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A review of flood mitigation benefit-cost analyses' inclusiveness of environmental watershed effects and environmental vulnerability: gaps in progress towards more resilient flood hazard decision-making

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US and EU flood mitigation policy both incorporate considerations of costs and benefits, and in recent years have taken steps to encourage accounting for positive and negative effects on vulnerable populations, broader non-market environmental impacts, and downstream effects beyond the target area of projects of flood mitigation projects. This work highlights the extent to which previous academic flood mitigation Benefit-Cost Analyses (BCA) papers have comprehensively considered such project effects. We do so through a systematic, PRISMA-style, review of BCA literature in the broader field of flood hazard mitigation and resilience decision-making. Our results suggest 1) most projects focus on monetizing property damages, 2) a gap exists monetizing ecosystem and environmental effects (especially linked to model-linked effects estimates), and 3) almost no BCA literature addresses distributional or economic or social vulnerability related impacts. Studies comprehensively incorporating structural, environmental, and distributional questions are almost nonexistent. This reflects the need for a larger research approach linking flood depth and exposure models to wider non-property and non-market damage assessment. Current BCA literature fails to wholistically bring together the relevant interdependent social and environmental effects of flood mitigation projects. This suggests the need for a research agenda promoting the consolidation of methods beyond traditional property damages, and models linking the environmental and distributional effects of mitigation projects.

KEYWORDS

benefit-cost analysis (BCA), ecosystem services, economic vulnerability, PRISMA, flood resilience

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1 Introduction

Flooding is a frequent and costly disaster in the US, with annual flood damages increasing from $4 billion in the 1980s to $17 billion in the 2010s, and are expected to continue to grow (Armal et al., 2020), in the US alone. Federal and state agencies [e.g., US Army Corps of Engineers (USACE), Federal Emergency Management Agency (FEMA), Building Resilient Infrastructure and Communities (BRIC), Community Development Block Grant Mitigation Funds (CDBG-MIT)] fund flood risk management projects, though limited resources necessitate Benefit-Cost Analysis (BCA) for project selection (Office of Management and Budget, 2003). BCA answers whether a project generates positive net estimated economic benefits (measured, for example, in Dollars or Euros) and, for multiple projects, compares the magnitude of these net benefits to allocate resources. By monetizing a project's gains and losses, a Benefit-Cost Ratio (BCR) or Net Present Value (NPV) can be calculated (2023). Projects with larger BCRs or NPVs are favorable to smaller ones, and larger magnitudes in either direction imply larger benefits. In policy, BCA analysis serves as a proxy for the social welfare benefit to society (Kind et al., 2019) because many public projects generate non-market returns. Non-market values are estimated monetary benefits or estimated monetary costs associated with goods and services that are not traded in traditional markets (e.g., clean water, biodiversity, recreational opportunities, cultural heritage and distributional considerations).

Weaknesses exist in conventional BCA in comprehensively assessing flood hazard mitigation projects due to their origin in project-level engineering cost estimates (Kind et al., 2017). First, BCA typically narrowly focuses on the risk and extent of flooding, overlooking other project effects. For example, grey infrastructure is a traditional engineering approach proposed for property risk reduction but offer few ancillary benefits, and have negative consequences that are difficult to monetize (Loomis, 2011). Conversely, nature-based solutions (NBS) (i.e., green infrastructure), acknowledge the potential to maximize benefits to society by harnessing natural processes, including non-flood-related benefits to society. Examples include bio-swales, wetland restoration, rain gardens, and other means of rainwater capture. Government and non-government entities in Europe and the US are increasingly consider green infrastructure among the potential project alternatives (Davis and Naumann, 2017) into BCA calculation. However, BCA tools have started to adapt but struggle to keep pace (e.g., FEMA BCA Toolkit, 2022), because unlike property risk reduction, these benefits are hard to monetize. Second, hazard mitigation BCAs traditionally ignore the distribution of effects across different types of populations [e.g., (Rose et al., 2007)]. For example, a BCA focused on property value may hypothetically recommend implementing a flood mitigation project in a 25-home neighborhood, each worth one million dollars, versus a 75-home neighborhood, each worth a quarter million dollars, even though three times as many people benefit in the latter. This showcases how investment decisions for infrastructure can favor wealthier populations. Federal agencies rarely consider the distribution of benefits across racial and income groups, inherently assuming vulnerability to storms is even across populations (Junod et al., 2021; McGee, 2021). Accounting for these may lead to improved project selection, design, and placement, and these distributional analyses are major components of the US National Science and Technology Council (NSTC)'s initiative, *Advancing the Frontiers of Benefit-Cost Analysis: Federal Priorities and Directions for Future Research* (OSTP, 2023), and the White House OMB's Office of Information and Regulatory Affairs' recent draft *Guidance for Assessing Changes in Environmental and Ecosystem Services in Benefit-Cost Analysis* (OMB, 2023).

