Developing more useful equity measurements for flood-risk management

Authors: Adam B. Pollack[1]*, Casey Helgeson[2,3], Carolyn Kousky[4], Klaus Keller[1]

Affiliations:

[1]Thayer School of Engineering, Dartmouth College; Hanover, 03755, USA.

[2]Earth and Environmental Systems Institute; Penn State University, State College, 16801, USA.

[3]Department of Philosophy, Penn State University; State College, 16801, USA.

[4]Environmnetal Defense Fund; Philadelphia, PA, USA.

*Corresponding author. Email: adam.b.pollack@dartmouth.edu

Abstract: Decision-makers increasingly invoke equity to motivate, design, implement, and evaluate strategies for managing flood risks. Unfortunately, there is little guidance on how analysts can develop measurements that support these tasks. Here, we analyze how equity can be defined and measured by surveying 167 peer-reviewed publications that explicitly state an interest in equity in the context of flood-risk management. Our main result is a taxonomy that systematizes how equity has been, and can be, defined and measured in flood-risk research. The taxonomy embodies how equity is a pluralistic and unavoidably ethical concept. Despite this, we find that most quantitative studies fail to motivate or defend critical value judgments on which their findings depend. We also find that studies often include only a single equity measurement. This practice can overlook important trade-offs between competing perspectives on equity. For example, the few studies that employ distinct principles show that conclusions about equity depend on which principle underlies a specific measurement and how that principle is operationalized. We draw on our analysis to suggest practices for developing more useful equity indicators and performing more comprehensive quantitative equity assessments in the broader context of environmental risks.

Main

Communities face uneven exposure to environmental harms[1–10]. An emerging environmental management goal is for public programs to promote equitable distributions of both benefits and costs within and across communities[4,6,9,11–25]. However, public programs often lack guidance on how equity is, or should, be measured and considered in program design, implementation, and evaluation[25–30]. It is difficult for practitioners to draw from research because many studies focus on how to define equity rather than how it can be measured[8,10,14,15,31–36]. Further, when guidance about equity measurements is included, there is typically little attention to how measurements reflect underlying values. In the few exceptions we are aware of[32,33], examples of equity measurements span a relatively narrow breadth in terms of outcomes and ways to define equity[6,8,15,37,38].

Because what is meant by equity can vary widely, it is important that equity is defined and measured deliberately and transparently to meet policy goals and to facilitate inclusive policy design and evaluation[8,15,30,34,35,37,39–43]. The ambiguity about equity that is currently common in practice and research may hide implicit value judgments made by analysts or decision-makers. In contrast, transparency can help decision-makers deliver on ambitious promises about equity in distribution, procedure, recognition, and other dimensions[14,15,32]. Further, transparency can bring greater clarity to challenging decisions and equip constituents with the knowledge about whether their values are being represented[11,44–46].

Here, we synthesize ethical and quantitative frameworks across an interdisciplinary literature base to provide guidance on how equity in outcomes can be clearly, consistently, and robustly measured in the context of flood-risk management. While this guidance is needed in many contexts, we focus on the management setting of flood risk for several reasons. First, a growing body of research has documented that both common and devastating floods exacerbate existing social inequalities, driving growing policy interest in equity[8,12,14,15,35,37,39,41,42,47–63]. Second, there is often a large debate among key constituents as to how to define equity in a particular flood risk management context[8,15,34,35], making a focus on flood risk an instructive case study for other management domains[33,64,65]. Third, focusing on one management area allows for greater depth of inquiry about distributional equity measurements than related studies[31,33]. Our scoping choice is not meant to diminish the importance of equity in other policy domains or of other types of equity. By virtue of our analysis sample (See Methods), and not by design, our analysis is limited to a focus on outcomes because analyzed quantitative measurements did not focus on other forms of equity such as procedure, recognition, or capabilities. This does, however, suggest an important research and policy gap related to these other forms of equity for work on flood risk management.

