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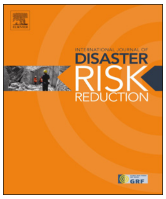

Does mitigation save? Reviewing cost-benefit analyses of disaster risk reduction

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ABSTRACT

The benefit-cost-ratio (BCR), used in cost-benefit analysis (CBA), is an indicator that attempts to summarize the overall value for money of a project. Disaster costs continue to rise and the demand has increased to demonstrate the economic benefit of disaster risk reduction (DRR) to policy makers. This study compiles and compares original CBA case studies reporting DRR BCRs, without restrictions as to hazard type, location, scale, or other parameters. Many results were identified supporting the economic effectiveness of DRR, however, key limitations were identified, including a lack of: sensitivity analyses, meta-analyses which critique the literature, consideration of climate change, evaluation of the duration of benefits, broader consideration of the process of vulnerability, and potential disbenefits of DRR measures. The studies demonstrate the importance of context for each BCR result. Recommendations are made regarding minimum criteria to consider when conducting DRR CBAs.

1. Introduction

1.1. Mitigation saves: lives, environment, money

Disaster risk reduction (DRR) has long been recognized in the literature for its role in mitigating the negative environmental, social and economic impacts of natural hazards. For example, the US Federal Emergency Management Agency (FEMA), found an average benefit-cost ratio (BCR) of 4 in a review of investments in 4000 mitigation programs in the US [63,54]. Still, DRR benefits are largely under-quantified in comparison to the frequency of disasters and the resulting impacts, especially in developing nations [54]. For example, for flood mitigation in Mozambique, the post-disaster aid request was 203 times the unfulfilled pre-disaster request [55].

Additionally, myths have arisen surrounding BCRs for DRR. The most infamous is the often-quoted ratio that the World Bank is purported to have calculated that DRR saves $7 (sometimes $4–7) for every $1 invested. The 7:1 ratio continues to be used today, often without citing a reference, for example, by top UN officials [80], government organizations (USAID, e.g. [3]), and NGOs (Center for American Progress, e.g. [57]; Oxfam, e.g. [68]). The World Bank no longer promotes that specific statement and recommends that the ratio not be used (Kull, personal communication). The origins of this ratio could not be tracked down, with the earliest citation found so far being [13] stating, without a source, that 'The World Bank and U.S. Geological Survey calculate that a predicted $400 billion in economic losses from natural disasters over the 1990s could be reduced by $280 billion with a $40 billion investment in prevention, mitigation and preparedness strategies'. When each author was contacted, given the length of time that had elapsed since Dilley and Heyman [13] was published, it was difficult for either to provide more information.

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It is also important to note that DRR does not inevitably or necessarily have a favorable BCR, as noted in some studies analyzed throughout this paper. There is also the question about whether or not a hazard must manifest for the BCR to be appreciated. For instance, if flood risk reduction measures are taken inside a property but no flood manifests over the lifetime of that building, are the benefits of the measures accrued and was it worthwhile to take the measures? These risk management discussions are limited in the studies. More could also be discussed regarding co-benefits of DRR measures, so that measures undertaken yield gains irrespective of a hazard manifesting.

Nevertheless, as disaster costs continue to rise and as politics continues to shift towards justifying actions in financial terms, the demand has increased to demonstrate the economic benefit of DRR to policy makers and decision makers [17,2,40,27,53]. If the financial benefits can be shown, a stronger possibility exists for investment in disaster mitigation actions, although that is by no means certain.

Yet, for example, despite FEMA's work [63,54], in the U.S., only 10% of earthquake- and flood-prone households have adopted mitigation strategies [54]. That despite floods from Hurricane Katrina (2005) and Hurricane Sandy (2012) each costing more than $100 billion—with a similar figure expected as the cost of the next major U.S. earthquake whether that strikes Los Angeles, St. Louis, or Boston. Meanwhile, studies cover a wide range of parameters in terms of locations, DRR measures, hazards, and temporal scales, including approaches which might not always be considered as core DRR activities even though they are and should be central to DRR.

For example, Kull [52] utilize a 'people-centered' resilience-driven flood risk reduction approach in India finding greater economic efficiency, lower initial investment costs, and returns that are not sensitive to assumptions traditionally made during CBA (e.g. discount rates, future climate conditions) when compared to structural flood mitigation measures in the region. Khan [47] demonstrates technology interventions, such as a new boat winch system in Vietnam. The Red Cross (2008) presents one of a few examples of evaluating the benefits of training with the inclusion of First Aid training in its CBA for its work in Nepal. Mechler [62] and Kull [52,53] include climate change scenarios in their CBAs, perhaps providing a more comprehensive projection of potential costs. Dedeurwaerdere [12], UNIDSR (2002), and Nepal Red Cross [64] evaluate ecosystem restoration approaches such as reforestation of mangroves and rain forests, which contribute to sustainable livelihoods, ecosystem stability, and reduce risk.

The plethora of studies on, and the concern about, disaster costs has led to studies compiling this information. For example the global and multi-peril databases generated by Munich RE and CRED (the EM-DAT database) span space, time, and hazard types. The equivalent approach for DRR benefits does not exist. This paper is a start towards setting up a framework for comparing DRR BCRs across multiple case studies in space, in time, and for different hazards and vulnerability characteristics.

2. Methods and questions

Cost benefit analysis (CBA) is an established economic tool for comparing the benefits and costs of a given project or activity [50,2,18,82,53]. CBA consist of four primary stages: (i) project definition, in which the reallocation of resources being proposed are identified (ii) identification of project impacts, including assessment of additionality (net project benefits) and displacement ('crowding-out'), (iii) evaluating which impacts are economically relevant, that is, quantifying the physical impacts of the project and (iv) calculating a monetary valuation, discounting, weighting and sensitivity analysis [26]).

As Venton [82] and many other studies demonstrate, the utility of CBA extends beyond a tool for cost comparison to decision support. Referring to an Oxfam study undertaken in El Salvador in 2010, Venton [82] reflects on the finding that the use of community-based silos and storage practices to protect crops were not actually cost-effective, in large part due to cultural barriers to collective storage that dictated the need (and expense) of individual household silos. CBA was instrumental in this case in evaluating alternative measures, better enabling a discussion between community based organizations (CBOs) and the government to find a culturally acceptable and cost-efficient solution.

CBA has limitations that are recognized, some of which are inherent to every analysis. For example, for environmental issues, (i) technical limitations for the valuation of non-market goods, such as wildlife or landscapes, (ii) inability to predict what project impacts will be on ecosystems, (iii) lack of methods for incorporating uncertainty and irreversibility [26]). Other frequent criticisms of CBA for DRR and other purposes are a lack of quantification of the distributional impacts (e.g. who benefits and who pays?) [52], ethical concerns over associating a monetary value to life [60], and quantifying other intangibles [54]. More contextually, CBAs for DRR tend not to quantify social and environmental impacts, while some of these benefits are qualitative and therefore are not quantifiable with CBA—or even comparable in terms of costs and benefits.

Despite these limitations, CBA is still a commonly relied upon metric for communicating benefits to decision makers. CBA can be used to formulate economic arguments for investment in risk reduction, rather than responding to the impacts of a future disaster event [82]. In terms of specific components of the CBA, the benefit-cost-ratio (BCR) is an indicator used to summarize the overall value for money of a specific project.

The examples of CBA for DRR cited above range across hazard types, geographies, scales, and vulnerabilities. These studies rarely report the costs and benefits of these DRR strategies in a systematic manner to facilitate an understanding of which technique might be best in which circumstance.

This study compiles and compares original CBA case studies reporting DRR BCRs, without restrictions as to hazard type, location, scale, or other parameters. To be included here, a study must provide a new, quantitative BCR for a DRR initiative, indicating the savings obtained for the investment. Only studies reporting such numbers, and the methodologies and data used to obtain the ratio, are included. For instance, studies only describing methods or without full data analysis

Table 1
Descriptions of DRR activities, benefits, costs and main study parameters.