Recent shifts within the US seek to address these weaknesses in policy evaluation (Federal Register, 2021) and funding, such as CDBG Disaster Recovery funding mandating that low- and moderate-income communities benefit from a potential project. Several BCA tools have incorporated ecosystem services, such as

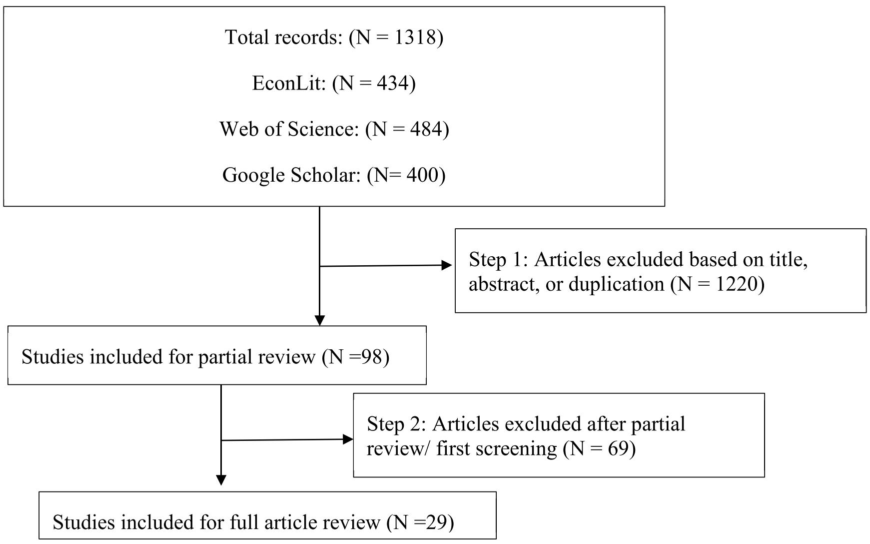

FIGURE 1
Flow Diagram of Article Selection Process based on PRISMA.

the FEMA BCA toolkit (2023). USACE instituted its Engineering with Nature initiative and a new framework to promote the development of non-monetary benefit indicators and multi-criteria analysis (MCA) to better acknowledge a broader range of effects (Wainger et al., 2023). Currently proposed USACE "Principles, Requirements, and Guidelines" (PR&G) published for public comment in April 2024 provide guidelines to consider long-term impacts and cumulative effects, ensuring projects contribute to broader societal goals, such as climate adaptation and social economic vulnerability. Moreover, federal policies emphasize sustainability, resilience, and equitable development as pillars of federal investments (OSTP, 2023; Federal Emergency Management Agency, 2024). However, MCA has limitations associated with non-commensurability, lack of transparency, and reliance on committee scoring (Linkov et al., 2004; Levy et al., 2007). Our review examines BCA studies, a well-known and used framework that ideally incorporates and monetizes all effects to facilitate comparison and recognizes the importance of economic vulnerability and comprehensiveness in evaluating policy alternatives (Loomis, 2011) but struggled greatly in practice (Kind et al., 2017; Hudson and Botzen, 2019). Furthermore, finding generalizable BCRs for hazard reduction are difficult across time and space (Shreve and Kelman, 2014).

Outside of United States, the European Floods Directive (2007/60/CE) emphasizes that flood risk evaluation should include BCA on a long-term time horizon to evaluate the impact of mitigation measures which will incorporate ecosystem services and distributional effects (Molinari et al., 2016; Nasiri et al., 2019). Following the European Directive, in Spain, flood mitigation measure assessment should include an explicit environmental objective and social analyses in BCA (Ballesteros-Cánovas et al., 2013). Despite this directive existing for well over a decade, the EU found that, "fully fledged Cost–benefit Analyses (CBA) are rarely carried out by countries and Cost-Effectiveness Analyses (CEA) are often limited only to some typologies of measures." (EC, 2021; Pellegrini et al., 2023). The European Commission found that "costs and effectiveness of nonstructural measures are often difficult to quantify and, therefore, these types of measures are often discarded in economic ranking procedures. Few countries provide detailed information about the application of natural flood management options." (European Commission, Directorate-General for Environment, 2021) This has led to a focus on mixed and multi-criteria decision making, leaving a gap in the ability to economically justify flood risk reduction.

