of an urban one-storey W1 building is $106/m^2). Then, we compare the risk reduction per district. Next, we calculate the average risk ratios per cell and the total AALs in the current situation and in both DRR scenarios by combining the risk ratios and AALs of floods and earthquakes per scenario (schematically represented by the purple line in Figure 4). Figure S2 shows the value of the exposure (in US$) per district for the current situation, the two DRR scenarios and the optimal scenario.

3.4. Optimal Scenario and Sensitivity Analysis

The assessment of the asynergies allows us to also calculate the optimal scenario. Rather than using the absolute AALs, we optimize at a cell level for the lowest risk ratio by comparing both DRR scenarios. Next, we aggregate the optimized risk ratios to district and country level by taking the mean risk ratio per cell. We compare the relative AALs of the two scenarios with each other rather than with the current scenario as the higher maximum damage values of the upgraded building stock are likely to cause the DRR-scenario AALs to always be higher than the current AALs. Finally, the optimal scenario is used to calculate the sensitivities of decreasing the total risk ratios when implementing one DRR measure over the other. This

Table 2
Flood and Earthquake Risk in Afghanistan in the Current, Both DRR and the Optimal Scenario

	Current	Flood DRR	Earthquake DRR	Optimal
Total				
Average risk ratio per cell	0.0095	0.000998	0.00104	0.00096
Total AAL (US$/year)	5.2 M	8.5 M	5.9 M	7.7 M
Total exposure (US$/year)	588 M	1.1 B	759 M	930 M
Floods				
Average risk ratio per cell	0.0066	0.00078	0.00088	0.00079
Total AAL (US$/year)	3.5 M	6.5 M	4.9 M	6.3 M
Earthquakes				
Average risk ratio per cell	0.0028	0.00020	0.00015	0.00017
Total AAL (US$/year)	1.7 M	2.05 M	1.0 M	1.3 M

Note. For the current, flood DRR, earthquake DRR, and optimal scenarios, the following are shown as a total (combining floods and earthquakes) and per hazard: (1) the average risk ratio (AAL per year/exposure) per cell, (2) the total AAL (per year) for Afghanistan and (3) the total exposure for Afghanistan. The absolute total AAL in the optimal scenario counterintuitively exceeds that of the earthquake DRR scenario. This is caused by the optimization of the risk ratios rather than an optimization of the absolute AAL. The values in this table only account for the exposure in the flood zones. Note that the values presented are only for the residential buildings in the flood zone.
AAL, average annual loss; DRR, disaster risk reduction.

sensitivity is calculated as how much the risk ratio of one hazard would need to change for the other DRR measure to be equally or more effective in decreasing the risk ratio.

4. Results and Discussion

First, we discuss the findings of the current flood and earthquake risk in Afghanistan. Next, we show the relative AALs for floods and earthquakes for both DRR scenarios, and discuss the asynergies. Then, we discuss the most optimal scenario combining the lowest AALs from each scenario and a sensitivity analysis of the DRR measures. Finally, we discuss the limitations of our study and opportunities for future research.

4.1. Flood and Earthquake Risk Assessments

Figure 5 shows the results of the current flood and earthquake risk assessments in Afghanistan: for floods we find a risk ratio of 0.0066 (0.66% per year) and for earthquakes we find a risk ratio of 0.0028 (0.28% per year). For earthquakes, the northeast stands out as the region with the highest relative earthquake risk. Since we only account for the flood zones, the absolute AAL for earthquakes in (1.7 million dollars) is low compared to other studies for earthquakes that also consider damages outside of the flooded areas (Table 2). When comparing our findings with the World Bank (2018) report, they find residential building risk ratios per square kilometre ranging from 0.00027% in the southwest to 3% in the northeast for earthquakes.