Authors	Target benefactors	Level	Hazard(s)	DRR activities evaluated	DRR activity benefits	Vulnerability: valued items (description)	Vulnerability: items not valued, rationale (where provided)	Time frame	Discount rate	Cost-benefit (C/B) or benefit-cost (B/C)	Structural, non-structural	Framing
Venton [82][a]	Agricultural–pastoralists in Mzimba District, Malawi	Community based	Drought	Provision of alternative crop types and early-maturing seed varieties; donation of 2 breeding goats to each household; training in soil water conservation (swc); contingency planning for future shocks	Improved crop yields; increased livestock numbers; increased use of swc techniques (e.g. Water-harvesting and micro-irrigation)	Maize yield and number of goats per household; loss of education and labor avoided ; proxy for loss of life avoided, e. g. Earnings that adults would have made if alive were estimated)	Any indirect impacts	10-yrs	0, 10%	(B/C) 24 to 35 (for 10%, 0% discount rates, respectively)	Non-structural	Backward-looking
Khogali and Zewdu [48]	(1) Pastoralists forced into semi-permanent resettlements in Al Manaar, Derudeib; (2) agricultural-pastoralists in Lashob; (3) households in the Hamisiet region; (4) water for nomadic pastoralists and their livestock who migrate annually	Community based	Drought	(1) Construction of terraces; (2) construction of earth embankments;(3) Communal Vegetable Garden (irrigated); (4) hafir construction (large hole dug in the ground that stores runoff water)	(1) Households able to produce sorghum that were previously not able to; (2) sorghum production during drought; (3) sorghum and vegetable production; (4) reduced death and improved health of livestock; reduced conflict	(1) Increased production capacity: sorghum,vegetables, livestock; (2) construction, materials, training, labor, seeds, maintenance; (3) number of households in the area benefitting from project; value of sorghum; (4) livestock, wages lost from inability to work	(1–3) Land is not sold in region and has no market value; (4) cost of maintenance for embankments (made of soil); water; market prices	10-yrs (1–3); 15-yrs (4)	10%	(C/B) (1) 1: 61; (2) 1: 2.4; (3) 1:1800; (4) 1:2.7	Structural and non-structural	Assesses benefits from different DRR program activities
Mechler [62]	Residents in drought prone Uttar Pradesh, India	Community based	Drought	(i) Subsidized micro-crop insurance for spreading drought risk, development of (ii) groundwater irrigation and (iii) a combination of i, ii	Reduced income by the farmer from diversion activities, reduced relief expenditure	Groundwater irrigation, borehole construction, pumping water, insurance premiums and technical assistance	Other social benefits and benefits to broader societal groups; out of scope of project, as it considered a certain demographic (vulnerable, poor farmers)	43 yrs (2007–2050)	0–20%	(B/C) 1–3.5	Non-structural	Forward-looking
Khan [47]	Residents vulnerable to earthquakes in	Community based	Earthquake	Utilizing straw-bale in building construction	Reduced price of building materials,	Building materials, maintenance and cost of reduction in	Human life (ethical implications)	30 years	12%	(C/B) 2.0	Structural	Ex-ante (forecast based)

Table 1 (*continued*)

Authors	Target benefactors	Level	Hazard(s)	DRR activities evaluated	DRR activity benefits	Vulnerability: valued items (description)	Vulnerability: items not valued, rationale (where provided)	Time frame	Discount rate	Cost-benefit (C/B) or benefit-cost (B/C)	Structural, non-structural	Framing
	Kathmandu, Nepal			instead of brick construction	reduced heating/cooling costs, straw-bale structures are resistant to earthquakes (reduced lives lost), decrease in child labor (common for brick construction), improved air quality	floor area necessitated by the wider straw-bale construction for a typical 2 story house Kathmandu, decreased health costs						
Kunreuther and Michel-Kerjan [54][a]	Students and school staff in 35 of the most seismically active developing countries	National study	Earthquake	Retrofitting schools in 35 seismically active countries in the developing world so they are earthquake resistant	Over the next 50 years an estimated 250,000 lives could be saved in 35 countries with an investment of $300 billion to retrofit schools. As the value of life (human life) component is increased in the analysis the BCRs increase, e.g. for a human life of $1.5 M, 13 countries have a BCR > 1, $75 billion could be spent on retrofitting schools and more than 135,000 lives could be saved	Human life, cost of retrofitting schools (construction)	Social, environmental benefits (beyond scope of study)	10-, 25-, 50-yrs	5, 12%	(B/C) as value of life increases, BC exceeds one for many countries for retrofitting schools (e.g. at 3% discount rate, BC exceeds 1 for 13 of the 35 countries and 135,000 lives could be saved over the next 50 yrs)	Structural	Evaluates the costs and benefits of alternative programs and policies for reeducating future damages and fatalities from natural hazards and facilitating recovery
Holland [33]	Residents in Navua, Fiji	Community based	Flood	Early warning system	Decreased economic loss from: reduced injury (people have warning/ more time to evacuate), personal and	Economic losses totaled from household losses (homes, premises, possessions), business losses, payment from government, NGOs,	Certain humanitarian aid items, trauma and irreplaceable items, days lost for school children due to water shortages	20-yrs	3, 7, 10%	(B/C) 1,7 (for government, international stakeholders, respectively)	Non-structural	Assesses impacts across sectors and distributional issues (as cited in [82])

					commercial losses (people have more time to move valuables), reduced aid from government and other sources (people can better protect possessions)	charity organizations, other losses (trauma/ medical).						
EWASE [16]	Communities in flood prone regions of Austria	Community based	Flood	Effectiveness of early warning systems in small river basins that have short hydrological response times compared to the cost of structural flood measures	Increase in lead time may provide valuable time for completion of preventative measures; however, a false alarm will have economic costs	Early warning system (investment costs, maintenance and physical assets and maintenance, and operating costs)	Not included in CBA were intangible damages, but these are addressed separately in a multi-criteria assessment	20-yrs	3%	(B/C) (early warning system) 2.6–9.0	Non-structural	Assesses potential economic benefits of early warning system/ meteorological services versus costs of early warning system/ meteorological services
Holub andFuchs [34]	Local buildings/ infrastructure in Austrian Alps	Community based	Flood	Local structural measures	Prevented damage to buildings/ infrastructure in study site	Potential damage to buildings from flash floods; cost of local structural measures	Downstream benefits; value of items within buildings	80-yrs	3.5% (interest rate)	2.1–6.7	Structural	Comparative analysis of mitigation studies
Mechler [61][b]	Piura, Peru residents in flood prone area	Community based	Flood	Polder construction	Elevating existing dykes and adding polders decreases flooding risk	Private sector: housing damaged or destroyed; education and health, water and sewage, agricultural, industry, commerce and service sectors: assets destroyed or damaged (buildings, machinery, roads, etc.)	Environmental damage (no data) and environmental benefits (e.g. increased reforestation due to increased rainfall)	30-yrs	12%	(B/C) 2.2–3.8	Structural	Backward-looking
Also published in Mechler [61][c]	Semerang, Indonesia residents in flood prone area	Community based	Flood	Return on an integrated water management and flood protection scheme (e.g. reducing ground subsidence by decreasing groundwater withdrawal), improved drainage to mitigate tidal inundation)	Reduced flooding and inundation	Construction and operation costs for structural mitigation measures	Broader social benefits not included	54-yrs (2005–2059)	12%	(B/C) 1.9–2.5	Structural	Forward-looking

Table 1 (*continued*)