Flood mitigation projects have compared nature-based flood mitigation or non-structural solutions to community risk. The inclusion of additional benefits and economic vulnerability issues may alter BCR outcomes of both nature-based and grey infrastructure flood risk mitigation projects, altering which projects move forward. However, not accounting for the multiple or distributional effects may lead to sub-optimal policy in terms of social welfare (Circular A-94, 2023). In addition to valuing property protection and project execution and maintenance costs, some commenters argue that "…full cost and benefit analysis of green and gray interventions should reflect the full range of values that beneficiaries associate with the green interventions…" (Vollmer et al., 2022), which could include both externalities and the distributional consequences of projects relative to social vulnerability (National Academies of Sciences, Engineering, and Medicine, 2019), which may exacerbate existing social vulnerabilities (Tate et al., 2015).

There are multiple effects of flood risk management projects, ranging from property and crop protection to recreation, public health, and social economic vulnerability, and some of which are difficult to measure. For the NPV estimate produced by BCA to accurately measure the social welfare benefits or costs of publicly funded projects, such effects should be considered. This study assesses to what extent academic literature has captured a broader range of effects for BCA/NPV in evaluating flood mitigation projects. Our motivation is to document whether consistent literature on systematized approaches to integrative BCA has emerged that can inform practice and implementation of effective economic evaluation tools for practical decision making. This is to eventually inform a new generation of decision support tools based on the state of the art and co-production with decision makers (Vollmer et al., 2022). To best foster the development of decision support tools, it is necessary to understand the state of the art and gaps in current knowledge, and we address this through a systematic literature review of studies that include relevant flood mitigation BCAs, examining each for 1) the extent to which they incorporate a range of effects, including positive and negative externalities, and 2) whether they consider the types of populations that live in the areas affected by the flood mitigation project.

2 Literature search and coding methods

We initially searched for articles using a snowball approach, examining the references of relevant articles. We then developed inclusion criteria: a study must calculate benefits and costs for a flood mitigation project and provide a BCR or NPV of that project such that a policy recommendation can be made. We searched seven different keyword phrases on EconLit and Web of Science: "Flood hazard mitigation and cost-benefit analysis and net present value", "Stormwater mitigation and cost-benefit analysis"; "Stormwater and cost-benefit analysis"; "Environmental justice and cost-benefit analysis and flood"; "Watershed cost-benefit analysis and flood"; "Flood mitigation and cost-benefit analysis"; and "Equity in flood risk". Each of these keywords were selected to address and search for literature regarding BCA in the flood hazard mitigation projects. We also included terms like stormwater, watershed and environmental justice to search for different literature which addresses the scale of the mitigation projects and equity. Both keyword "Environmental justice and cost-benefit analysis and flood" and "Equity in Flood risk" were selected to address the distributional impacts.

The last search yielded a total of 1,318 entries. We then developed inclusion criteria: a study must calculate benefits and costs for a flood mitigation project and provide a BCR or NPV of that project such that a policy recommendation can be made. At the first stage of the selection, we went through the title and abstract to understand whether the article included BCA or NPV of the flood mitigation project. As we selected articles strictly based on BCA in flood mitigation projects, we ignored any article that measures environmental externalities or distributional effects as non-market valuation but does not include the BCA framework. Also, we excluded any article that includes social vulnerability but does not include those as attributes of the BCA of a flood mitigation project. Initial inspection removed 1,220 articles from consideration based on title, abstract, or duplicate articles, with a total of 98 articles receiving a full inspection. Among these 98 articles, only 29 articles met our inclusion criteria after the full review of each of the articles. Supplementary Material SA shows details of the article search and selection process.