In accordance with the pluralistic nature of equity, we use the phrase “equity indicator” to describe measurements that are explicit about how equity is defined and transparent about why measured quantities reflect underlying values. Our intention in using the term “indicator” is to evoke the common understanding of indicators as ways to represent hard-to-quantify and potentially pluralistic attributes[66–70]. For example, economic policy is informed by many indicators such as the unemployment rate and the consumer price index[71]. In health, indicators

like blood pressure, cholesterol levels, and blood glucose concentration inform doctors' and patients' choices about health management options[72]. Given the lack of explicitness and transparency in much research[8,10,15,31,32] and practice[25–30], the use of "equity indicator" may help reorient equity measurement practices around needed qualities like clarity. To promote clarity in reading the subsequent analysis, we define this and other key terms in Box 1.

Box 1: Key terms used throughout this Analysis.

1. **Equity** is a pluralistic concept that is often invoked to represent underlying values about fairness through interconnected dimensions of recognition, procedure, and distribution[6,11,32]. Definitions of equity can vary because different constituents in different management settings may hold a wide set of potentially divergent values. In this analysis, we focus on how analyzed studies specifically define equity and represent this definition of equity in a quantitative way.

2. We refer to a study's definition of equity as a **notion of equity**. Please see the Methods for a detailed description of how we classified a parsimonious set of notions of equity.

3. We refer to the explanation of how a specific measurement supports or reflects a notion of equity as a transparent **justification** or **rationale**.

4. We define **equity indicators** as measurements that are explicit about which underlying values about equity are measured and transparent about why measured quantities reflect these underlying values. We require that equity indicators have an explicit notion of equity and a transparent equity rationale.

5. We call measurements that do not meet our definition of an equity indicator but are explicitly conducted with the goal of drawing equity implications a **stated equity measurement**.

Results

In search of equity indicators (henceforth, indicators) we analyzed research with a stated interest in evaluating equity in flood-risk management to systematically classify how equity has been, and can be, defined and measured. Guided by these questions, we developed a taxonomy to summarize our results and map observed equity indicators to this taxonomy. We find that although equity is a widely invoked concept, it is generally not measured. When equity is measured, it is rarely measured with explicit and transparent attention to underlying values. The resulting taxonomy presents an accessible set of indicators to interested parties and our mapping suggests ways forward to improve equity measurement practice.

We surveyed a sample of 167 papers that take an analytical perspective on equity in flood-risk management (See Methods). Most of these studies (99) include quantitative methods. Only 11 of these quantitative studies include indicators. Of the remaining quantitative studies, 33 include stated equity measurements. Most quantitative studies (55) do not include equity measurements, but prominently feature the concept of equity.

A taxonomy of flood-risk equity indicators

Our main result is a taxonomy of indicators that characterizes how equity can be defined and measured in flood-risk research (Figure 1). We individuate indicators in terms of (I) what outcome is distributed? (II) across which scale? (III) with respect to what other characteristics? and (IV) why do the measured quantities indicate equity? We define classes within distinct measurement components (i.e. "Benefits" is a class within the outcome types measurement component) based on our analysis of stated equity measurements and indicators. We classify justifications based on our analysis of all 167 studies and additional references on underlying theories about equity cited therein.

[Insert Figure 1 here]

We begin by classifying different approaches to providing an equity rationale because they are the fundamental qualities of indicators. We identify four general approaches. First is "invoking a principle," in which authors reference principles guided by a specific theory related to ideal or fair distributions. These could include theories about social welfare[15,34,60,65,73,74], environmental justice[4,6,8,10,75], or could include citing moral principles like egalitarianism[34,65,73]. Alternatively, studies could appeal to equity rationales that are distinct from theoretical principles. This includes authors interpreting policymaker attempts to define equity in a policy or regulation[19,20,26,76] ("interpreting a policy mandate"). Another category is "Ad Hoc Rationale" in which researcher discretion is used as a justification. For example, one study measures house-level benefit-cost ratios from different interventions and states that if the median benefit-cost ratio across houses is greater than one, this indicates an equitable outcome because it means the majority of people benefit[77]. While this appears to be perhaps based in utilitarian reasoning, the researcher does not cite or reference any policy, principle, or social engagement, suggesting it is their own judgement [77]. Finally, qualitative studies highlight the value of attempts to capture societal-based judgements or preferences for equity which may involve social engagement and specific attention to aspects of recognition and interactional justice[6,11,32,35,52–54,78] ("reflecting societal values").