For floods, the higher AAL values are found in the border areas: near the northern border with Turkmenistan (the areas around Mazar-i Sharif and Kunduz), near the north east border with Pakistan and in the South near Pakistan (e.g., Reg-e Khan Neshin). These are areas with both higher exposure values as well as higher proneness to both floods and earthquakes (as shown in Figure 2). At 3.5 million dollars, the absolute AAL for floods in the flood zones is also low compared to other studies, as the World Bank (2018) found a flood AAL of 9.8 M ($/yr) for residential buildings. These lower AAL values for floods and earthquakes can be explained by the assumption that there are no people living in the 5-year flood zones (these buildings were distributed outside the 5-year flood zone as explained in Section 3.2.2).

4.2. Assessing Asynergies

To assess the asynergies between the two DRR scenarios, we compare the risk ratios of flood and earthquake risk in both scenarios. The total value of the current exposure in the flood zones is US$ 588 million, which increases in the flood DRR scenario to US$ 1.1 billion and in the earthquake DRR scenario to US$ 760 million. As expected, we see in Table 2 that the absolute AAL value goes up as a result of the increased exposure value.

When looking at the total risk ratios (combining flood and earthquake risk) in the flood and earthquake DRR scenarios (Table 2), we find that the total risk ratio is only marginally lower in the flood DRR scenario (0.00099 or 0.09%) compared to the earthquake DRR scenario (0.0010 or 0.1%). These findings suggest that at a national level, proofing the built environment to resist floods is most beneficial in addressing both hazards, but it would require a larger invest in upgrading the built environment. Both DRR scenarios are a large improvement on of the current situation (0.0095 or 0.95%). When assessing the asynergies of earthquake DRR on flood risk, we find that flood risk under the earthquake DRR (0.00088 or 0.088%) is higher compared to the flood risk in the flood DRR scenario (0.00078). Vice versa, when assessing the asynergies of

