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Efficient Flood Risk Mitigation and Intersectional Equity Implications: A Case Study in New Orleans

Nathan Geldner (nathangeldner@gmail.com)
Purdue University https://orcid.org/0009-0002-8657-4701
David Johnson
Purdue University https://orcid.org/0000-0002-2364-340X
James Doss-Gollin
Rice University
Klaus Keller
Dartmouth College https://orcid.org/0000-0002-5451-8687

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Abstract

Government agencies often require cost-benefit tests for environmental risk mitigation measures. These tests implicitly prioritize more valuable assets and may therefore produce inequitable outcomes. Previous studies propose directly prioritizing vulnerable groups or minimizing Gini coefficients, but these violate popular notions of procedural equity. We propose an alternative non-monetary risk measure which treats homes as equally valuable, improving distributional outcomes without violating procedural norms. As a case study, we compare optimal fixed-budget housing elevation strategies in New Orleans which respectively minimize flood risk measured as (i) economic damage, and (ii) the proportion of a structure's replacement cost. The latter strategy allocates more resources to impoverished neighborhoods and reduces proportional damage to housing by an additional 11% at the expense of 2% of economic damage. Composite strategies provide more favorable tradeoffs (4% of proportional damage for 0.04% economic damage). This analysis demonstrates the value of non-monetary risk measures in pursuing equitable outcomes.

Main

To effectively mitigate climate related risks, decision-makers and analysts must first decide what metrics to consider as they rank and prioritize protection projects. Cost-benefit analysis (CBA) remains the predominant decision criterion in applied mitigation efforts and governmental policy writ large.[1–6] Many institutions such as the Federal Emergency Management Agency and the U.S. Army Corps of Engineers are required to perform CBA for all flood risk mitigation projects and grants, although FEMA has recently relaxed their cost-effectiveness requirements for marginalized communities.[7,8] Typical implementations of CBA treat the direct structure damages avoided over a project's lifetime as a key benefit, which implicitly prioritizes projects that protect expensive structures. This has the potential to worsen existing social inequity.[9,10] Substantial differences already exist between racial and income groups in air quality,[11–13] water quality,[14–16] and flood risk.[17–19] This potential for harm is increasingly salient; the growing adoption of analyses which characterize flood risk at the level of individual structures [20–22] makes it possible to algorithmically design interventions at the level of individual homes which (inadvertently) selectively protect expensive structures, the effects of which may then be masked by data aggregation.[23–25] Action to mitigate these outcome gaps or otherwise prevent policy action from worsening them is required as a matter of standing federal policy.[26] Practical efforts to reduce these outcome gaps however are hindered by divergent perspectives on how to define and operationalize equity.[27–31] This research presents an alternative decision metric from those used in traditional const-benefit analysis which yields improved equity outcomes from the perspective of multiple competing definitions of equity.

Equity, as defined by the federal government, refers to the consistent and systematic treatment of all individuals in a fair, just, and impartial manner.[32] The tension between conflicting ideals of equity complicates the design of policies which seek to lessen gaps in environmental risk outcomes. While a

wider range of perspectives exist, this work focuses on the tension between deontological egalitarianism and prioritarianism as described by Parfit.[33] Deontological in this context refers to the belief that the morality of an action comes from the action itself rather than the consequences of the action. As a consequence, deontological egalitarianism (hereafter referred to as egalitarianism) mandates that each individual is granted equal consideration and individual treatment irrespective of outcomes. Egalitarianism does not hold equality in final distribution of resources, or the resolution of unequal status quo resource allocations as normative aims, although they may be desirable for other reasons. This egalitarian ideal of equity is strongly tied to the notion of procedural justice, which is broadly similar in mandating that people are treated equally[34] but relates more to whether individuals perceive allocation process as fair and impartial than to the allocation mechanism itself.[35] In contrast, prioritarianism mandates that we prioritize the welfare of the least advantaged members of society in pursuit of more equal outcomes.[33] Prioritarianism is strongly related to the notion of distributive justice, which requires that resources are distributed in a way which is fair or just.[36] Also relevant is the notion of corrective justice, which holds that if some party is harmed for the gain of another, the harmed party is entitled to restitution.

A natural prioritarian solution to unequal environmental risk outcomes would be to directly prioritize socially vulnerable groups.[37] However, this would violate the egalitarian ideal of equity which requires that individuals are given similar consideration irrespective of the *status quo* resource allocation. An egalitarian perspective may judge the elimination of outcome gaps as a valid instrumental good, but likely opposes explicit prioritization of disadvantaged groups as unfair. An egalitarian perspective might see explicit prioritization of disadvantaged groups as a justified measure of corrective justice under the premise that disadvantage experienced by those groups results from systemic violations of procedural justice. However, recent political trends suggest that many decision-makers in US states threatened by coastal flooding would reject this premise.[38–40] A substantial body of research shows that disagreement between prioritarian and egalitarian perspectives on equity hinders the remediation of racial disparities along a wide range of issues.[27–31] In order to feasibly mitigate existing disparities in environmental risk outcomes or otherwise avoid worsening those disparities in the near term, it is therefore necessary to develop risk mitigation strategies which do so without violating egalitarian equity norms.