The "outcome types" component includes broad classifications of the outcomes considered (this could be considered an answer to the question – "equity in what?"). Many risk assessments carefully distinguish flood hazard (the physical peril), exposure (people or capital in the path of the peril), vulnerability (susceptibility to damage) and risk (the potential for consequences through the interactions between hazards, exposures, and vulnerabilities)[76,79–84]. In the literature we analyzed, studies considered exposure, vulnerability, and risk as outcome types. Another class of outcome measure are the benefits as might be included in a benefit-cost analysis framework[60,85] which we refer to in the Figure as "benefits." Note that we are also grouping in

this category what might be called "co-benefits," or positive outcomes not directly of interest to the policy. For example, one study suggests that households that resettle after a buyout in close proximity to their former neighbors are better off than households that resettle further from their former neighbors[75]. Our "Recovery" category refers to post-flood outcomes, sometimes measured in reference to a pre-flood state, such as paid insurance claims[86] or time to rebuild[87]. Our categorization of the outcomes addressed in a study may sometimes differ from the language used in the study itself. In particular, some of the analyzed studies conflate exposure with risk; for consistency, we apply the definitions of these terms that reflect the definition of risk presented in the IPCC's sixth assessment cycle, regardless of language used in the study[76,79–84,88].

The "aggregation units" component includes the scale and definition of spatial boundaries at which the distribution of an outcome is measured. "Individuals" refers to consideration of outcomes at an individual, household, or building level. "Neighborhoods" refers to community-defined neighborhood boundaries which are an important spatial boundary in many theories of environmental justice[2,6]. For example, Bullard[2] highlights the importance of evaluating the distribution of an outcome of interest at the scale it is most likely produced, such as a neighborhood, in order to identify inequities. "Small areas" refers to population-based administrative boundaries that approximate neighborhoods, such as census block groups or tracts in the United States, which are often used due to their convenient data availability. Outcomes are also measured over relatively large areas like cities or regions.

The "other characteristics" component includes demographics, measures of environmental burden, and procedural disparities. These are used to assess if inequities exist along a particular dimension although some measurements do not include other characteristics and we classify these as "none." Within our "Demographics" category, we include individual variables, such as income, as well as when multiple demographic characteristics are combined into an aggregate index to proxy hard to quantify attributes such as vulnerability or disadvantage[10,93]. "Environmental burden" refers to groupings based on measures of environmental quality, such as access to nature, protection by green infrastructure, or exposure to pollution or other environmental hazards[86]. It is worth noting that some environmental burdens, or goods, could also be conceived of as relevant outcomes. "Procedural disparities" include discriminatory practices, such as those that produced historically redlined neighborhoods[94], and policies that produce distinct groups subject to different procedural factors and experiences. For example, one study highlights that insurance claims filed by houses with different sewage systems are treated under different review processes in Sweden[95,96].

This taxonomy highlights the large variety of ways equity has been, and can be, measured. This diversity of approaches, and ways to measure the same underlying concept differently, is why explicitness and transparency about values and methods is needed. An illustrative example of this key point comes from a detailed reading of one stated equity measurement in our sample[104]. This measurement is based on the (I) proportion of a city's population in modeled flood hazard extents (exposure) (II) across small areas with respect to (III) demographic groups[34]. This measurement is explicit that any inequality in exposure across groups is inequitable. In fact, the study states that groups exposed to more flood hazard have a "discriminatory" situation relative to the population. In the study, the authors report that some demographic groups, which they call

the most vulnerable, have disproportionately high exposure to flooding and conclude the situation is inequitable. However, other studies from different locations have found that the distribution of exposure across demographic groups show that affluent groups can have disproportionately high exposure to flooding[34]. It seems unlikely the authors of the first study would have labeled this inequitable (despite being unequal), but without a transparent justification for why their measurement reflects their representation of equity, it is not possible to consistently apply their equity definition. Alas, the lack of transparent guidance introduces ambiguity and increases the chances of misinterpretation.