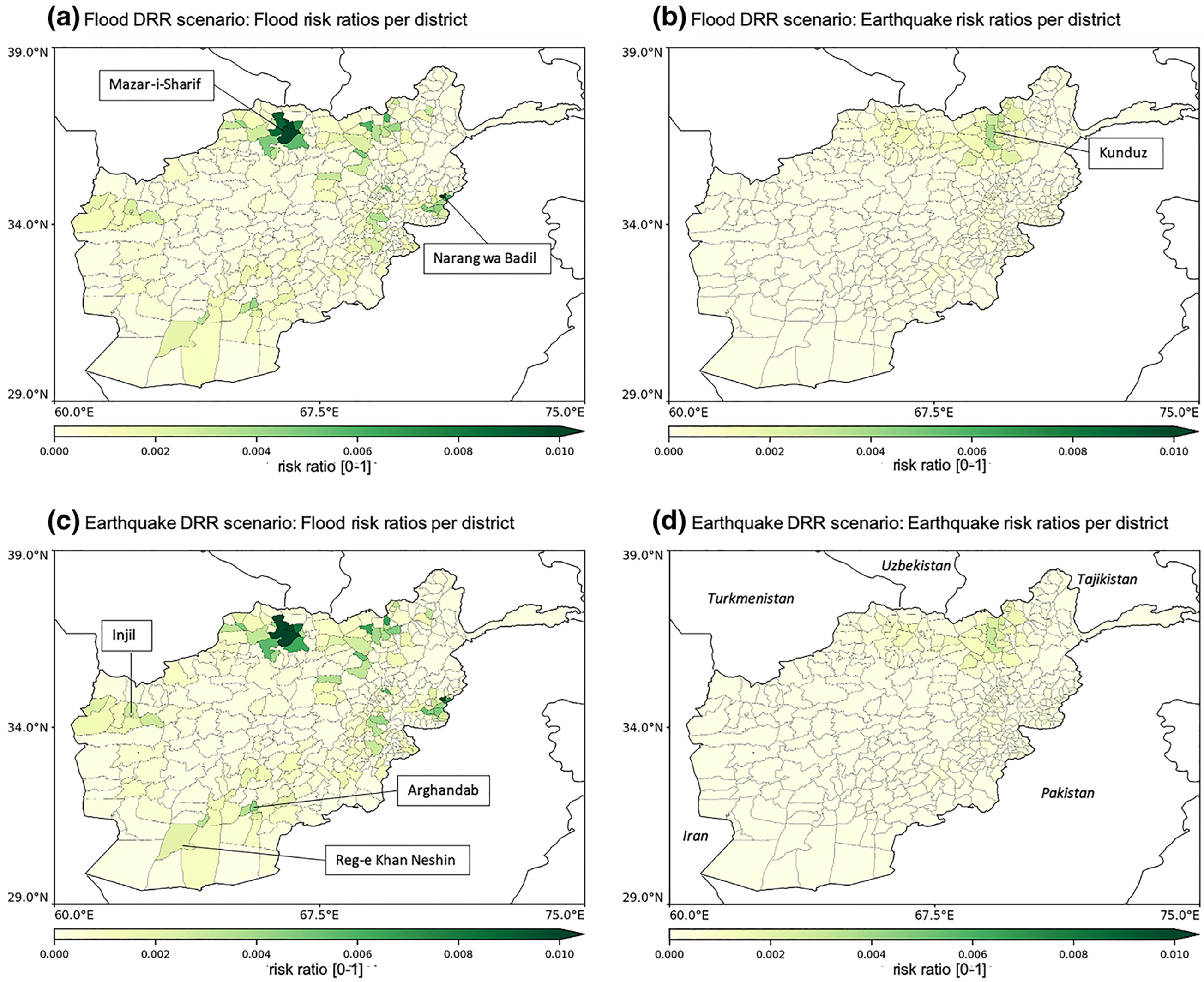

Figure 6. Flood and earthquake risk ratios for the flood DRR scenario (respectively a and b) and the earthquake DRR scenario (respectively c and d). We refer to Figure S4 for the absolute AALs per district for floods and earthquake risk in the two DRR scenarios. AAL, average annual loss; DRR, disaster risk reduction.

flood DRR on earthquake risk, we found that earthquake risk in the flood DRR scenario (0.00020 or 0.02%) is higher than the earthquake risk in the earthquake DRR scenario (0.00015 or 0.015%). It is important to note that the total absolute AAL value is highest in the flood DRR scenario. This is caused by the high value of the exposure in that scenario.

Figure 6 shows the spatial distribution of the risk ratios per district and per hazard in each scenario. To assess the asynergies of DRR measures at a district level, we compare the differences in risk ratios (asynergies) of each hazard in both DRR scenarios. When looking at the flood risk ratios in the two DRR scenarios (Figures 6a and 6c), we find that the flood risk ratio is lower in the flood DRR scenario (Figure 6a) than in the earthquake DRR scenario (Figure 6c) for each region, but some regions stand out. The largest difference between the total risk in the flood DRR (summing Figures 6a and 6b) versus the earthquake DRR (summing Figures 6c and 6d) scenario is found in the district of Narang wa Badil, which is located east of Kabul in the border region with Pakistan. Here, the total risk ratio in the earthquake DRR scenario is 0.03 higher than the total risk ratio in the flood DRR scenario. This is mainly caused by the local difference in the flood risk ratio in the flood DRR scenario (0.017) versus the flood risk ratio in the earthquake DRR scenario (0.02). The difference between the earthquake risk under both scenarios (Figures 6b and 6d) is 0.0002 despite its location in one of the more earthquake prone regions of Afghanistan. This could be explained by numerous flood events of the Kunar river in recent years, which has been the deadliest hazard type in the region and has caused severe damages (Atta-ur-Rahman & Shaw, 2015). Another large difference between the total risk in the flood DRR versus the earthquake DRR scenario is found in the region around Mazar-i-Sharif which is the fourth largest city of Afghanistan. The difference in flood risk between the two DRR scenarios is very small (<0.000015) in areas around the districts of Injil, Reg-e Khan Neshin, and Arghandab. For earthquake risk, the largest asynergy (the difference between the earthquake risk ratios in both scenarios) is found in the region around Kunduz (Kunduz). Here, the earthquake risk in the flood risk scenario is 0.0007 higher than the earthquake risk in the earthquake scenario. This coincides with the area of the country with the highest earthquake hazard (Figure 2). The absolute risk in both scenarios (Figure S4) shows the same patterns as those of the risk ratios. It is important to note that we optimized for the risk ratios and that therefore the absolute AAL in the optimal situation is higher than that of the earthquake DRR scenario (Table 2).