The capacity of CBA to worsen existing socioeconomic disparities and therefore violate prioritarian notions of equity is evident from its core premises. To perform a cost-benefit analysis one first compares the sum total of a project's expected discounted economic (i.e., monetary) benefits to the sum total of the project's discounted financial costs. One then measures the performance or cost-effectiveness of the project by the ratio of the benefits to the costs.[4] As benefits are expressed purely in economic terms, CBA places greater value on the protection of expensive assets than the protection of inexpensive assets. In light of well-studied geographical and racial disparities in wealth,[41] it is clear that purely CBA-driven evaluation of protection projects has the potential to neglect historically marginalized communities with lower average building costs.

The severity of economic and racial gaps in environmental risks is starkly highlighted in the flood risk faced by the city of New Orleans, Louisiana. Predominantly Black neighborhoods in New Orleans bore the brunt of lives lost during Hurricane Katrina in 2005.[19] Laska and Morrow[42] argue that the severity of the outcome of Katrina was in part driven by inequality among racial and income groups. The speed and effectiveness of post-Katrina recovery efforts differed wildly between socio-economic and racial groups in ways that are only visible upon sufficiently granular analysis.[43,44] There were substantial racial disparities in immediate post-Katrina relief investments even when controlling for socio-economic status.[45] The existing disparities in environmental risk across racial and economic groups and the possibility that CBA could worsen them raise two main questions addressed in this study: (1) How much can a CBA approach worsen these disparities? (2) Can one remedy these disparities in a way that satisfies both egalitarian and prioritarian ideals?

Few studies have compared algorithmic cost-benefit maximizing flood risk interventions with equity-driven alternatives. Those which have either pertain to equity between regions in the design of flood protection structures[9] or integrate a Gini coefficient or equity weighting of flood exposure in the design of urban drainage projects or ecological restoration.[46–48] Similar studies in the area of water resource management have also used a Gini coefficient or a coefficient of variation of benefits as an equity measure.[49–51] These studies consistently find that inclusion of equity criteria in decision-making changes the design of interventions and identify trade-offs between equity and efficiency depending on how equity is operationalized. To our knowledge however, no such study examines flood risk interventions which are made at the level of individual structures. Additionally, every such study examines an equity-oriented strategy which either explicitly prioritizes poorer residents or explicitly targets equal final resource distributions, violating egalitarian norm of granting equal procedural consideration to individuals irrespective of status quo or final resource allocation. This suggests a research gap; if CBA worsens socioeconomic disparities, then there is a pressing need for a method to design flood risk mitigation strategies at the structure level that mitigates the potential harms of CBA without violating egalitarian equity norms.

Recently available methods for characterizing flood risk at the level of individual buildings have increased the scope of potential harm from traditional cost-benefit analysis. Building-level interventions have proven effective in mitigating flood risk,[52–55] and the Coastal Louisiana Risk Assessment Model (CLARA) is able to characterize changes to the flood risk faced by individual buildings across coastal Louisiana under a range of protection projects including those at the level of individual buildings.[21] It is therefore possible to generate, evaluate, and optimize mitigation projects at the level of individual buildings. A mitigation project which discriminates between individual buildings in risk mitigation naturally carries a far greater potential for inequity than one designed at the level of spatially broad and socioeconomically diverse areas. While to our knowledge no applied flood risk mitigation policies have been implemented to date which were designed using building-level optimizations, it is necessary to investigate the potential equity impacts of such policies before efforts are made to implement them.

Risk Outcomes by Race and Income

This study follows recent recommendations[56] to help mitigate inequitable CBA outcomes through the inclusion of alternative decision criteria. This study develops optimally cost-effective flood risk mitigation strategies targeting individual single-family residences for elevation-in-place (i.e., raising the elevation above grade of the first inhabited floor), respectively minimizing expected direct economic damage (DED) as per traditional CBA, and an alternative egalitarian metric, denoted residence loss equivalents (RLE), which treats each home as if it had an identical value or replacement cost. In all cases, this study adopts a 50-year planning horizon when evaluating expected risks. Results show that strategies minimizing the egalitarian RLE are preferable to those minimizing DED from a prioritarian perspective, reducing income-related disparities in mitigation resource allocation and reducing nominal outcome gaps between Black and White New Orleans residents as measured by RLE. This article refers hereon to the DED-minimizing strategy as the “cost” strategy, and the RLE-minimizing strategy as the “housing” strategy.

Our analysis shows that Black residents receive the vast majority of mitigation resources under both the cost and housing strategies because they currently experience the overwhelming and disproportionate bulk of flood risk in New Orleans (Fig. 1). Black residents make up 59% of the population, but residences occupied by Black residents bear 79% of direct economic damage and 88% of residence loss equivalents. Black residents receive 81% and 90% of mitigation resources under the cost and housing strategy respectively. This is – perhaps – counterintuitive given the larger weight more expensive houses receive in the CBA framework and the current correlation between average house price and racial composition of a neighborhood. Our analysis reveals that the existing disparity in flood risks faced between Black and White residents in New Orleans is so overwhelming that Black neighborhoods bear the brunt of the flood risk burden within all considered strategies. This figure does show, however, that the housing strategy mitigates a large portion of the residence loss equivalent damage faced by New Orleans residents overall, thereby reducing the nominal size of the racial disparity in risk to housing (RLE).