Equity indicators as defined in flood-risk research

Despite our relatively large sample of quantitative studies (99 studies), we find few measurements that meet our standard for indicators. Only 11 studies include 22 indicators. We consider indicators that vary in any of the three measurement components (i.e. outcome types, aggregation units, other characteristics) as distinct indicators. For indicators identical in these components, we consider indicators distinct if they vary in terms of the specific justification for an interpretation of equity even if they share the same broad classification. For example, Jafino et al.[34] measures (I) the distribution of avoided flood losses (benefits) from different adaptation strategies (II) across Districts in Vietnam (large areas). There are no other characteristics at the District level that serve as a basis for comparison for the distribution of benefits. The authors aggregate benefits according to their interpretations of different moral principles which may lead to different conclusions about which policies lead to the most equitable distribution of benefits. In particular, Jafino et al.[34,40,73,86,97–100] finds that the policy preferred under a Rawlsian framework is undesirable under frameworks such as egalitarianism or utilitarianism. In terms of their equity rationales, this means that a framework which prioritizes benefits for the least advantaged individual (Rawlsian framework) leads to different policy preferences than a framework which prioritizes equality (egalitarianism) or overall well-being across Districts (utilitarianism)[75]. This example illustrates why it is important to separately classify indicators in terms of the specific justifications for a notion of equity and not only the overarching classification.

Despite the diversity of ways to quantitatively represent equity suggested by the taxonomy, analyzed indicators consist of a relatively small set of measurement components. Across the 22 equity indicators, benefits (17 indicators) are the most commonly considered outcome (Fig. 2). Other outcomes are considered only once (exposure, recovery, or funding) or twice (risk). Equity is most often measured at the individual scale (12) followed by large areas (8), and small census areas (2). Only five indicators consider other characteristics as a basis for comparison for the distribution of an outcome. Demographics are considered in three indicators and procedural disparities are considered in two. The vast majority (20) of the analyzed equity rationales invoke a principle. These principles are almost always a moral principle, like egalitarianism (i.e. everyone has equal) or sufficientarianism (i.e. everyone has enough), or based in welfare theory and rely on social welfare functions[76]. One study invokes theories within the field of

environmental justice to provide a rationale[77]. There is also one study that interprets a policy mandate[99] and one study that uses an ad hoc rationale as a justification[34,60,73,97–99,101].

[Insert Figure 2 here]

Although analyzed indicators consist of a relatively small set of measurement components, the consistency in how most indicators are defined suggests that some ethical frameworks are readily operationalizable for interested analysts. One strength of this kind of indicator is that the distributive principles they invoke provide needed clarity that stated equity measurements lack about why measured quantities indicate equity. For example, Kind et al.[33] uses equity weights to estimate social welfare and explicitly states that wellbeing is only derived from consumption (defined broadly). In their formulation, it is clear that their social welfare estimate is the only relevant outcome for drawing equity implications. This strong stance can contradict other ways of thinking about equity, but in stating their justification transparently, readers can determine whether they find the results consistent with their own values or understanding about equity. In addition, this clear guidance allows for great comparability to other indicators and the equity implications of measured quantities. The ethical literature on moral principles is extensive, encompasses more distributive principles than are operationalized in our analyzed studies, and a detailed survey is beyond the scope of our study's descriptive purpose. Good entry points for readers interested in operationalizing these and other principles are studies that employ these indicators[8,12,14,15,35,51–58,62,102,103] and the references therein. In addition, the review of Jafino et al.[8,10,51,104–106] is an insightful and useful overview of how to conduct measurements based on a broader variety of distributive principles.

The qualitative literature we analyze suggests a number of potentially relevant indicators that have not been employed[9,65]. For example, we do not find vulnerability (outcome type), neighborhoods or regions (aggregation unit), environmental burden (other characteristics), or reflecting societal values (justification) in any analyzed indicator. We highlight detailed examples of indicators in the supplementary materials to illustrate more of the diversity of possible indicators available to analysts. Please see table S1 for details on how we define each analyzed indicator.

How flood-risk research claims to measure equity

Our results highlight a need for increased attention to values and ethics in the measurement design stage of quantitative equity assessments is needed (Fig. 3). We find that most stated equity measurements (40 out of 66) explicitly cite environmental justice, distributive justice, or inequality as a basis for their notion of equity. However, because these studies lack transparent statements about why implemented measurements reflect underlying values about equity, analysts risk hiding implicit value judgments.