Despite the significantly lower replacement costs of adobe buildings, people are more likely to improve the ability of their houses to resist damages from disasters. In part this is caused by people's "place-attachment": rather than relocating to a less hazard-prone area, people continue living in the same area and decrease the vulnerability of their house (Jabeen et al., 2010). However, implementing the DRR scenarios will increase the absolute AAL compared to the current situation (Table 2). This means that people whose homes sustain damages due to a flood or an earthquake, would experience higher reconstruction costs. This could discourage people from actually implementing such building-level DRR measures.

4.3. Optimal Scenario and Sensitivity Analysis

Finally, we calculate the optimal situation for Afghanistan by comparing the risk ratios in the flood DRR and earthquake DRR scenario and selecting for each cell the lowest ratios (Table 2). We found that the average risk ratio per cell for the country can be minimized to 0.00096 (0.096%). This is 2% lower than the average flood and earthquake risk ratio in the flood DRR scenario and 8% lower than the average flood and earthquake risk ratio in the earthquake DRR scenario. We refer to Figure S5 for the figures showing the absolute AAL values per district for each hazard and the total risk.

Calculating the optimal scenario also allowed us to assess the sensitivity of the DRR scenarios in reducing the risk ratios. Figure 7 also shows the sensitivity of the DRR measures in impacting the flood and earthquake risk. The darker colors show larger asynergies. For example, in the darker blue areas it will be very unbeneficial to implement earthquake DRR measures. This is mainly the case in the western half of Afghanistan and in some of the regions bordering with Pakistan. In the middle of the country, indicated by the lighter colors, the risk would only need to change slightly for an opposing DRR measure to be equally effective. The dark red colors, concentrated on the eastern side of the country, show districts where it would be more beneficial to implement earthquake rather than flood DRR measures. This sensitivity is important to take into account when addressing the asynergies. When looking at the individual districts, we find that in Shibkoh and Kahmard the benefits of the flood DRR over earthquake DRR scenario are highest (respectively, 16% and 15%), while Bak and Khost wa Firing benefit most from earthquake DRR measures (respectively, 40% and 37%). This means, for example, that in the district of Bak the earthquake DRR scenario creates a much larger decrease in risk ratio and that the district would benefit greatly from the implementation of earthquake DRR measures. Conversely, Kahmard would benefit from flood DRR measures. The less darkly colored districts would benefit to a much lesser extent from either one of the DRR measures.

4.4. Limitations and Future Outlook

The aim of our study is to demonstrate scientists and policy makers the importance of accounting for DRR asynergies in risk assessments, rather than providing a policy recommendation for the Afghan government regarding its risk management. The flood and earthquake AAL values found in this study are lower than those found by other studies, mainly due to the mismatch between the WB and GLC30 data, the exclusion of the 5-year flood zones for both hazards and the focus on residential buildings while excluding multiuse buildings. The absolute AALs should not be considered as comprehensive, but the relative changes in AALs