Our analysis further reveals that the cost strategy principally benefits households with poverty-income ratio (i.e., the ratio of household income to the US poverty threshold) greater than 2, whereas the housing strategy provides greater benefits to lower-income households (Fig. 1). Taken together, the racial and income distributions of flood risk and mitigation investment show that the question of whether to target replacement cost (via DED) or cost-blind measures of housing risk (via RLE) becomes a question of how to allocate resources between wealthier or poorer predominantly Black neighborhoods, which is made more complicated in light of well-studied wealth disparities between Black and White populations more broadly.[57–62]

Risk Outcomes by Neighborhood

Assessed at the neighborhood level, predominantly Black neighborhoods visibly bear the brunt of flood risk in New Orleans (Fig. 2). Outside of the Lower 9th Ward, which receives substantial mitigation investment in both the cost and housing strategies, the cost strategy concentrates investment in the

predominantly middle-class Black neighborhood of Read Boulevard East, whereas the housing strategy distributes investment across a series of poorer, predominantly Black neighborhoods (Fig. 2, Fig. 3). One such neighborhood, Read Boulevard West, carries an expected 0.35 residence loss equivalents per household under the status quo and receives approximately zero risk reduction along either metric from the cost strategy. Implementing the housing strategy reduces the residence loss equivalents per household by 40% and its direct economic damage by 2%. Conversely, Read Boulevard East sees a roughly 9% reduction in both direct economic damage and residence loss equivalents per household under the cost strategy, and sees a negligible reduction in direct economic damage and 5% reduction in residence loss equivalents under the housing strategy. It is also worth noting that both predominantly White neighborhoods facing substantial flood risk as measured by direct economic damage, West End and Lakeshore, have 100% of their flood risk mitigated as measured by both metrics under both strategies. This indicates that the flood risk in these neighborhoods is concentrated in a small number of expensive structures that are inexpensive to mitigate. Among the other, predominantly Black neighborhoods affected, the cost strategy targets relatively more expensive homes in relatively higher-earning communities while the housing strategy targets less expensive homes in lower-income communities. The distributional equity of these competing allocations remains complicated: each strategy helps to mitigate a facet of the overwhelming risk burden facing Black New Orleans residents.

The tendency of the cost strategy to protect a smaller number of more expensive homes than the housing strategy is observable within neighborhoods as well as between neighborhoods. In the Lower 9th Ward, implementing the cost strategy reduces direct economic damage by 41% and residence loss equivalents by 56%. In contrast, the housing strategy reduces direct economic damage by 32% and residence loss equivalents by 77% while spending fewer resources in the neighborhood. This shows that even within the neighborhood, the cost strategy targets more expensive homes while the housing strategy targets a greater number of less expensive homes.

Intermediate strategies between the cost and housing strategies (i.e., strategies that place some weight on both DED and RLE reduction) perform well according to both metrics (Fig. 4). As preference for the housing strategy increases, residence loss equivalent reduction increases at the cost of direct economic damage reduction. Placing a small but non-zero weight on direct economic damage compared to the housing strategy reduces direct economic damage by an additional 0.5% at a cost of 0.02% of projected RLE. Placing a small weight on residence loss equivalents relative to the cost strategy reduces residence loss equivalents by an additional 4% at the cost of only a 0.04% decrease in direct economic damage reduction. As mentioned above, the question of how to balance protection of impoverished Black communities against protection of accrued wealth within Black communities is complicated considering broader racial wealth disparities. These results show that compromise strategies between targeting monetary and non-monetary risk metrics can be effective in balancing these competing priorities.

Discussion

This case study illustrates how targeting aggregate economic efficiency in environmental risk mitigation projects can allocate few mitigation resources to impoverished areas that need them. This research proposes and demonstrates a potential remedy: targeting an alternative risk measure which deliberately places an equal weight on each residence irrespective of its economic value. This alternative measure satisfies deontological egalitarian notions of equity which other approaches may fall short of, and also improves distributional outcomes from a prioritarian perspective. While direct economic damage and residence loss equivalents are equally valid efficiency metrics, the use of residence loss equivalents to direct risk mitigation decisions can to some extent correct for historical underinvestment in risk mitigation to marginalized, less affluent communities without explicitly including socioeconomic demographics in the decision calculus.