Authors	**Target benefactors**	**Level**	**Hazard(s)**	**DRR activities evaluated**	**DRR activity benefits**	**Vulnerability: valued items (description)**	**Vulnerability: items not valued, rationale (where provided)**	**Time frame**	**Discount rate**	**Cost-benefit (C/B) or benefit-cost (B/C)**	**Structural, non-structural**	**Framing**
Burton and Venton [5]	Residents in Philippines under natural hazard threat where DRR programs are implemented	Community based	Flood	Cost-benefit analysis of the Integrated Based Disaster Preparedness program (ICBDP) versus disaster response operations undertaken by the Philippines National Red Cross	The protection of assets such as housing, crops and livestock; health benefits such as access to safe water and social benefits such as the safe access of children to their schools	Construction cost of structural measures (hanging footbridge, sea wall, dyke)	Authors note that considerable data limitations limit the CBA to only looking at some of the small-scale physical mitigation projects undertaken through the CBDRM program	15-yrs	Not specified	(B/C) 24 (footbridge); 4.9 (sea wall); 0.7 (dyke)	Structural	Backward-looking
White and Rorick [84]	Residents in flood prone Kailali, Nepal participating in DRR program	Community based	Flood	Multi-sectored and relies on a mix of capacity building, physical and early warning interventions (e.g. bio-engineering for riverbank protection such as bamboo crib walls, plantations on the river bank, evacuation routes, boats, raised water points, embankment work and spurs, early warning systems, community planning and capacity building)	Reduced number of houses flooded, reduction in grain storage lost, asset loss in flooded homes avoided, crops were still lost, percentage of land lost to erosion decreased, infrastructure loss remained same, number of individuals exposed to contaminated drinking water avoided	Damage to houses flooded/assets in houses; grain-storage and annual crops lost, land permanently lost due to erosion, infrastructure lost, number of individuals exposed to contaminated drinking water; household sizes/ value of land owned	Qualitative social and environmental benefits were not monetized	10-yrs	10%	(B/C) 3.49	Structural and non-structural	Backward-looking
[64]	Residents in Ilam District, Nepal experiencing flood hazards	Community based	flood	Mitigation works (construction of flood containing walls, gabion boxes built in the river bed, tree planting on riverbanks), maintenance of tube wells, construction of evacuation	Households borrow money at 2% rate; land/ crops protected by mitigation works; livestock brought to safe areas during hazards due to preparedness plans; wells	Land, crops, houses protected by mitigation works; income generation loans; protection of water sources; first aid training	Livestock protected (minimal impact), greater protection of forest resources (outside of study scope), provision of shelter/relief items (outside of scope of study), social impacts such as improved coordination, empowerment of	15-yrs	10%	(B/C) 18.6 (sensitivity analysis 14.8)	Structural and non-structural	Backward-looking

				shelters, formation of community DRR units, emergency fund, first aid training, supply of a rickshaw ambulance	protected from contamination; houses still destroyed by fires/elephant attacks, but emergency fund (cash and grain) provides security for those affected; reduced cases of diarrhea/ illness, rickshaw provides faster visit to doctor		women, greater sense of security (cannot assign quantitative value)					
[28]	Residents in Dez and Karun River floodplains, Iran	Community based	Flood	Structural mitigation measures including dykes, levees, flood retention dams and flood diversion	Avoided or reduced flood damages	Construction costs	Social, environmental costs (outside of project scope)	25-yrs	10%	(B/C) 0.29–1.03 levees, 0.7–1.34 dams, 1.1 flood diversion	Structural	Backward-looking and forward-looking
Khan [46]	Residents in flood prone area of Lai Basin, Pakistan	Community based	Flood	(1) Expressway/ channel; river improvements; (2) early warning system; (3) relocation of houses along flood plain and restoration of area with wetland	(1) Highways more flood resistant; reduced peak river flow and increased flow capacity due to river improvements; (2) decrease risk of injury and loss of life from flooding, reduced damage to property if residents have sufficient time to take precautionary measures; (3) reduce or eliminate risk of households previously in the floodplain, ecological improvements through restoration	(Vulnerability) using risk and damage data from 2001 flood and triangulation of property values conducted with real estate agents in the floodplain; (depth damage) data from various regional and global studies of the region, corroborated with anecdotal evidence and qualitative surveys of the area; (economic effects) reported damage from 2001 flood; reported illness from malaria	Social benefits of flood prevention (e.g. reduced disease burden, trauma, disruption of livelihoods) not included because there was no reliable data	30-yrs	12%	(B/C) (1) 8.55–9.25; (2) 0.96; (3) 1.34	Structural and non-structural	Backward-looking

Table 1 (*continued*)

Authors	Target benefactors	Level	Hazard(s)	DRR activities evaluated	DRR activity benefits	Vulnerability: valued items (description)	Vulnerability: items not valued, rationale (where provided)	Time frame	Discount rate	Cost-benefit (C/B) or benefit-cost (B/C)	Structural, non-structural	Framing
Kull [52,53][c]	Residents in flood prone Gangetic Basin, Nepal and India	Community based	Flood	Individual level (raising house plinths and fodder storage units, rainwater harvesting, raising existing private hand pumps and toilets); community level (early warning system, raising community hand pumps and toilets, constructing flood shelters, establishing grain and seed banks, maintenance of key drainage bottlenecks, development of self help groups and purchasing community boats); society level (promotion of flood adapted agriculture and strengthening of healthcare system).	Reduce risk of death, injury or illness related to flooding; improve agricultural practices and productivity	Survey questionnaire collected information on specific disaster-related loss, coping, exposure, vulnerability, preference and cost/benefit data; cost of 2003 embankment project	Authors note that, while conclusions appear robust, data availability and quality still constrained the analysis	43 yrs (2007–2050)	0–20%	(B/C) 2–2.5	Structural and non-structural	Backward-looking (Nepal), backward-looking and forward-looking (In)
IFRC [39]	Residents in flood prone communities of Bangladesh	Community based	Flood	Creation of community groups to raise risk awareness and increase preparedness, construction of escape routes, set-up of community disaster emergency funds, construction of	Community groups raise hazard awareness, as well as health and sanitation knowledge; evacuation routes decrease loss of life and injury; emergency fund allows for	Household surveys and reports were utilized to estimate DRR program costs and benefits	Improved community cohesion/greater sense of security; lives saved, injuries avoided; hybrid vegetable seeds (future benefits), etc.	15-yrs	7.74%	(B/C) 1.18–3.04; future protective benefits (3.05–4.90)	Structural and non-structural	Cba conducted to assess economic efficiency of drr programs

				tube-wells to increase access to drinking water; training and awareness raising in health and sanitation	rebuilding after hazard events							
Kunreuther and Michel-Kerjan [54]	Residents in 34 countries most prone to flood damage	National study	Flood	Constructing a one-meter high wall to protect homes in 34 of the most flood prone communities global	For an investment of $904 billion in constructing walls around houses or $.5.2 trillion to elevate houses in 34 of the worst flood impacted countries 61,000 lives over the next 50 years could be saved	Expected reductions in damage to infrastructure, property and avoided fatalities	Other social, environmental benefits (beyond scope of study)	10-, 25-, 50-yrs	5, 12%	(B/C) 60 building one-meter wall; 14.5 for elevating homes	Structural	Forward-looking
Venton and Venton [81]	Residents in two drought/flood prone communities in In where DRR activities have been implemented	Community based	Flood, drought	Two communities with existing DRR programs were selected to evaluate the benefit of the DRR activities; impacts were analyzed in five categories (natural, physical, human, social and economic)	(Bihar) planting of trees to increase soil stability; village development fund able to provide loans for rebuilding; raised hand pumps ensure clean water supply; reduced losses and injury to people due to effective evacuation; provision of boats means community does not have to rent; (Khammam) raised hand pumps ensure water supply, reduce health problems, and ensure no blockage once floodwaters recede; provision of hand pumps allows for	(Bihar) installation of hand pumps, boats, motorbike for staff transport, construction of evacuation road, community training, personnel support costs (office rental, travel/lodging, stationary/printing, communication), personnel costs (project staff and consultancy)	Not valued because of lack of data: destruction of crops/soil from severe floods/drought; houses destroyed in floods; health costs of flood/drought; social relationship costs; health of survivors	20-yrs (Bihar); 15-yrs (Khammam)	10%	(B/C) Bihar (baseline scenario 3.17–4.58), raised hand pump: 3.2, potential future initiatives: 0.62, low interest loans: 57.8); Khammam (B/C) (baseline scenario 3.7–20.05)	Non-structural	Backward-looking