One reason the literature does not contain more measurements linked explicitly to moral frameworks could be a perception in some disciplines that researchers should not impose values on analysis. Several research communities see themselves as analyzing conditions but believe they should leave the value judgements to policymakers or other stakeholders. Unfortunately, it is just not possible to avoid making value judgements and - at the same time - report equity implications from measurements. It would be possible to limit attention to inequality—not equity—and many insightful studies do this or focus on other descriptive aspects of distributions of outcomes without inferring equity implications[20]. When this is the case, researchers should be explicit that they are leaving the equity interpretations up to others.

Stated equity measurements are also common in studies that invoke environmental justice for their notion of equity. Transparency is important in such studies because different theories in environmental justice each represent diverse and pluralistic views on how equity can be represented[4,6,9,11,32]. For example, environmental justice serves as the background motivation for recent policy guidance in the U.S. that calls for at least 40 percent of benefits from certain federal programs to accrue in communities with disadvantaged and historically marginalized groups[4,6,8–11,15,42]. But different environmental justice theories, such as those that are explicitly reparative in terms of distribution, may have different ways to define these groups and may offer different guidance about equity than the 40 percent criteria[2,4,6,107]. This illustrates that there can be major obstacles in understanding justifications for what is or is not equitable even when the same notion of equity is used.

[Insert Figure 3 here]

How might stated equity measurements change if they were held to a higher standard of transparency about reflecting the underlying values of background motivations? Based on theories in environmental justice cited in the analyzed studies, we can speculate on some potential indicators. Currently, exposure is the most commonly studied outcome (Figure 3). However, we interpret environmental justice theories as calling for consideration of a wider range of outcome measures, including risk, funding, recovery, or benefits because these theories draw explicit attention to the distribution of positive outcomes (our categories of benefits, recovery, and funding) and also burdens (our risk category)[93]. In terms of aggregation units, theories in environmental justice call for analysts to evaluate inequity at the spatial scales at which they are most likely produced, such as true neighborhood boundaries, as opposed to convenient administrative boundaries like small areas[2]. Relatedly, in terms of other characteristics, theories call for analysts to uncover the causal factors that produce inequities and create injustice[107]. Therefore, there could be more attention to procedural disparities and environmental burden as potential causal mechanisms for uneven distributions. For example, the discriminatory practice of redlining has been highlighted as a procedural disparity that produces inequities and creates injustice[4,95,108–111], but only one analyzed stated equity measurement considers redlining[112]. Despite the strong emphasis on identifying causal, as opposed to

correlational, links[108], methods in causal identification are only employed once in the analyzed studies[4,95,109–112].

We acknowledge that some choices analysts make may also be due to practical challenges like data limitations. For example, few studies discuss mismatches in how they measure equity (i.e. at the census block group or tract level) with what theory says is most relevant (i.e. at the neighborhood level) which might have implications for conclusions about equity[113]. We encourage future studies to correct this oversight. Whether or not authors agree with our interpretation of what underlying environmental justice theory implies about potential indicators, we believe that the explicit and transparent standards we define for indicators can help accomplish shared goals of understanding equity implications of flood-risk management.

Research priorities for quantitative equity assessments

Based on our analysis into how equity has been measured in flood-risk research, we have three main recommendations to advance the quantitative study of equity broadly related to the distributions of environmental burdens and benefits. First, we suggest that analysts who want to make claims about the equity implications of quantitative measurements adhere to the explicitness and transparency standards put forth here. Because equity is an unavoidably ethical concept, explicit notions of equity and transparent indicators are needed to produce normative guidance for interpretation. We expect this practice will contribute to a comparable evidence base of equity indicators and implications. In turn, a consistent and comparable evidence base can help produce generalizable insights about equity.

Second, analysts can help to sharpen the evidence base about equity implications by more deeply engaging in various interpretations of equity to define indicators that better capture the plurality of views about equity. There are similar recommendations for researchers studying related pluralistic concepts of social vulnerability and resiliency[34]. Relatedly, an omission in the current literature is the lack of indicators that define equity or justify the interpretation of measured quantities based on input from affected parties (reflecting societal values)[38,59,114]. Affected parties are likely to have the most context-specific knowledge of relevant outcomes, spatial scales, and other characteristics to consider for the equity concerns in their community[6,31,32,35,53,54]. This would also motivate the ethical underpinnings of the work by the impacted groups and not by the researcher.