Despite its evident advantages from a prioritarian perspective in dedicating mitigation resources towards impoverished communities, the implications of targeting residence loss equivalents as a risk metric from a corrective justice perspective are more nuanced than initially expected. We had hypothesized that targeting direct economic damage would invest a large portion of mitigation resources towards wealthy, predominantly White communities, and that targeting residence loss equivalents would direct those resources to impoverished communities with larger Black populations. Instead, this study has found that the burden of flood risk by any metric in New Orleans falls so overwhelmingly on largely middle class and poor neighborhoods, all predominantly Black, that efficient flood risk mitigation targeting either metric invests the majority of mitigation resources towards predominantly Black neighborhoods. As a result, the choice between targeting direct economic damage and residence loss equivalents amounts to a choice between protecting middle class and poor neighborhoods. This complicates matters from a corrective justice perspective, as while prioritarian notions of distributive justice suggest prioritizing poorer neighborhoods and therefore targeting residence loss equivalents exclusively, doing so may deprive residents of middle class Black neighborhoods of the mitigation resources needed to maintain existing adaptive capacity in the face of flood risk.

Fortunately, this study identified compromise strategies that balance economic and egalitarian measures of cost effectiveness and perform well in both metrics. Compared to the status quo of seeking purely economic efficiency, substantial gains in these egalitarian measures can be achieved with only modest sacrifices in economic efficiency. This is highly useful to analysts and decision-makers interested in balancing the needs of poor and middle class neighborhoods facing severe flood risk in New Orleans; an intermediate strategy can efficiently provide protection to both poor and middle class neighborhoods which would be largely neglected by a strategy targeting one metric to the exclusion of the other. As the data elements required to calculate such egalitarian and hybrid risk measures are a proper subset of those used to calculate economic damages as per traditional cost-benefit analysis, their use can be integrated into existing analytical workflows in an operationally straightforward manner. This provides a tractable and parsimonious approach to better incorporate equity considerations into environmental risk management decisions, where budgets and schedules are tight and concerns for social equity are of increasing political salience. Hopefully, the proposed approach can help policy makers to design risk

management strategies that better balance economic efficiency and equity outcomes when considering a range of perspectives on equity and justice.

Methods

Flood risk mitigation projects are frequently selected on the basis of which project most cost-effectively minimizes direct economic damage (DED) in expectation. The Coastal Louisiana Risk Assessment model used by Louisiana's Master Plan estimates a discretized annual exceedance probability distribution for flooding at a given structure's location for 22 return periods ranging from the 2-year flood (i.e., 1-in-2 chance of occurring or being exceeded in a given year) to the 2000-year flood. The damage suffered by a given structure as a fraction of its replacement cost is estimated by USACE methods as a piecewise linear function of flood depths. The replacement cost of an individual structure is estimated using structure-level attributes (e.g., square footage, number of stories) combined with valuation assumptions from the FEMA Hazus-MH model.[63] The expected discounted value of direct economic damage over time can therefore be expressed as

$$\mathbb{E}\left[DED\right] = \sum_t \sum_s \sum_e p_{s,t}\left(e\right) D_s\left(e\right) r\left(s\right) \gamma^t$$

,

where t denotes years elapsed, s indexes structures, e represents plausible flood elevations, $p_{s,t}\left(e\right)$ denotes the probability that structure s in year t will face flood elevation e, $D_s\left(e\right)$ denotes the damage suffered by structure s and its contents as a fraction of their replacement cost resulting from flood elevation e, $r\left(s\right)$ denotes the replacement cost of structure s and its contents, and γ denotes the economic discounting rate.

The use of direct economic damage as a characterization of risk carries a number of benefits – dimensionless cost/benefit ratios and net present values in units can be easily calculated and interpreted as the costs and benefits of a protection project are both expressed in units of dollars. Further, policies which minimize DED under a fixed budget appear to be socially optimal if we neglect distributional impacts or otherwise assume that *post-hoc* wealth transfers implicitly resolve problematic distributional impacts as is commonly assumed in resource economics.[64] The chief weakness of DED as a decision metric is clear from its formulation – if all residences are exposed to equal flood elevations and therefore suffer an equal amount of damage proportional to their replacement costs, a scenario which might reasonably be described as all residents having equal exposure to flood risk, a DED-minimizing strategy would preferentially protect more expensive residences. To address this weakness, we define a similar flood risk metric with a nearly identical formulation, but which explicitly does not consider the replacement value of a residence, which we shall refer to as Residence Loss Equivalents (RLE).

$$\mathbb{E}\left[RLE\right] = \sum_t \sum_s \sum_e p_{s,t}\left(e\right) D_s^*\left(e\right) \gamma^t$$

.

RLE here represents an attempt to capture similar information to DED without consideration for a residence's replacement value. The use of D_s^* rather than $D_s\left(e\right)$ denotes damage to the structure alone rather than the structure and its contents. In equalizing the weight applied to the total loss of a residence, we effect a deontologically egalitarian metric which explicitly grants each household equal procedural consideration regardless of the financial value of the home. In addition to supporting decision processes compliant with egalitarian principles of equality and ultimately serving prioritarian aims to a greater extent than traditional CBA, RLE carries the distinct advantage that it can be calculated using a proper subset of the data and methods required to calculate RLE.