Table 1 (*continued*)

Authors	Target benefactors	Level	Hazard(s)	DRR activities evaluated	DRR activity benefits	Vulnerability: valued items (description)	Vulnerability: items not valued, rationale (where provided)	Time frame	Discount rate	Cost-benefit (C/B) or benefit-cost (B/C)	Structural, non-structural	Framing
					easier access to water, enabling livelihood activities and easier irrigation of fields							
Dedeurwaerdere [12]	Residents in Philippines impacted by floods and lahars	Community based	Flood, lahar	Rainforestation farming (15 yrs); bamboo plantation (10 sq km, 4 yrs); river channel improvements (3 yrs);	Reduction in economic losses from flooding/ lahars	Potential economic losses (PELs) were based on the economic values of the existing investment per sector, e.g. agriculture (mainly crops); Properties (industry and private investments); Infrastructure (roads, bridges and the like). Benefits of the natural disaster management are then measured as the difference between PEL without and with the project.	Environmental or social benefits, no data	3-yrs (River channel improvement); 4-yrs (bamboo plantation); 30-yrs (rainforestation farming)	12%	(B/C) Rainforestation 30; Bamboo plantation 14.74; river channel improvements 3.5 (dredging, dike construction, widening and channel excavation/ dredging, construction of floodways)	Structural and non-structural	Forward-looking
MMC [63][d], [20,72,-22,85]	Selected communities and representative national sample, (USA)	National study	Hydro-meteorological (general)	Varied by community	Loss avoided: property damage (e.g. buildings contents, bridges, pipelines), direct business interruption loss (e.g. damaged industrial, commercial or retail facilities), indirect business interruption loss (e.g. ordinary multiplier or ‘ripple’ effect),	Supplemental methods were used to assess direct property losses from floods and tornadoes; casualty losses from hurricanes, tornadoes and floods; business interruption losses for utilities; environmental and historic preservation benefits; and process mitigation activities; project cost data	Uncertainty in models/database and heterogeneity of communities; ‘ripple effects’	1998–2005 (Communities); 1993–2003 for national study	2%	(B/C) 3.5–5.1; average of 4 across programs	Structural and non-structural (depending on type of grant)	([63] and Supporting studies) assessing the future savings from mitigation activities

					nonmarket damage (e.g. environmental damage to wetlands, parks, and wildlife and damage to historic structures), human losses (e.g. deaths, injuries, homelessness), cost of emergency response (e.g. ambulance service, fire protection)							
Guocai and Wang [27]	End-users of meteorological services in China	National study	Hydro-meteorological (general)	Meteorological services, divided into public and for various economic sectors	Economic benefits gained through (public) utilizing weather service for planning and avoiding losses; (government, business) disaster planning	Survey method evaluates participants economic benefit via I) willing-to-pay, II) cost-savings, and III) shadow-price methods	Accuracy of the meteorological services; additional costs of the service (TV, radio, internet); uncertainty	Not specified	not specified	(C/B) 1:40	Non-structural	Backward-looking
NOAA [66]	End-users of GOES-R meteorological products in aviation, energy (electricity and natural gas), irrigated agriculture, and recreational boating	National study	Hydro-meteorological (general)	Improved meteorological forecasts utilizing GOES satellites	Improved tropical cyclone forecasting (more effective action to protect property and enable evacuation); enhanced aviation forecasting (improvements in avoidable delays, value of passenger time avoided, avoidable physical assets and maintenance costs, and avoidable risk of aircraft/life	Costs associated with improving meteorological program (e.g. technology, infrastructure, program costs)	Other potential benefits of the GOES-R satellite were not valued, e.g. benefits to human health (monitoring of harmful events such as algae blooms and forest fires); monitoring of water quality, river flows and reservoir management, monitoring of ocean resources (sea surface temperature near corals, ocean current monitoring) were not valued	12-yrs (2015–2027)	7%	note: CBA results not presented in ratios; dollar amounts of estimated savings given.	Non-structural	Forward-looking

Table 1 (*continued*)

Authors	Target benefactors	Level	Hazard(s)	DRR activities evaluated	DRR activity benefits	Vulnerability: valued items (description)	Vulnerability: items not valued, rationale (where provided)	Time frame	Discount rate	Cost-benefit (C/B) or benefit-cost (B/C)	Structural, non-structural	Framing
					lost); more accurate temperature forecasts (improved energy demand expectations and savings in electricity/natural gas sectors); enhanced forecasts lead (more efficient irrigation of crops)							
Khan [47]	Fishermen impacted by severe weather in Vietnam	Community based	Hydro-meteorological (general)	Installation of a boat-winch system	Money saved on fuel cost, safety (no one is required to stay on ship), time (boats are pulled into shore faster); less disruption to livelihoods because wait times are reduced	Sunken boats and ships, damaged boats and ships, cost of livelihood disruption from false alarms, damaged houses	'Peace of mind' knowing that they would not have to wait long hours for their boats to be hauled ashore; this cannot be valued	30-yrs	12%	(B/C) 3.5	Non-structural	Backward-looking
IFRC [38]	Vietnam residents in or near coastal afforestation programs	Community based	Hydro-meteorological (general)	Mangrove afforestation along coastline (for wave-damping action plus habitat benefits for fishes/fisheries); bamboo planting between river banks and dykes; tree planting along coastline (for wind-breaking capabilities)	Protective benefits of mangroves (reduced costs in: sea-dyke maintenance, disaster-induced material losses (public infrastructure, buildings, crops, livestock, aquaculture) and non-material losses (injuries, death), indirect (long-term)	Protection fees, planting costs (community wage fees)	Wider ecological benefits; data availability	31-yrs (1994–2025)	7.23%	(B/C) 18.64–68.92 (depending on afforestation activities in different communities)	Non-structural	Forward-looking

					losses (e.g. reduced productivity due to saltwater intrusion or injuries), shoreline stabilization); economic benefits (planters' income, increased yield from collection of animals or animal products or wood collection), ecological benefits (carbon value, nutrient retention, sediment retention, biodiversity habitat)							
World Bank [90]	End-users of national meteorological services in Belarus, Georgia and Kazakhstan	National study	Hydro-meteorological (general)	Proposed modernization of the national meteorological services (e.g. improving status/ capabilities and delivery)	Avoided economic loss from natural hazards	Damages incurred from hydrometeorological hazards, e.g. to agriculture, communal services, transport and communication, additional costs of irrigation, energy	Does not consider losses resulting from less-than-critical hydrometeorological phenomena, i.e., those that are not classified as emergencies; aside from this, the statistics do not cover all aspects of weather impact on the economy	3–5 yrs	10%	(B/C) 3.3 (Belarus); 5.7 (Georgia); 3.1 (Kazakhstan)	Non-structural	Forward-looking
Venton and Venton [81][e]	Islanders in 3 Maldivian islands where cyclones and severe weather are a concern	Community based	Hydro-meteorological (general)	Based on Safe Island Protection (SIP) plan, which is not explicitly detailed in the text, but includes both structural and non-structural mitigation measures	Vilufushi rehabilitated after tsunami to a 'safer island'; decreased damage from severe weather	Hazard assessment and impact from DIRAM1/2 databases; climate change assessment primarily literature based; probability of hazards was presented as a range (lack of data); 'income over life' method (for lives lost); proxy values for economic value of	Does not include the wider impacts of a safer island program, such as costs of relocation, decreased infrastructure costs on 'abandoned islands', or macro level impacts to GDP because the study focuses on the islands themselves	50-yrs	0–15%	Thinadhoo (SIP): 0.39–1.40, selected SIP: 0.52–1.85, limited protection: 1.13–3.65; Viligili (SIP): 0.28–1, selected SIP: 0.29–0.96, limited protection: 0.42–1.33);	Structural and non-structural	Forward-looking (Thindahoo, Vigili), backward-looking (Vilufushi)