Because the focus of our analysis is descriptive of how indicators can be defined, and how they have been defined so far in flood-risk research, it is beyond this study's scope to detail the plethora of notions of equity and equity rationales that can be operationalized for indicators. Our hope is that the taxonomy on how indicators can be defined, the extensive references to foundational literature on notions of equity and equity rationales, and the examples of indicators presented in this text can serve as a starting place for interested readers.

Third, we recommend that analysts engage with the concept of robustness in conducting quantitative equity assessments. Following on our previous recommendation, considering many diverse perspectives on what equity means can also complicate decisions. We point readers to the studies of Ciullo et al.[115] and Jafino et al.[8,12,15,27,41,42,61,115] which evaluate policies in rival ethical frameworks as a potential way forward. These studies provide impressive clarity about

which strategies are preferred under specific values systems and are potentially robust to different perspectives about equity. This is especially important because equity is a widely stated management principle in flood-risk management[117] but new policies are often silent on how equity will be measured. As such, trade-offs and synergies are often hidden from current public discourse and decision-making processes. A related aspect of robustness is whether equity implications are robust to different defensible ways of mathematically operationalizing an indicator. We could not find a study analyzing this question in our analysis. Broader use of indicators in analyses that make use of the concepts of rival framings and robustness may help decision makers navigate trade-offs and equip individuals with the knowledge to hold policymakers accountable for equity promises.

In closing, we emphasize that although explicit notions of equity, transparent indicators, and robust assessments are important, they are just one component of advancing equity in quantitative studies. For example, procedure, recognition, and interaction considerations are distinct and important but generally not often incorporated into analyzed equity assessments[116]. A holistic equity assessment integrates across these equity considerations and accounts for pluralistic conceptions of equity beyond distribution alone. We propose our taxonomy as a potentially useful step in this direction. While we focus on the example of flood risk, we hope that the insights can inform researchers, decision-makers, and stake- and rights-holders in many other areas on how to analyze - and hopefully improve - equity.

Methods

Our analysis consisted of four main methods. Here, we provide a high-level overview and in the subsequent subsections go into detail for how each method was implemented. First, we searched for articles that fit our analytical scope. We aimed to identify studies that prominently feature the concept of equity, have an explicit notion of equity, and transparently explain how their measurement(s) of equity reflect underlying values about equity. Second, we read all studies in our final sample in detail and classified them according to their explicit notion of equity. We also read the key references on notions of equity and equity rationales that are cited in studies. Third, we identified stated equity measurements and indicators, and we classified them according to key characteristics. Following these steps, we synthesized the results of our literature-based analysis to develop a parsimonious but generalizable taxonomy for how equity indicators can be defined. Finally, we performed a simple data analysis to produce Figures 2 and 3 and calculated summary statistics reported in the manuscript.

Search protocol

On September 26, 2022 we used the following search query in Web of Science: "**(flood*) AND (*equit*) AND (estimat* OR analy* OR empirical*)** (Topic) and **Article** or **Review Article** (Document Types)" limiting results from 1/1/2012 onwards. We aimed to limit the sample to studies that take an analytical perspective on equity in flood-risk management, with an emphasis on analyses that include quantitative estimates. This search returned 222 documents. Other search queries were considered but returned too many articles to process in the detail desired for our analyslis. As an example, one consideration was "**(flood*) AND (*equit* OR *just*) AND (estimat* OR analy* OR empirical*)** (Topic)" to include papers that strictly use concepts of

justice and language such as “just,” “unjust,” “justice,” or “injustice” instead of equity, but are clearly thematically related. This returned 2,782 results.

Of the 222 documents, we dropped one paper because it has no mention of equity or related concepts, one paper because there is no attention to equity in outcomes, 34 papers because there is no flood focus (i.e. flooding may be mentioned in the abstract but isn’t a focus of the research), one paper because it is only available in a foreign language, and 15 papers because equity isn’t meant as fairness (i.e. “equitable threat score” prediction metric in precipitation forecasting). The remaining 167 papers are our final sample referenced in the main manuscript.