To investigate the distributional and therefore prioritarian-relevant implications of our risk measures, we identify coastal protection projects for the city of New Orleans which simultaneously minimize DED and RLE assuming flood hazard consistent with Louisiana's 2023 Comprehensive Master Plan for a Sustainable Coast.[21] These projects apply elevation-in-place retrofits to single-family residences within the New Orleans levee system under a fixed 100 million dollar budget to minimize the weighted average of DED and RLE under varying relative weights. In the limiting case, the strategy which minimizes DED alone is referred to as the "cost" strategy, and that which minimizes RLE alone is referred to as the "housing" strategy. We first project changes to flood risk over a 50-year planning horizon resulting from elevation-in-place retrofits at one-foot intervals. Flood depth exceedances are modeled at decadal time slices according to the changing environmental conditions (e.g., sea level rise) of the Coastal Master Plan's Lower landscape scenario. Risk is calculated at 5-year intervals with linearly interpolated flood depth exceedances, treated as constant within those 5-year intervals, and aggregated with a discount rate of zero.

Optimal elevation strategies are derived by sorting individual structure retrofits by cost-effectiveness in the relevant metric and iteratively removing redundant strategies, e.g., eliminating a 1-foot elevation-in-place of a given residence for which a 2-foot elevation-in-place is selected, until the fixed budget is fully expended without redundancy. Intermediate strategies are derived by scalarizing DED and RLE with arbitrary relative weights before calculating the cost-effectiveness of the resulting composite metric. We estimate the distributional impacts of these strategies under the assumption that the occupants of these residences have the same demographic features of the Census block group in which they reside as given by the 2019 American Community Survey.[65] For both the readability of mapped figures and the privacy of individual households, all mapped figures are shown as neighborhood averages based on neighborhood definitions published by the city of New Orleans.[66]

Declarations

Data Availability

Demographic information from the 2019 American Community Survey is available from the US Census Bureau at https://data.census.gov/. Neighborhood definitions from the city of New Orleans are available at https://portal-nolagis.opendata.arcgis.com/maps/e7daa4c977d14e1b9e2fa4d7aff81e59/about. Data on structure replacement cost, elevation cost, and residual expected annual damage over a 50-year period as well as demographic information merged in at the census block group level are available for every modelled residence in New Orleans with all location information removed excepting neighborhood ID is available at https://github.com/geldner/Efficient-Flood-Risk-Mitigation-and-Intersectional-Equity-Implications along with the script used to generate strategies and tabulate results. Flood depth exceedances informing risk estimates are from Louisiana's 2023 *Comprehensive Master Plan for a Sustainable Coast*, with data viewer at https://mpdv-23.bridges2.psc.edu/.

Software Availability

Once the Louisiana *Comprehensive Master Plan for a Sustainable Coast* is finalized, the Coastal Louisiana Risk Assessment model code will be available at https://github.com/CPRA-MP. As mentioned above, the script used to generate strategies and tabulate along with the data necessary to do so (with location information beyond neighborhood removed for the privacy of residents) is available at https://github.com/geldner/Efficient-Flood-Risk-Mitigation-and-Intersectional-Equity-Implications.

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Author information

Authors and Affiliations

Purdue University School of Industrial Engineering:

Nathan B. Geldner, David R. Johnson

Rice University Department of Civil and Environmental Engineering:

James Doss-Gollin

Dartmouth College Thayer School of Engineering:

Klaus Keller

Author Contributions:

N.B.G. conceived of the study, designed the research, carried out the analysis, and prepared the manuscript. D.R.J. designed the original flood risk model used for the study as part of previous research, adapting it for use with single-family residences in New Orleans specifically, and contributed to writing the manuscript. J.D-G. and K.K. provided crucial input in how to frame the analysis and visualize and interpret results and contributed to writing the manuscript.

Ethics Declarations

The authors declare no competing interests.