As a supplement, we searched our most relevant search term, "BCA of flood mitigation measures" on Google Scholar to identify influential articles not found in the primary search, which produced 400 additional entries. From the Google Scholar search we looked through the most cited articles, and their citing literature. This literature review was conducted in mid-2022, and we acknowledge that flood risk and resilience is a rapidly evolving field, but we conducted follow-up Google Scholar searches in fall 2024, and have included some newer literature in our discussion. This informal follow-up finds similar trends More recent literature advancing methods is related to potential future inputs to BCA regarding distributional methods (e.g., (Serafin et al., 2024), concepts (Pollack et al., 2024), granular landscape scale risk assessments (Sanders et al., 2023), and general literature on broader impacts and insurance (You and Kousky, 2024) and ecosystem services (Petsch et al., 2023; Zhang and Qian, 2024), but not fundamental changes in research on BCA including project NPV estimates based on integrative and diverse effects. To structure our literature review, we adopted the PRISMA framework (Figure 1), which includes a systematic approach for identifying, screening, and selecting relevant studies.

Of the 98 articles included for partial review, 29 articles met our inclusion criteria, with complete references in Supplementary Material SB. Some studies focused on a more sophisticated methodology rather than policy prescription, ignoring many of the additional effects or distributional impacts. This is important to mention because the results below are not indicative of the quality of the studies. Supplementary Material SC lists the 69 excluded articles. Reasons for exclusion include only estimating costs (e.g., (Taghinezhad et al., 2021), or benefits (e.g., (Watson et al., 2016), of flood mitigation (not both) or review papers of flood mitigation or BCA (Whitehead and Rose, 2009). This meant that articles generally revieing disaster risk reduction generally (Shreve and Kelman, 2014) were not included.

We examined to what extent each flood mitigation BCA study incorporated flood mitigation effects. After considering several frameworks (e.g., Millennium Ecosystem Assessment, FEMA's BCA toolkit), we selected the ecosystem service logic model (ESLM) that conveys various effects of gray and green infrastructure for stormwater management produced by GEMS within Duke University's Nicholas Institute. The GEMS model is peer-reviewed (Olander et al., 2021) and identifies the separate effects caused by a potential intervention, mitigating double counting. Its categories of effects include Cultural Values, Economic Activity, Human Health, Social Disruption, Property Protection and Value, Climate Mitigation & Greenhouse Gas (GHG), and Water System Costs. Beyond the ESLM, we also considered whether the BCA considers effects outside the target area ("Spatial Spillovers"). For example, traditional gray infrastructure may decrease flood risk to the target area by moving water elsewhere, inadvertently increasing downstream flood risk. Lastly, we inspected each article for their consideration of distributional effects or economic vulnerability. Examples of economic vulnerability measures include the percentage of renters, the percentage of minorities, or the Social Vulnerability Index (SOVI) in an affected area. We adopted similar categories as GEMS while addressing environmental effects. For accounting for externalities, we included spatial spillovers criteria and for addressing the distributional impacts we included that as our last category (Table 1).

TABLE 1 Project effect and economic vulnerability descriptions.

Project effect	Consideration for the project's effects for...
Cultural Values	…Knowledge and other values (sense of place, livelihood options, existence value, traditional and local value, neighborhood/community cohesion)
Economic Activity	…Economic activity (recreation and tourism, fishing and shellfish harvest, local businesses, opportunity cost, and restoration)
Human Health	Human health (i.e., waterborne disease, drowning and other injuries, mental health and psychological wellbeing, food security, mosquitos, and skin and respiratory effects)
Social Disruption	Avoided social disruption effects (productivity loss such as school days/workdays, the value of statistical life, displacement/relocation/emergency cost)
Property Protection and Value	…Avoided property damage (building, contents, inventory, facilities, infrastructures) or change in property value
Climate and GHGs	…Climate mitigation effect or greenhouse gas mitigation effects
Water System Cost	…Water system costs (wastewater treatment cost, freshwater cost, drinking water treatment cost, gray stormwater infrastructure, cost to property owner)
Spatial Spillovers	…Effects to others outside of the location analyzed, including downstream effects
Equity	…Distributional effects for the types of people affected

We inspected and coded each article for these nine, with additional detail in Table 1. The extent to which the BCAs incorporate these effects varies, ranging from fully monetizing or only briefly acknowledging an effect. Each category was coded as: M-Monetized (a dollar value is assigned), Q-Quantified (the magnitude of the change is assigned), A-Acknowledged (recognized but not monetized or quantified), or O-Omitted if the particular effect is not addressed by the research paper's project, either because it is ignored or not applicable since some effects are project specific, such as Climate and GHG effect is potential effect for floodplains, but not applicable for levee projects). We also delineated and inspected for potential sub-effects per category. For example, in Table 1, economic activity has five sub-effects: recreation and tourism, fishing and shellfish harvest, effects on local businesses, opportunity cost, and restoration. Codes are not mutually exclusive because multiple codes may apply within one category due to these sub-effects. For example, "M, A" in economic activity within a study indicates that at least one sub-effect is monetized and at least one aspect is acknowledged. All authors reviewed and coded articles. To maintain consistency, several coding iterations occurred to develop a coding format to inspect included studies.