Table 1 (*continued*)

Authors	Target benefactors	Level	Hazard(s)	DRR activities evaluated	DRR activity benefits	Vulnerability: valued items (description)	Vulnerability: items not valued, rationale (where provided)	Time frame	Discount rate	Cost-benefit (C/B) or benefit-cost (B/C)	Structural, non-structural	Framing
						Vilufushi, as the island was destroyed during a tsunami				Vilufushi (SIP: 0.50–1.95)		
[54]	Residents in 34 countries most prone to wind damage	National study	Hydro-meteorological (general)	DRR measures to improve roof protection in hurricane and cyclone prone regions	\$951 Billion to undertake this loss reduction measure in the 34 countries most exposed to severe wind damage; all of them exhibit a BCR > 1. Doing so could save 65,700 lives over the next 50 years.	Expected reductions in damage to infrastructure, property and avoided fatalities	Other social, environmental benefits (data availability, scope of study)	10-, 25-, 50-yrs	5, 12%	(B/C) 2.2–6.07 for human life \$40k-6 M	Structural	Forward-looking

[a] Three separate CBAs within Kunreuther and Michel-Kerjan [54] are reported on separate rows.

[b] Two separate CBAs reported in Mechler [61] are shown on separate rows.

[c] Results from original Kull [52] study are reported and expanded upon in Kull [53]

[d] Results are reported only from the primary MMC [63] study. Other studies are noted as supporting studies, but not explicitly detailed here.

[e] The range of values listed for BCRs are for minimum and maximum hazard occurrence scenarios, respectively.

(e.g. [11,20]) or references listing other studies without analysis (e.g. [2,23]) are not considered here. There are three key metrics of economic efficiency within CBA: the benefit-to-cost ratio (BCR) or cost-benefit ratio (CBR), the internal rate of return (IRR) and net present value (NPV), which in most circumstances are equivalent [53]. Here we have chosen the BCR, as it is commonly used to communicate with decision makers. This leaves out studies which do not report a BCR, but helps to scope this paper. Certainly, no study can be comprehensive but this paper compiles a large range of publications.

3. Results

Table 1 details main CBA parameters for the studies reviewed including primary DRR activities, costs, benefits and general framing. When noted by authors of the studies, general categories of items not valued, but relevant to the CBA, are listed. The majority of studies ($N=22$) were conducted at the community scale with fewer national scale studies ($N=7$), the latter of which tended to be for meteorological services (e.g. [63] and related studies; [66]). Identified or intended benefactors of the DRR activities were largely residents in regions where hazards are common (e.g. the general public (locally ($N=19$), nationally ($N=6$)), however some studies identified benefactors by livelihood (e.g. farmers/agro-pastoralists ($N=2$), fisherman/fishing communities ($N=1$)), with one study identifying students as primary benefactors ($N=1$).

The framing was relatively evenly split between ‘backward-looking’ ($N=10$) and ‘forward-looking’ ($N=8$) with some applying both approaches ($N=3$). ‘Forward-looking’ studies are more difficult in the sense that they require an understanding of future risk, which is especially challenging with the uncertainty of climate change and climate change modeling [82,52,53]. Other studies were either included as an element of a broader project, or as a part of a feasibility or impact study ($N=7$).

3.1. Discount rates

The majority of studies used a single discount rate of 10–12% ($N=16$) with the minority applying a discount rate less than 5% ($N=3$). Some studies investigated a range of discount rates with two studies investigating a discount rate of 0–20% [52,53] and the rest investigating a smaller rage, e.g. 0–10% ($N=1$), 5–9% ($N=2$), 5–12% ($N=1$), 0–15% ($N=1$). Venton [83] argue that a very low or zero discount rate should be applied for environmental projects, as protecting the environment for future generations should have as much value as protecting the environment today. The higher the discount rate, the stronger the preference is for present benefactors and the greater the burden becomes for future generations [83,53]. A high discount rate of 10–12% is standard practice for many development projects, thus assuming that future generations will be better off and better able to cope with hazards [53]. However, examining the full sensitivity over the full range of 0–20% helps to better understand the implications of the chosen rate [52].

3.2. Maximum BCR values reported

Maximum BCR values from the case studies evaluated showed a broad range across hazard type and geography. Table 2 provides a summary highlighting maximum BCR findings. The highest BCR, 1800, was reported for drought risk reduction measures for an irrigation program supporting communal gardens in the Sudan [48]. Across all hazard types, BCRs for DRR ranged from 3 to 15 in the regions with studies. Southeastern Asia (e.g. Indonesia, Philippines, Vietnam) has the most widely reported BCRs across hazard type, including severe storms, drought, flood, earthquake, and volcanic hazards.

3.3. Results by hazard type

Flood risk reduction was the most commonly reported BCR ($N=15$), with an average value of 60 for 35 developing countries for constructing a one-meter wall around houses, and 14.5 for elevating houses, in flood prone regions [54]. The highest BCR values pertaining to flood risk reduction were reported for mangrove forestation projects in Vietnam. The ‘Community-based Mangrove Reforestation and Disaster Preparedness Programme’ reported a BCR range of 3–68 (excluding ecological benefits) and 28–104 (including ecological benefits) [38].

DRR effectiveness with regards to volcanic hazards is the least reported in the case studies evaluated, with the sole record being for the Philippines. Newhall [65] [1] report ‘the monitoring and response costs at US$56.5 million while the amount of property damage averted as a result of the monitoring and response is estimated at a minimum US$500 million not including over 5000 lives saved.’

3.4. Types of DRR activities

Most studies had elements of both ‘structural’ (e.g. measures such as installing dykes, or levees) and ‘non-structural’ (e.g. measures such as developing an evacuation plan, training, and establishing community funds) DRR activities. The majority of studies reported difficulty with valuing certain components of non-structural activities. ‘Non-structural’ activities often require valuing social and environmental aspects that do not have a market value (e.g. sense of security, peace of mind and avoided property damage). Similarly, though direct costs are somewhat easier to estimate for structural measures (e.g. cost of construction materials, maintenance and labor), indirect costs and benefits are rarely included.

3.5. Categories of items that were valued

General categories of items valued were developed to allow for basic comparisons across studies. ‘Agricultural’ includes seeds, crop productivity and area of land used for agriculture. ‘Early warning system/meteorological services’ refers to early warning systems and also general meteorological services. ‘Ecosystem services’ refers to items

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[1] Newhall [65] not shown in Table 1; BCR values not reported.

Table 2
Summary of maximum BCR values reported.