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Figures

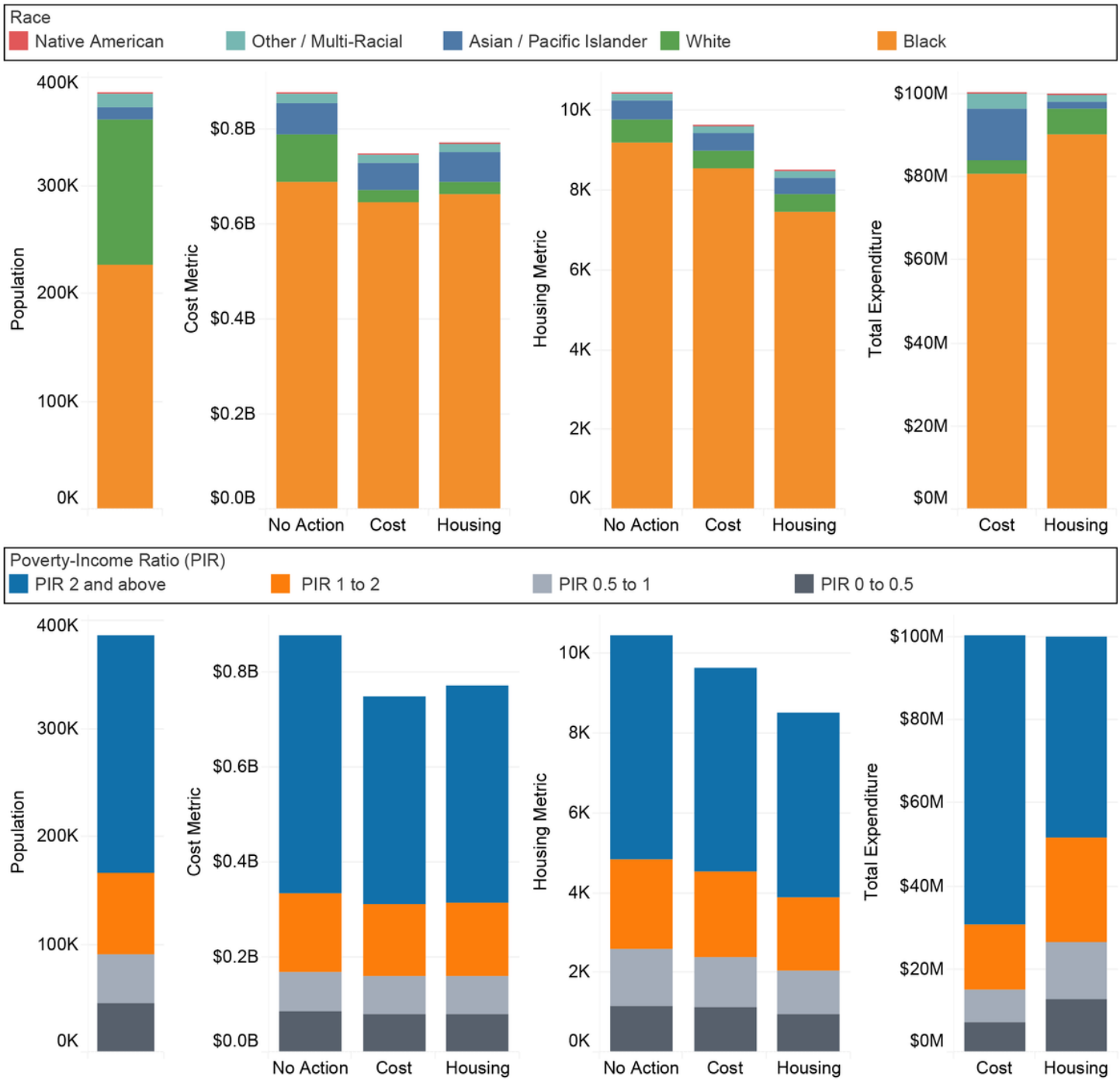


Figure 1

Housing strategy displays small increment in protection investment in Black communities and substantial increment in protection investment in lower-income communities. Total population, aggregate single-family residence flood risk estimates measured as direct economic damage and as residence loss equivalents, and total expenditure under no-action, cost, and housing strategies. Top row disaggregates measures by race and bottom row disaggregates measures by poverty-income ratio. Risk measures and

spending are estimated at the individual building level and demographic estimates assume homogeneity within census block groups.