3 Results

The outcomes of our review of the 29 articles' project effects, spillovers, and equity appear in Table 2. These studies published in various disciplinary journals; 45% engineering, 17% interdisciplinary, 17% economics, 17% environmental, and 4% emergency management (categorized using the journal's aims and authors' department). Property protection (87%) and economic activity (45%) are monetized by a majority of studies, and correspondingly, the two categories are infrequently omitted. Social disruption and spillovers are monetized or quantified less frequently but acknowledged by one-fourth and one-fifth of studies.

The majority of studies omit the remaining seven categories of effects, most often cultural value (79%), followed by climate and GHG (76%), human health (72%), social disruption (72%), and water cost (62%) (Table 2). An important caveat is that omission may occur because a study ignores the potential effect or does not apply to that study. Culture, Human Health, and economic vulnerability all have cumulative percentages of M, Q, and A of approximately 20%, meaning that the majority of studies overlook them (O = 80%). Less than one-fourth of studies monetize ecosystem services, such as climate effects and water costs. These are sometimes acknowledged, almost universally, if the impact is positive, omitting negative impacts, and generally for larger non-spatial or model-linked effects. Few, such as Nordman, Isely et al. (2018) and Alves, Gersonius et al. (2019) include more specific environmental quality estimates linked to models. Still, these tended to be framed in stormwater literature, not traditional flood hazard mitigation project BCA. Overall, studies rarely quantify environmental effects through modeling and monetize via categorical benefit transfer or merely acknowledge ancillary environmental impact.

4 Discussion

We reviewed to what extent 29 flood mitigation BCA studies considered nine categories of flood mitigation. More than half of the studies omitted these effects in their study except for property protection and economic activity. Excluding property protection and economic activity, studies sometimes acknowledged these effects but infrequently monetized or quantified them and were infrequently designed to identify negative effects. This pattern is also true for spatial spillovers. Four-fifths ignored economic vulnerability and distribution of flood mitigation project benefits, with even fewer studies acknowledging, quantifying, or monetizing equity. A recent study of US Community Development Block Grant (CDBG) mitigation funds in Jefferson Parish, United States, published in 2023 only monetized structural damages, but noted the need for analyses to expand to indirect losses and effects on different socio-economic groups (Al Assi et al., 2023).

We have several potential explanations for these outcomes. First, several categories for environmental externalities are non-market effects of flood mitigation which are added in Table 1, so they are not easily incorporated, as in the case of structural damages where the building industry allows for cost estimates. Nearly half of BCA studies were done by engineers, whose expertise often focuses on project assessments' hydrological and structural effects instead of making more robust social welfare impact estimates (Kind et al., 2017). The property focus means there are still gaps in the literature linking flood hazard mitigation to diverse sets of damages, as well as risk and distributional analysis of non-structural effects (OMB, 2023). The types of damage curves used in property damages have not matured in broader literature for individual damages, social impacts, and environmental damages to a degree that they have entered common engineering and BCA practice. One traditional non-monetary benefit frequent in other areas of environmental BCA literature is health effects, both fatal and non-fatal (e.g., air pollution and Value of Statistical Life (VSL) or mortality risk reduction (Dedoussi et al., 2020), where few flood hazard BCA include monetized estimates that are frequently used in regulatory decision making around pollution control (e.g., EPA-821-R-23-003). We suspect this is due to the lack of developed depth-response, or event-response, relationships between flood exposure and health outcomes. There is evidence, for example, of the link between flooding and ecosystem services related to flood protection and non-fatal gastrointestinal disease (de Jesus Crespo and Fulford, 2018; Crespo et al., 2019), but these lack quantified links to flood-depth and exposure models. The challenge in this sense is twofold, which is first to develop a broader set of risk-based flood-depth and exposure model effects curves, and then to fill gaps in the monetization of those exposure outcomes as benefits and costs amenable to inclusion in BCA (OSTP, 2023). As we will discuss below, these barriers are even greater when considering economic vulnerability because of the potential for heterogeneous vulnerabilities of different population sub-groups.