Authors	Country	Hazards	BCR max
Venton [82]^{S}	Malawi	Drought	24.0
Khogali and Zewdu [52]	Sudan	Drought	1800.0
Holland [33]^{S}	Fiji	Flood	7.3
Mechler [62]^{CC}	India	Drought	3.5
Khan [47]^{S}	Nepal	Earthquake	2.0
Kunreuther and Michel-Kerjan [54]^{S}	World (35)	Flood	60.0
	World (35)	Wind damage	6.07
	World (35)	Earthquake	5.1
Holland [33]^{S}	Fiji	Flood	7.3
EWASE [16]^{S}	Germany	Flood	9.0
Holub and Fuchs [34]	Austria	Flood; mass movements	1.7
Mechler [61]^{S}	Peru	Flood	3.8
	Indonesia	Flood	2.5
Burton and Venton [5]^{S}	Philippines	Flood	31.0
White and Rorick [84]	Nepal	Flood	3.5
Nepal Red Cross [64]^{S}	Nepal	Flood	18.6
Heidari [28]	Iran	Flood	1.3
Khan [46]	Pakistan	Flood	25.0
Kull [52,53]^{S,CC}	India	Flood	2.5
Kull [52,53]^{S,CC}	Pakistan	Flood	25.0
IFRC [39]	Bangladesh	Cyclone; flood	4.9
Venton and Venton [81]^{S}	India	Flood	57.8
Dedeurwaerdere [12]	Philippines	Flood; lahar	30.0
MMC [63] (and supporting studies)	USA	All	5.1; overall average 4
Guocai and Wang [24]	China	All	4.0

(S) denotes sensitivity analysis was conducted and (CC) denotes climate change modeling was incorporated.

valued pertaining to recreational, biodiversity- and watershed-services and ecosystem goods or products. 'Educational' refers to time spent training or disruption to education. 'Emergency aid' refers to all aspects, e.g. perishable and non-perishable goods, labor, and transport of goods. 'Physical assets and maintenance' refers to construction, building materials, energy and maintenance costs. 'Other' refers to qualitative items not commonly valued, such as the value of human life. These categories are subjective and are meant only to frame a discussion of what generally is and is not valued.

A majority of the studies valued physical assets and maintenance ($N=25$). As typically these items have widely accepted market values, this is the easiest category of items to value. Livelihood disruption was another common category ($N=7$), likely because a majority of the studies were community-based and livelihood disruption can be a major factor impacting a community during and after a hazard. More direct costs, for example loss of wages (e.g. markets temporarily closed, buildings/infrastructure temporarily damaged), are more easily estimated, but also usually require a qualitative survey or discussion with relevant experts to collect this information.

Indirect costs from livelihood disruption, such as mental and physical health costs, are noted by many studies as being underrepresented. Early warning and meteorological services studies ($N=3$), which looked at the national scale, focused on specific sectors (e.g. [66] focused on agricultural and aviation, among other categories). Community-based studies also commonly looked at sector specific losses, for example, for agriculture ($N=5$). All studies reviewed reported that actual benefits were underestimated due to either limited data sources, inability to assign a monetary value to social or environmental goods, or some combination of the two. Whitehead and Rose [85] are comparatively unique in their valuing of ecosystem services ($N=1$); many studies refer to ecosystem benefits from DRR activities, but few quantify these benefits.

Human life was valued in 3 studies (e.g. separate DRR activities reported in Kunreuther and Michel-Kerjan [54]). Other studies, for example Khan [47] did not value human life, but if they had, would likely have reported much higher BCRs. In the Kunreuther and Michel-Kerjan [54] study, the benefit of retrofitting schools in the most seismically active countries to better safety standards does not exceed the cost for most countries until the value of human life is added.

Finally, one study reported on emergency aid and included funds from non-governmental organizations (NGOs) and other funding bodies, which were grouped in the 'other' category (e.g. [33]). A minority of studies evaluated specific health costs, e.g. reported cases and associated costs of specific diseases like malaria, or general costs from diarrhea outbreaks, commonly associated with water contamination during floods (e.g. [46]), which were also grouped in the 'other' category. Guocai and Wang [24] were also grouped in the 'other' category, as the study took an economic approach surveying respondents' willingness to pay.

3.6. Individual case studies

Comparing individual case studies reveals several trends in the BCR data: the wide gaps in geographic coverage and the prevalence of studies evaluating physical and economic vulnerabilities, as opposed to social and environmental vulnerabilities Mechler [61] addresses elements of environmental vulnerability in considering 'fragility', e.g. degree of damage as a function of hazard intensity for the environmental region impacted by the hazard, as well as direct and indirect economic impacts of flooding. Mechler [62] conduct a CBA in Indonesia including both qualitative and quantitative methods, providing BCR values for all four vulnerability categories. Other examples incorporating both qualitative and quantitative analyses of social vulnerability into the CBA include: The Nepal Red Cross [64] evaluation of the benefits of First Aid training; and Khan [46] and Kull [53] presentation of 'people-centered' resilience-driven strategies, which evaluate interventions at the individual scale.

3.7. Robustness and complexity of models: sensitivity analyses and consideration of climate change impacts

Sensitivity analyses were reported in several studies (e.g. [5,16,81], 2009; [33,61], 2008; [47]; [52,53]; Kunreuther and Michel-Kerjan [54]). Climate change modeling or scenarios were rarely incorporated into the CBA studies evaluated. Studies incorporating both a sensitivity analysis and consideration of the impacts of climate change in the CBA were limited (e.g. [52,53,47]).

3.8. Scale

National scale studies focused on evaluating the DRR benefits of: (1) improved weather forecasting systems (e.g. [23,24,56,58,69,89,90])[2] covering a very limited number of countries including the USA, Croatia, Belarus, Georgia, Kazakhstan, Nepal, and Samoa, (2) the costs of implementing structural DRR measures, such as elevating houses or constructing walls around houses to mitigate against earthquakes and floods (e.g. [54]), or (3) efficiency of DRR programs in the USA (e.g. [17,63,20,72,22]) and Nepal [64]. National scale studies were absent for the majority of Asia, Australia and South America.

Ecosystem restoration approaches were frequently evaluated at the sub-national or regional scale, for example mangrove forestation in Vietnam [38] and river basin improvements in Germany [16], India [52] and Pakistan [46]. Ecosystem restoration of floodplain or relocation out of the floodplain was evaluated on a hypothetical basis.

4. Discussion

4.1. By hazard type

The case studies are dominated by certain hazards, such as floods, droughts, and earthquakes. Other environmental hazards such as wildfires, tornados, extreme temperatures, and volcanoes are comparatively absent, even though deaths and damage related to natural hazards are not always dominated by the hazards for which BCR studies exist, depending on the location (e.g. [41,75]). Floods and droughts are likely highlighted due to the frequency with which they occur at a large damage scale, but that argument does not hold for earthquakes. Part of the bias is likely to be the ease of calculating costs and benefits of measures to reduce risks to floods, droughts, and earthquakes. Studies examining CBA for other hazard types such as technological hazards, epidemics and pandemics, both human and zoonotic diseases (e.g. diseases that transfer from animals to human) that may or may not occur in relation to a natural hazard, are absent from the studies reviewed here.

Studies such as Newhall [65][2] demonstrate the feasibility of making those calculations for other hazards, suggesting a relatively easy way to expand the DRR BCRs for DRR studies. Part of the bias is also likely to be the popularity of CBA with engineers who often dominate flood and earthquake risk reduction initiatives—but who also dominate tornado risk reduction measures but not necessarily drought risk reduction measures. As such, the bias might simply be inertia, in that the hazards dominating the literature for DRR BCRs then inspire others to pursue similar work.

4.2. By geographic region

Longitudinal studies comparing benefits of specific DRR strategies or approaches across countries or locations with similarities are largely absent from the literature. For instance, even though the number of case studies for Southern and Southeastern Asia is high in comparison to other regions, there is a lack of longitudinal comparisons for these countries. Some regional meta-studies exist, for example, IADB [35] evaluate DRR in the LAC region; however, this study does not present an original CBA, thereby emulating the trend in available regional studies.

Nonetheless, the comparative lack of studies from Latin America in this paper could be because available documents, namely peer-reviewed papers and policy documents, are dominated by English, especially for online sources. Personal discussions with members of La Red de Estudios Sociales en Prevención de Desastres (LA RED, The Network for Social Studies on Disaster Prevention) suggested that extensive material is available in Spanish for Latin America, but it is not as formalized or systemized as the English-language literature and does not always provide data of the form sought here.