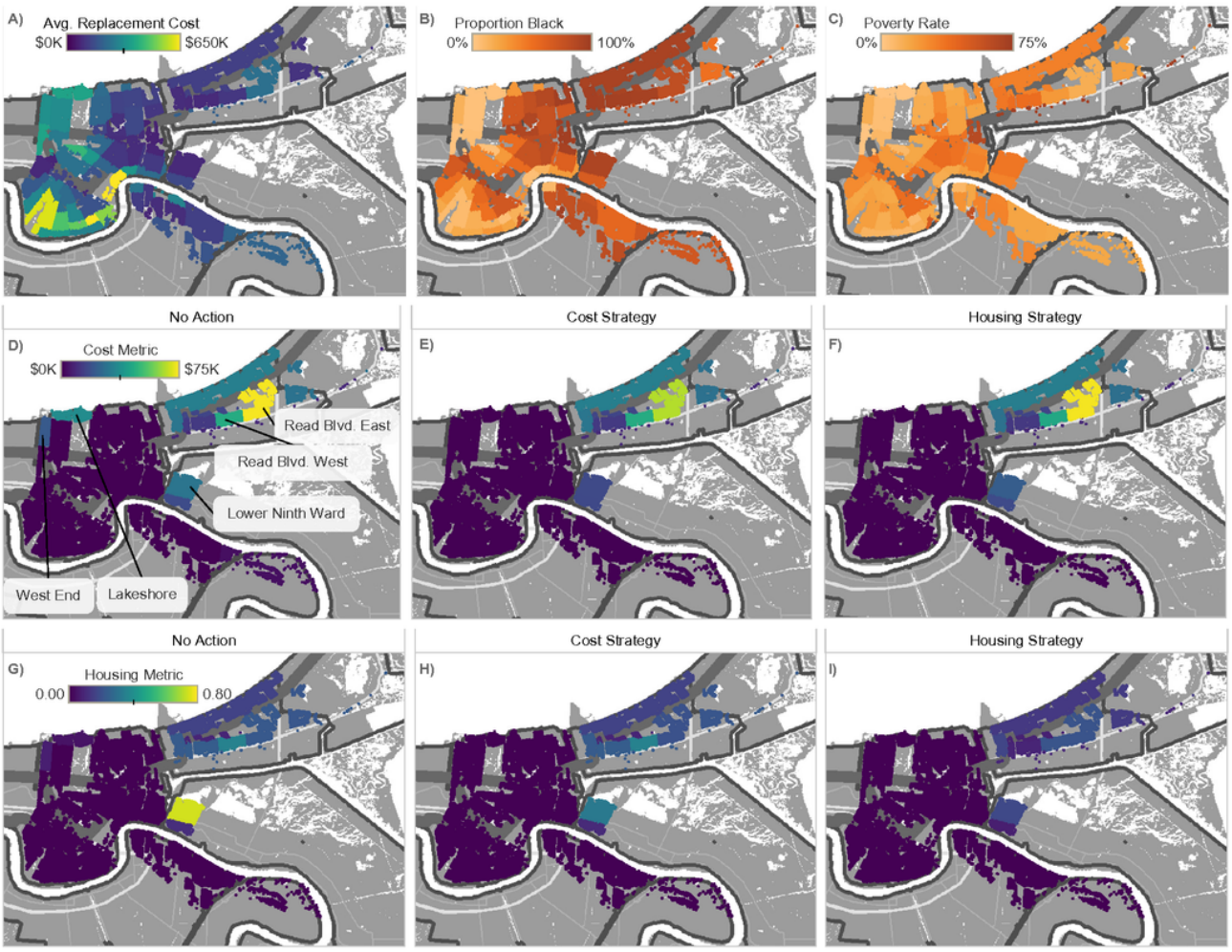


Figure 2

Housing strategy concentrates protections in Read Blvd. East (and the Lower 9th Ward) while cost strategy invests broadly in impoverished Black Neighborhoods across New Orleans East (and the Lower 9th Ward). Map shows salient neighborhood characteristics and flood risk measures across no action, cost, and housing strategies. A) shows the average replacement cost of single-family residences in each neighborhood. B) shows the proportional Black population of each neighborhood. C) shows the poverty rate. D), E), and F) show neighborhood average direct economic damage per household under no action, cost, and housing strategies respectively. G), H), and I) show neighborhood average residence loss equivalents per household respectively. Colored points on the map reflect the locations of individual single-family residences. Select neighborhoods are labelled in panel D).

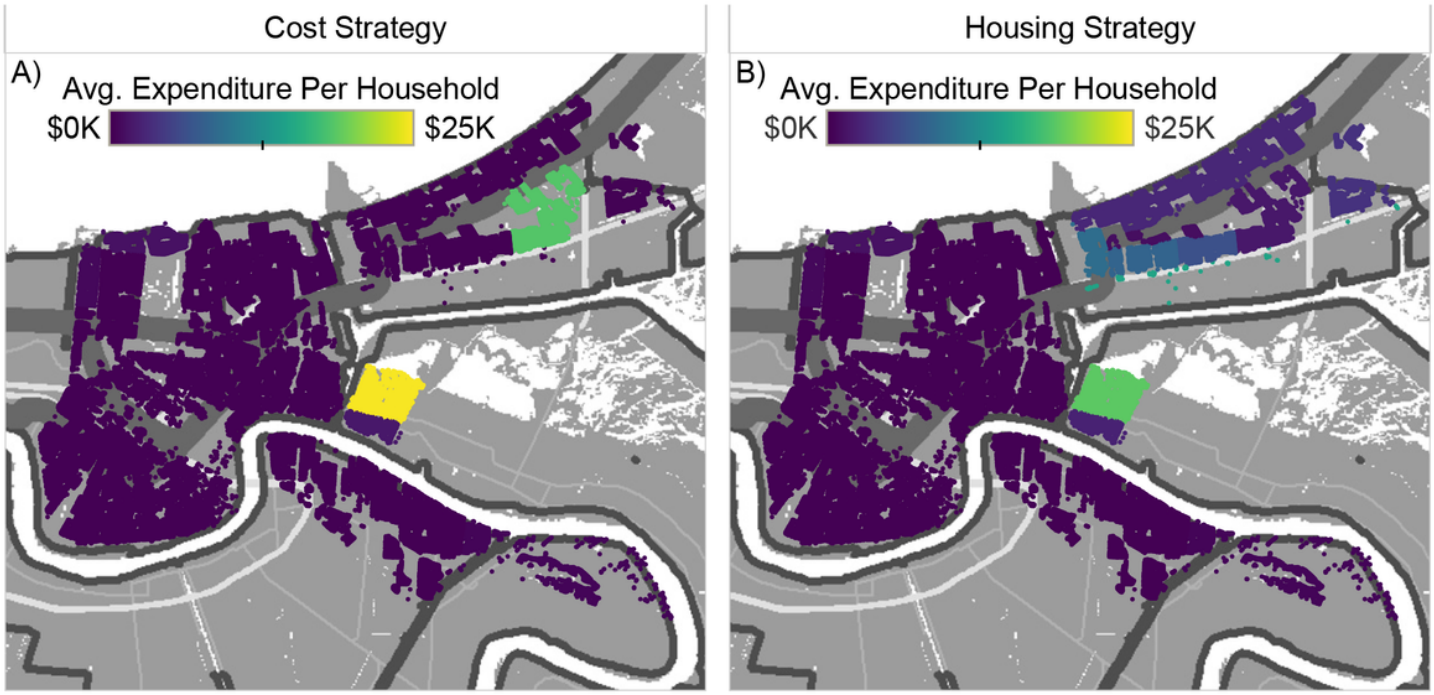


Figure 3

Housing strategy concentrates protections in Read Blvd. East (and the Lower 9th Ward) while cost strategy invests broadly in impoverished Black Neighborhoods across New Orleans East (and the Lower 9th Ward). Map shows average expenditure per household at the neighborhood level for cost and housing strategies. Panel A) shows cost strategy and panel B) shows housing strategy.