Second, flood benefits and damages are often framed in terms of volume, and translating to water quality and ecosystem services as co-benefits is new (Bokhove et al., 2019). We noted that many ecosystem effects are acknowledged but rarely monetized, especially after directly quantifying the effect. This may stem from data availability; if enough data exists to quantify the impact, then the researcher is likely to monetize it; otherwise, they can only acknowledge it. Only recently has the turn towards "nature-based solutions" opened the door to more holistic environmental cost analysis of flood mitigation impacts (Lo et al., 2021). Before nature-based solutions, there was very little incentive to address wider environmental impacts, and negative environmental impacts are almost never reported in project-level flood BCA. Over the last decade, several well-known tools (e.g., CLASIC, InVEST) have emerged to incorporate life cycle cost, ecosystem services, performance, and co-benefits of projects (Loomis, 2015; Egan et al., 2018), facilitating the integration of modelling with

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TABLE 2 List of flood mitigation BCA articles.

First author (Year)	Cultural value	Econ. Activity	Human health	Social disrupt	Property protect	Climate and GHG	Water costs	Spill-over	Equity
1. Alves et al. (2019)	O	M	Q	O	M	M	M, A	O	O
2. Arrighi et al., (2018) [b]	O	O	O	O	M	O	O	O	O
3. Atoba et al. (2020)	O	Q	O	O	Q	O	O	O	O
4. Atoba et al. (2021)	O	M	O	O	M	O	O	O	O
5. Burnett et al. (2017)	A	M	O	O	O	O	A	O	O
6. Cooper et al. (2016)	O	Q	M, A	M	M, Q	O[c]	M, A	O	O
7. Davlasheridze et al. (2018)	O	M	O	O	M	O	O	O	O
8. Dittrich et al. (2019)	M	M	O	O	M	M	O	A	O
9. Dong and Frangopol (2017) [b]	O	O	O	O	M	O	O	O	O
10. Florec et al. (2017)	O	M	O	M	M	O	O	O	O
11. Garrote et al. (2019)	O	M	O	O	M	O	M	O	O
12. Huang et al. (2018)	O	O	O	O	M	A	A	O	O
13. Johnson et al. (2020) [b]	O	O	O	O	O	O	O	A	O
14. Kind et al. (2017)	O	O	O	O	M,Q	O	O	O	M,Q
15. Kind et al. (2020) [b]	O	O	O	O	M[b]Q	O	O	O	M
16. Kousky and Walls (2014)	O	M, A	O	O	M, A	A	M	A	A
17. Kousky et al. (2013)	O	M, A	A	Q, A	M, Q	A	O	M, A	O
18. Molinari et al. (2021)	O	M, A	O	A	M	O	O	A	O
19. Nelson and Camp (2020)	O	O	A	A	M	A	M	O	O
20. Nordman et al. (2018)	M	M	O	O	M	A	M	M	O
21. Oladunjoye et al. (2019)	A	A	A	A	A	O	A	O	O

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TABLE 2 (*Continued*) List of flood mitigation BCA articles.

First author (Year)	Cultural value	Econ. Activity	Human health	Social disrupt	Property protect	Climate and GHG	Water costs	Spill-over	Equity
22. Ramirez et al. (1988) [b]	O	O	O	O	M	O	O	O	O
23. de Ruig et al. (2020) [b]	O	O	O	O	M	O	O	O	O
24. Tate et al. (2015)	O	A	O	A	M	O	O	O	Q
25. Ventimiglia et al. (2020)	A	M, A	A	O	M	O	O	O	O
26. Vojinovic et al. (2016)	A	A	O	O	M, Q, A	O	A	O	A
27. Watson et al. (2016)	O	A	A	O	M	O	A	M	O
28. Wobus et al. (2021)	O	O	O	O	M	O[c]	O	O	O
29. Yildirim and Demir (2021)	O	M	A	A	M	O	O	O	O
Percent[a] Monetized	6.9	44.8	3.4	6.9	86.2	6.9	17.2	10.3	6.9
Percent[a] Quantified	0	6.9	3.4	3.4	20.7	0	0	0	6.9
Percent[a] Acknowledged	13.8	27.58	24.1	20.7	10.3	17.2	24.1	13.8	6.9
Percent[a] Omitted	79.3	34.48	72.4	72.4	6.9	75.9	62.0	75.9	82.8