4.3. Non-BCR approaches

The NOAA [66] study (Table 1) highlights an example of a CBA following traditional techniques, but not reporting a BCR value. Results are instead reported as money saved. There are likely many other studies that report findings in similar terms, however, we did not examine these studies here, as it precludes comparison of BCR values. Additionally, there are alternate approaches to evaluating the costs and benefits of a project, which are not discussed due to the scope of this paper. One such example is Cutter et al [8] which utilized country-level socioeconomic and demographic data to generate an index of social vulnerability to

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[2] Studies not reporting BCR values were not included in Table 1 with the exception of NOAA [66], used to illustrate the point that many CBAs do not report BCRs and instead report money saved or using another metric.

environmental hazards (e.g. the Social Vulnerability Index, SoVI).

4.4. Longevity of DRR benefits

There was limited evaluation of how long the DRR benefits last, some studies examined only one or a small range of discount rates, and few studies included discussion of costs and benefits changing over time. Monitoring and evaluation of DRR tends to be linked to donors' project cycles, focusing on outputs of disaster planning versus the impact such as the extent to which lives and assets are better protected as a result of DRR improvements [36]. Frequency of hazard events and the potential for cascading or 'ripple effects' are rarely considered in CBAs with one exception being the MMC [63] studies, which do consider ripple effects.

4.5. Less traditional DRR approaches: ecosystem-based DRR

Ecosystem restoration—for example, forestation with mangroves or rain forests, other forms of biomimicry, floodplain orchards, or other agroforestry techniques—can all be considered both DRR and sustainable conservation strategies, which would also link to local livelihoods if implemented properly. The contemporary term is 'ecosystem-based DRR' [70], also cited in the literature as 'natural- or ecological-infrastructure' which is gaining popularity for implementation but for which costings are rarely available [14,25,49,42,77].

In the context of DRR, it would be advantageous to have a more substantive understanding of CBA for ecosystem-based DRR. Mangroves, while distributed across 118 countries, have the highest concentration in 15 countries in the tropics and subtropics [21]. Mangroves are said to offer physical sea defenses, including absorbing and dampening wave action, slowing erosion rates, and fostering biodiversity and sequestering carbon. Indonesia has roughly 22% of the global total of mangroves; Brazil and Australia have about 7% each; and Bangladesh and India have approximately 2–3% each [21]. However, CBA for using mangroves for DRR were only reported in two separate case studies for Vietnam (UNIDSR, 2002; The Red Cross, 2008) and their (and coral reefs') effectiveness in mitigating tsunami and surge damage is not straightforward (e.g. [9]).

Agroforestry techniques such as using floodplain orchards, polyculturing of annuals and perennials, or rainforestation support, as is common practice for many indigenous groups in the Amazon [6], may not be widely recognized DRR techniques, since they are infrequently cited in the DRR literature. These techniques promote DRR through ecological conservation, e.g. reducing soil erosion and maintaining the hydrologic cycle, which mitigate physical risk from natural disasters, as well as enabling livelihoods and the use of traditional knowledge. Similarly to mangrove planting, the costs and benefits of sustainable agriculture techniques as DRR strategies have limited coverage in the literature.

The sole reference found here was Dedeurwaerdere [12], who analyzed the potential cost-benefit of rainforestation in the Philippines, reporting a BCR of 30 for a 15-year, 1000 hectares (10 km^2) project. In comparison, IFRC [37] evaluated artificial structural measures, e.g. seawall and dykes, in the Philippines, reporting BCR values of 4.9 and 0.67, respectively. That suggests the big gains feasible through ecosystem-based DRR compared to artificial structures.

CBAs for DRR involving environmental components could benefit from techniques for quantification, valuing and marketing of ecosystem services. For example, internationally agreed upon methods and standards exist for the quantification and monitoring of forest carbon and carbon offsets are currently marketed. No similar markets exist for watershed- and biodiversity-services, though the concept of 'biodiversity offsets' has been proposed in some areas such as England. Forest carbon valuation methods could be used to assign a value to ecosystem services in physical 'risk-based' hazard models where appropriate, as generally these services are not currently valued in impact assessments. However, ethical concerns regarding offsetting effects on society and nature and irreversibility remain to be addressed. Another consideration is that forests and other ecosystems have disaster risk reduction benefits that extend beyond carbon uptake. In fact, this point is a major concern about using quantifiable ecosystem services in conjunction with CBA: that the focus might end up on a small number of services without being comprehensive.

4.6. Additional considerations

Relocation of people outside of hazard zones is frequently considered as a DRR measure, raising significant ethical and justice questions regarding who makes the decisions, who pays for the decisions, and who is affected by the decisions. No case studies were found which presented backward-looking BCR for relocation, despite a large literature on population movement for DRR and after a disaster.

Overall, the literature displays no consensus regarding how CBA analyses should be conducted, what base variables to include, or how to deal with limitations of CBA as discussed earlier. For example, should CBA for DRR be conducted by area, by population, hazard type, vulnerability type, other variables, or a combination? Should the benefits of education and training, which are most commonly not calculated, with a few exceptions (e.g. [64]), be a mandatory variable for inclusion and assessment? Consequently, comparing CBAs might have limited validity due to them using different baselines and/or methodologies.

Sometimes CBA is not independent of the DRR measure itself. For example, structural flood defenses are easily costed, as are the property and possessions (and potentially lives) which are 'protected'. But then the DRR measure itself influences the situation, thereby affecting CBA. In the case of structural flood defenses, people gain a false sense of security due to the visibility and hardness of the measures, leading them to build and settle in areas 'protected' by the flood defenses without taking adequate, further DRR measures. That is, the presence of the structural measures leads to reliance on them and hence an increase in the property, possessions, and people who are vulnerable in cases of defense failure [15,19,79].

Kull [53] extend this discussion by pointing out that certain DRR options may generate 'disbenefits' or negative externalities. They cite the example of embankments protecting an area from a flood, but simultaneously increasing the risk of water logging, which is associated with increases in vector-borne diseases and decreases in crop productivity. Many studies discuss why certain DRR measures might not be cost-effective if the BCR is close to or less than one, but few evaluate disbenefits or potentially negative spillover effects.

4.7. Can CBAs highlight vulnerability?

Vulnerabilities, rather than hazards, are the root cause of disasters [29,30,59,86–88]. As the literature shows, vulnerabilities are not caused by nature or the environmental hazards, but instead are social constructions [32,67].

Overall, the CBA studies tend to generalize vulnerability into four broad categories: economic (financial capacity to return to a previous path after a disaster); environmental (a function of factors such as land and water use, biodiversity and ecosystem stability); physical (related to susceptibility of damage to engineered structures such as houses, damns and roads; population growth); and social (ability to cope with disaster at the individual level as well as capacity of institutions to cope and respond) [61]. While all four categories are recognized as important, social and environmental impacts are more qualitative in nature and therefore the focus of CBA for DRR tends to be on the quantitative economic and physical impacts.

A common approach in many government guidelines is to utilize Multi-Criteria Analysis (MCA) to address the qualitative variables, such as social and environmental benefits, of a project as a subset within the CBA [1]. That is, MCA is used to address the qualitative costs and benefits and CBA is used to address the quantitative costs and benefits. MCA utilizes expert opinion—such as democratic voting, a panel of experts, a consensus model, or focus groups—to select the criteria and the rating options for the model. MCA's flexibility allows for a greater range of awareness and involvement across scales; for example, joining views of an individual household or a panel of international experts—but adds complexity and subjectivity.

MCA could play a significant role in highlighting the longer-term implications of DRR. Brouwer and van Ek's [4] integrated CBA and MCA approach to flood control policy in the Netherlands found that, while structural measures were more cost-effective in the short term according to the CBA, floodplain restoration can be justified using both the CBA and MCA considering socio-economic and ecological impacts in the longer-term. That outcome was not visible utilizing CBA alone. MCA may be more efficient at highlighting social and environmental vulnerabilities and thus benefits than CBA alone.