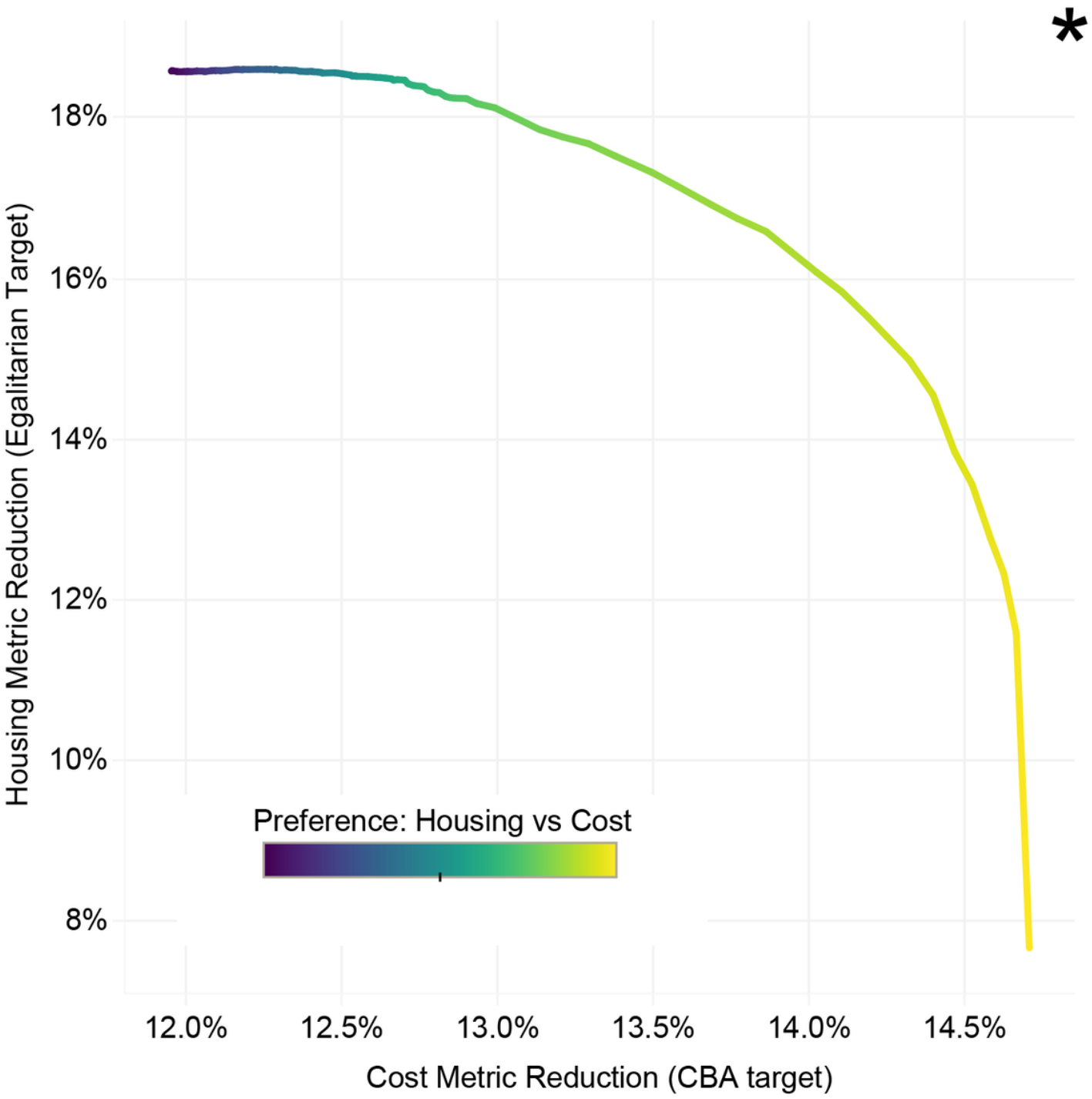


Figure 4

Intermediate strategies show favorable tradeoffs. Plot shows Pareto frontier between direct economic damage reduction and residence loss equivalents reduction for a fixed budget of 100 million US dollars. Segments in purple to the top-left reflect a high weight placed on residence loss equivalents reduction, as in the housing strategy, and segments in yellow towards the bottom-right reflect a high weight placed on direct economic damage reduction, as in the cost strategy. Ideal point shown with black asterisk in upper right.