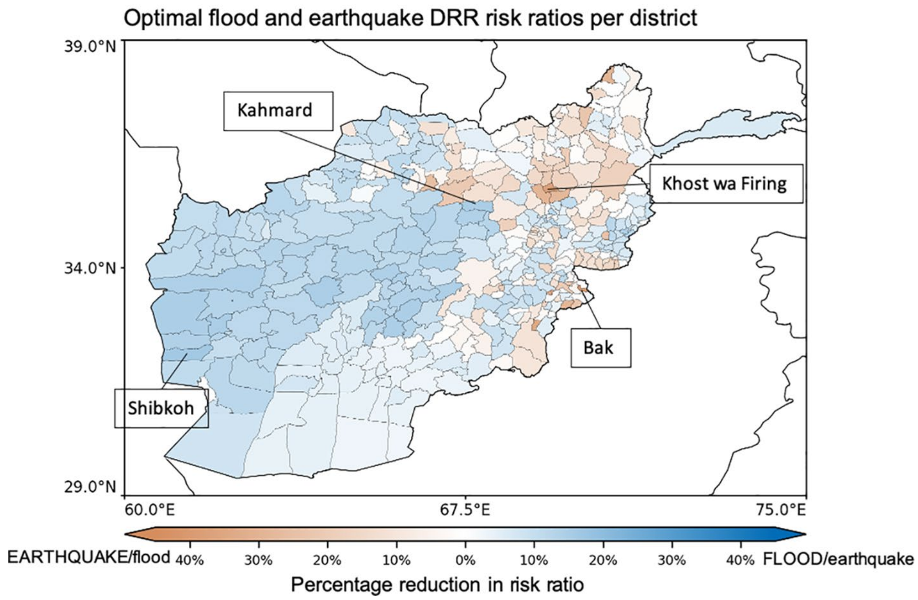

Figure 7. Optimal flood and earthquake risk ratios per district and the sensitivity of the DRR measures in percentage reduction of the risk ratios. The optimized risk ratios were aggregated to district and country level by taking the mean risk ratio per cell. Per district, the lowest risk ratio is shown for the total flood or earthquake risk in the Flood DRR scenario (blue values) or Earthquake DRR scenario (red values). The color gradients show the percentage in reduction of the risk ratio of one DRR scenario over the other, with in red the districts where the percentage reduction in risk ratio is larger in the earthquake DRR scenario and in blue the districts where the flood DRR scenario results in a larger percentage reduction in risk ratio. DRR, disaster risk reduction

in the DRR scenarios do provide insights into how asynergies between structural DRR measures can impact the total risk.

There have been several discussions in the literature about the complexity of disaster vulnerability and vulnerability encompasses more than just poor construction or development of the built environment in hazard-prone areas (Godschalk, 2003; McEntire, 2005; Wisner et al., 2004). Although decreasing the vulnerability of an entire country's building stock to better withstand natural hazards may appear unrealistic, it does provide preliminary insights into the potential asynergies of DRR measures between different hazard types. It enables us to better understand the interactions between different single-hazard-tailored measures, how commonly the issue of opposing effects due to single-hazard type building measures arises and ultimately helps urban planners in deciding what type of measure is worthwhile in which area. This allows policy makers to spatially differentiate building codes and other building-level DRR measures to address the most prevalent risk while not compromising risk of other hazard types. It should also be noted that in Afghanistan, the brick industry is much larger than the wood industry (Lister & Karaev, 2004). Hence, the transition to brick would be a more realistic scenario. Nonetheless, it is important to account for the potential asynergies of the use of bricks in earthquake prone areas. Moreover, we calculated the asynergies only for two simple DRR scenarios. A choice for different DRR scenarios (e.g., building on stilts as a flood DRR measure) would lead to different findings. For future research it would be beneficial to also examine other possible DRR scenarios and account for changing hazard and exposure conditions. Moreover, exposure data were available at a district level. Ideally, when calculating asynergies with the purpose of directly influencing policy measures, we recommend using more detailed data.