4.8. Recommendations of minimum criteria to improve DRR CBA

Currently there is no consensus on the minimum criteria necessary for conducting a comprehensive CBA for DRR. For instance, there is no standard or systematic approach detailing what variables need to be assessed to represent vulnerability, disaster consequences, or even the appropriate spatial and temporal scales for determining CBA, vulnerability, or disaster consequences.

Vulnerability is not homogenous, nor are the benefits gained from DRR. Most DRR CBA studies either focus on poor or marginalized groups, as these are commonly the most vulnerable to disaster, or alternatively, consider vulnerability to be rather homogenous, e.g. broad scale programs evaluating the effectiveness of weather forecasts or government subsidies. While it is unrealistic to think that vulnerability can be comprehensively assessed (e.g. [59,86,87,88]), CBAs could be improved by a more systematic approach that better defines the context in which vulnerability is assessed so that the CBA is then contextualized appropriately and can be interpreted and compared within that contextualization. One consequence would be knowing what lessons are and are not transferable amongst different contexts.

Another challenge within the standardization of CBA for DRR is which consequences to consider in the calculations. In forward- and backward-looking DRR CBAs, it is common to consider obvious and immediate disaster consequences, such as physical damage to infrastructure, loss of life, injuries, and systems failures. Further consequences, often appearing after the initial hazard has dissipated, are less frequently considered. Examples are psychological health impacts, continued water logging or salinity of crops, business interruption, bankruptcies, and long-term migration.

Including climate change modeling results does not necessarily enhance a CBA for weather- and climate-related hazards. Variability in the accuracy and precision of climate data, difficulty associated with projecting and predicting hazard occurrence, and challenges in incorporating future social behavior and policies, contribute to the uncertainty of future climate impacts. Using the models to develop scenarios for climate evolution and consequent weather extremes, especially when down-scaled to regional or local levels, can help to depict a more comprehensive portrait of the hazard side of the expected risk over the lifetime of the suggested benefits from a DRR intervention, thereby further highlighting the benefits of DRR measures across multiple scenarios.

That suggests a further limitation in comparing DRR CBAs, notably across hazards. For well-studied fault lines, such as the San Andreas fault in California, future probabilities of the hazard occurring are available [76,7] meaning that, given the knowledge of building codes and construction practices, the benefits of additional DRR measures are calculable [71,73]. For changes in flood regimes, as a result of climate change as well as infrastructure development, understanding the hazard and vulnerability changes is much more challenging with larger uncertainties [78,43]. DRR CBAs might have different levels of usefulness depending on the hazard and depending on the hazard drivers, such as climate change, which are considered for analyzing CBAs in forward-looking studies.

Additionally, spatial and temporal scales of the CBA calculation can impact the validity of the assessment of DRR benefits. The issue of long-term disaster impacts, and hence potential benefits, from a DRR intervention is discussed above. Regarding spatial scale, CBA studies that fail to consider wider impacts within a wider system are not necessarily truly representing the costs or benefits. Levees affect the hydrological regime both upstream and downstream and exacerbate flooding in other places [79]. In comparison, earthquake-resistant technologies, despite their heavy reliance on structural approaches, save lives [74] with no foreseen long-term consequences. The basic examples above illustrate the complexities related to scale and vulnerability and the importance of considering scale when evaluating the benefits of DRR.

As was emphasized by Deaton [10], disaster mitigation must be informed by a strong understanding of the public and private sector decision process. Consideration must be given to how these decisions will impact cost- and benefits- over the long-term and across scale. For example, crop insurance schemes must not only consider what perils, crops, and amount of indemnification to cover, but also consider farmer understanding of the program and capacity required for farmers involved to make claims.

CBAs should not just mirror the conceptual process of mitigation planning, but be used as a tool for improvement at various stages within this process. CBAs should be an opportunity to promote investment in DRR and evaluate successes and failures of pilot programs. At the same time, CBAs are not a panacea and need to clearly outline what can and cannot be valued for a given project.

Many examples were given where DRR practitioners have overcome noted limitations, e.g. Khan [47] evaluated the CBA of straw-bale for its efficiency as a building material and the potential for positive environmental benefits in Nepal, such as reduced greenhouse gas (GHG) emissions in comparison to traditional brick materials. The largest benefit of using straw-bale materials in housing is its resistance to earthquakes that are common to the region. However, analyzing the CBA of straw-bale as a sustainable building material, instead of assessing its value for earthquake mitigation, sidesteps the issue of assigning a value to human life.

The majority of CBAs presented here have deliberately avoided valuing human life. The reason is the ethical challenges of selecting a monetary value for human life [60], which many find inappropriate in principle. One interesting outcome of a large number of the studies on DRR CBAs is that, even without considering the value of life and other intangibles, high BCRs emerge. This is not always the case, for example, Kunreuther and Michel-Kerjan's [54] CBA assessing costs to retrofit schools in seismically active countries did not exceed a BCR value of one for many countries until a value was assigned to human life. Thus, assigning a value to human life in that example may have benefits.

We recommend greater consideration of the context and methods used to assess vulnerability, disaster consequences, and spatial and temporal scales as areas that need further investigation and standardization to improve upon current DRR CBAs.

5. Conclusions

This study reviewed individual CBA case studies reporting BCRs spanning different geographies, hazard types, and vulnerabilities. Many results emerged displaying solid evidence to support the economic effectiveness of DRR, but several key limitations were identified, including a lack of: sensitivity analyses of the CBA, meta-analyses which critique the literature, consideration of potential impacts of climate change, evaluation of the duration of benefits, broader consideration of the process of vulnerability, and potential disbenefits of DRR measures. To represent the potential benefits of DRR more comprehensively to decision makers, these concerns will need to be addressed.

Yet the studies also lucidly demonstrate the importance of context for each BCR result. It is not clear that averaging BCRs across case studies produces a useable result for policy or decision makers, because the circumstances of the studies tend to be quite different—particularly with respect to vulnerability. The BCR technique generally has limited applicability for factoring in vulnerability. The contextual aspects of each case study tend to be the vulnerabilities.

Part of understanding and incorporating context is the influence of culture on hazard, vulnerability, risk and disaster [31,51]. When determining costs and benefits, the values assigned can differ depending on who is asked, with different perspectives assigning different values for property, land, and infrastructure. Additionally, the metrics used for costs and benefits have been absolute, specific values, such as $3 million or €5,000. Vulnerability theories (e.g. [59]) also discuss the need for proportional metrics, such as stating that 12% of assets would be lost or that benefits accrued would be 135% of current value. Reporting proportional vulnerability and proportional gains for CBAs would avoid biasing measures towards helping those who are affluent, and who therefore stand to lose a lot in absolute measures, compared to those who have little to begin with, so even a small absolute loss can be most of their assets.

Several studies demonstrate that these difficulties can be addressed more robustly to some degree, as long as the context is retained. For example, using shared learning dialogues (SLDs), a participatory and multi-stakeholder approach to assessing vulnerability, (e.g. [46]) helps to understand the origin of the numbers leading to the BCR. Evaluating training benefits [64] is another approach needed across more case studies.

As such, comparing locations, hazards, or scales might not yield results which are meaningful for decision-making. Instead, to determine financially whether or not a DRR measure or process should be implemented, calculations need to be made for that specific case study, potentially employing MCA or SLDs during the planning stages to guide longer-term social and ecological goals.

Rather than simply reporting a single ratio, these calculations should also consider how the DRR measure or process might affect the costs and benefits, which values are not included in the calculations, and the contextualities for that case study. It seems that disaster mitigation can indeed save money in numerous circumstances, but 'How much money can we calculate will be saved?' is not the only question.

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