[a]additiona. O, Omitted, A, acknowledged, Q, Quantified, and M, Monetized.
[b]The percenage is calculated based on 23 articles focused on policy recommendations (i.e., excluding methodological BCAs, indicated by "B" in the first column of Table 2).
[c]Cooper, Grcia et al. (2016) and Wobus et al. (2021) address climate change's non-stationary impacts on damages, not mitigation benefits or costs.

estimates of non-market environmental costs and benefits more accurately. However, as in the case of heterogeneous depth damage curves beyond traditional structural practices, this is only now trickling into the literature. Much of the wider social impacts literature has been slow to trickle into BCA research, in part because much of that literature uses categorical constructs for topics such as resilience or community cohesion (Zhang and Alipour, 2021), which frequently are not framed in terms of the economics of net present value and may be reported in terms incommensurate with monetization methods. Other emerging approaches suggest using standardized pre-post ecosystem services impact frameworks to standardize reviews in the face of challenges implementing comprehensive environmental valuation (Souliotis and Voulvoulis, 2021).

Third, framing economic vulnerability in the Benefit-Cost Analysis is new in policy, and methods for understanding distributional consequences are novel and challenging (Pappalardo and La Rosa, 2023; Pollack et al., 2024). Many of the articles linked to BCA framings or literature do not incorporate the community living around the project area based on standardized methods to monetize different levels of flood vulnerability because these are only now emerging as a way of more robustly estimating these effects. Doing so may require working over large scales with spatially detailed data linked to parcels, individuals (or micro areas), and structures, and also understanding upstream-downstream impacts of projects and how the distribution of risk in the watershed relates to social vulnerability and environmental justice concerns (Sanders et al., 2023; Serafin et al., 2024). There are problems with watershed models that involve their cost and computational burden for project-level evaluation and project-level BCA. Accordingly, these analyses are still developing. However, overlooking projects' total costs and benefits, including externalities to non-target communities and economic vulnerability, can hinder NPV calculation, reflecting social welfare implications and obfuscating project recommendations (Shah et al., 2017).

Our work shows the gap in BCA literature in documenting robust social welfare impacts of projects via the robust estimation of the complex social and environmental trade-offs related to flood mitigation prioritization and evaluation. In this sense, our research provides novel systematically collected empirical evidence of the gaps identified by the Office of Management and Budget in its report, *Advancing the Frontiers of Benefit-Cost Analysis: Federal Priorities and Directions for Future Research* (OSTP 2023). We understand that future studies recommend that future BCA studies acknowledge a broader set of effects and the types of people affected by the proposed project, which can speak to the criticism of BCA's prioritization of property protections over vulnerable populations and the environment (Finkel, 2018; McGee, 2021). Improved comprehensiveness may be achieved with more robust interdisciplinary teams of experts evaluating flood mitigation, as often occurs in MCA research (Abdullah et al., 2021). This requires linking BCA practice to more empirical multifaceted damage research, more robust environmental modelling relating to the effects of diverse flood mitigation projects on water quality and ecosystem services, efforts to monetize existing environmental model outputs, addressing scalar questions comprehensively, and incorporating emerging efforts to quantify how flood mitigation may deteriorate or increase efforts at equity in terms of the distribution of watershed risks, costs, and benefits. Efforts to enhance the range of effects and distributional consequences of flooding exist (Kind et al., 2016), but further work is needed to develop a BCA approach that addresses the full range of externalities and distributional consequences that affect the net social benefits of projects.

This research could take the form of systematic reviews on the interface of the physical effects of flood hazard mitigations with environmental and social models based on ecosystem service categories, such as those provided by GEMs, and processes to monetize the outcome of those models by category of impacts. There should also be further research on model based BCA and more parsimonious approaches (Souliotis and Voulvoulis, 2021), both related to ecosystem services (Vollmer et al., 2022) and distributional questions related to social and economic vulnerability (Kind et al., 2017), via coproduced design with practitioners given the practical barriers and costs related to BCA implementation (Douthat et al., 2023), and the importance of context and culture on BCA valuation (Shreve and Kelman, 2014).

Author contributions

FA: Formal Analysis, Investigation, Writing–original draft, Writing–review and editing. SB: Data curation, Formal Analysis, Investigation, Writing–original draft, Writing–review and editing. JP: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Supervision, Writing–original draft, Writing–review and editing. TD: Conceptualization, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

Supplementary material

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