Another limitation that was not taken into account is that of corruption. Corruption is one of the key issues in DRR (Alexander, 2016; Kenny, 2012; Lewis, 2011), especially for buildings, as the construction industry has been shown to be the most corrupt industry of the global economy (Betts & Farrell, 2009). Over the past 30 years, Eighty-three percent of the deaths attributed to collapsed buildings due to earthquakes occurred in anomalously corrupt countries (Ambraseys & Bilham, 2011). Daniell et al. (2014) show that Afghanistan, despite its high earthquake risk, ranks very poorly on a scale of corruption (high) versus adequacy of its seismic codes (low) and capital stock per capita (low). Despite the understanding of how to decrease the risk of earthquakes, measures such as implementing and reinforcing building codes continue to be jeopardized especially in developing countries (Kenny, 2012).

Although we recognize the importance, accounting for potential malfunctions in simulating the adverse effects of DRR measures is impossible. Another important aspect is people's affinity with and access to different construction materials and techniques. For example, Kennedy et al. (2008) discussed how in Aceh (Indonesia) timber houses are safer compared to masonry houses, as many people build their houses themselves and have a far better understanding of timber building techniques compared to masonry. While the WB data were obtained in collaboration with local stakeholders, the DRR scenarios were not designed in consultation with local stakeholders. Future research should aim for such co-production of DRR scenarios.

These limitations also influence the definition of the optimal scenario. Here, we choose to optimize to the lowest relative AAL. While the spatial detail of our approach reflects individuals or small communities adjusting their own houses to be more flood or earthquake resistant, many other aspects can and should be taken into account when optimizing to a locally ideal DRR situation, such as the cost of upgrading and maintaining a higher quality house and the availability of and access to building materials.

5. Conclusions

Many DRR measures, whether taken by individuals or enforced through policies, are aimed at decreasing the vulnerability of individual objects such as buildings. While many countries face the risk of multiple hazards, building-level DRR measures are often tailored to decrease the risk of one hazard and can have potential negative impacts on the risk of another hazard. We refer to these effects as "asynergies" of DRR measures.

We provide an overview of common asynergies between flood and earthquake DRR building measures. This is applied to a case-study of Afghanistan to demonstrate the asynergies of flood and earthquake DRR measures at a district level. In a case study of Afghanistan, we first calculated the AAL for floods and earthquakes in the current situation using hazard, exposure and vulnerability data from the World Bank (2018). In the current situation this average is 0.66% per year for floods, and 0.28% per year for earthquakes. Next, we created two DRR scenarios to simulate a flood risk reduced situation and an earthquake reduced situation by changing the building stock. We found asynergies for both hazard types in each DRR scenario when looking at the average risk ratios per cell. We find that the flood risk ratio in the earthquake DRR scenario (0.088%/year) is higher compared to the flood risk in the flood DRR scenario (0.078%/year). The same holds for the inverse, with the earthquake risk ratio in the flood DRR scenario (0.020%/year) being considerably higher than the earthquake risk ratio in the earthquake DRR scenario (0.015%/year). When summing the flood and earthquake damages we arrive at total risk ratios of 0.098%/year under the flood DRR scenario, and 0.104%/year for the earthquake scenario. When assessing the optimal set of risk measures (choosing for each district the lowest risk ratio) we find that the total risk ratio can be decreased to 0.096%, which is 2% lower than the flood DRR scenario and 8% lower than the earthquake scenario. The optimal measure differs spatially throughout Afghanistan, but in most districts (based on the optimization on cell level) it is more beneficial to take flood DRR measures. However, in the districts where it is more beneficial to take earthquake measures the difference is considerable (up to 40%, while flood measures are only up to 16% better in individual districts).

A better understanding of asynergies in DRR measures between different hazard types is crucial in informing policy makers and allows them to adjust building-level DRR measures accordingly to promote a more sustainable development. Future research is required to continue addressing existing knowledge gaps in the asynergies of DRR measures tailored to different hazard types in general and for local case studies in particular. Future research should focus on improving our scientific understanding of asynergies, and the calculation of asynergies as part of risk assessments should be mainstreamed.

Conflict of Interest

The authors declare no conflicts of interests.

Data Availability Statement

The Afghanistan World Bank data used for this research can be obtained through: https://disasterrisk.af/geonode_risks/data_extraction/

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