As is the case in any analysis based on a sample of published studies, there are important limitations related to potentially relevant articles left out of the subsequent analysis. One reason articles are left out is that equity in flood risk is an emerging field of study and many relevant articles have been published since our search query on September 26, 2022. Another reason is that Web of Science continuously adds journals to its core collection. The following query link (https://www.webofscience.com/wos/woscc/summary/f91b51e2-4d94-4530-8ca4-443930528de7-51b03fba/relevance/1) returned 222 documents on September 26, 2022. However, on October 25th, 2022 and January 25th, 2023, the same query returned 227 and 244 documents, respectively. Since the search was limited from 2012-01-01 to 2022-09-26 in all searches, this reflects unknown additions to the Web of Science core collection of journals. While the list of journals can be obtained, there is no publicly available archive of this list. The final reason is that our search term may not be comprehensive.

These limitations affect all articles that are based on a sample of published studies. Some studies perform the same search across multiple databases to mediate the effect of the second limitation. Because our sample only includes 42 studies that measure the distribution of an outcome and interpret this as an equity measurement, it is possible that any excluded relevant studies may impact the mappings displayed in Figure 2 and 3 of the main text, and possibly the taxonomy in Figure 1. Follow-up research can test the robustness of the taxonomy and mapping by including more recent articles and sampling across more databases. For example, there may be a number of relevant studies captured in the search string that returned 2,782 results that are not included in our sample. There may also be other terms analysts can use that return a larger, but still manageable, number of articles for the same kind of analysis conducted here. However, even with the threat of omissions, we extensively analyze more studies in our final sample than related analyses. Therefore, while the classification and mapping may be affected by omissions, we think our analysis is robust, helpful, and fills the identified research gaps.

Identifying notions of equity

First, each study was classified based on whether it was a qualitative or quantitative assessment. A study was considered quantitative if it performs any statistical analyses or calculates any descriptive statistics on modeled or observational data. This includes survey-based research that performs statistical analyses. Our final sample includes 68 qualitative and 99 quantitative assessments.

Second, we examined which notions of equity are employed across studies. A notion of equity is a broad classification of how equity is defined in a study. Coding a notion of equity as explicit,

and further assigning a classification for the definition, is potentially subjective. We used the following rules to classify six categories:

- **Unclear**: Equity is used self-referentially throughout the manuscript. Equity is never qualified by another term, such as "gender equity," and is taken as undefined. Alternatively, equity might not be used in a self-referential way, but what is meant is still ambiguous. For example, one study explains that equity refers to the distribution of benefits and costs without grounding this definition in an ethical concept.

- **Inequality**: Equity and equality (or inequity and inequality) are used interchangeably, and besides this substitution, the study would otherwise be classified as (1) Unclear. We take the view that because inequality can be interpreted through a variety of moral lenses[117], such as strict egalitarianism or an envy-free distribution of resources, interchangeably using equity and equality without pinning down either pluralistic concept is as good as being unclear about a definition of equity. However, since this interchangeable use occurs several times, we felt it was important to classify inequality as its own notion of equity for the descriptive purposes of this analysis.

- **Environmental Justice**: Environmental justice is mentioned in the study. There are some studies which refer to social justice, not environmental justice. We evaluated the citations used in these articles to determine which of the four justice frames used in the classification scheme these most closely correspond to. These few cases all cite extensively from the same literature as the studies that explicitly cite environmental justice. Therefore, these studies are included in this category.

- **Distributive Justice**: Distributive justice is mentioned in the study, or an explicit moral principle (such as Rawlsian or libertarian fairness or justice) is stated and cited.

- **Climate Justice**: Climate justice is mentioned in the study.

- **Gender Justice**: Gender equity of justice is mentioned in the study.

Only a few studies cite climate justice or gender justice in stating their notions of equity. However, these are all qualitative studies which is why these notions of equity are not displayed on Figure 3.

Finally, we tracked whether equity is used in the title, abstract (including keywords), methods, results, and/or remainder of a manuscript. The Web of Science "Topic" search looks through the title and abstract and keywords for the terms supplied. Therefore, each study includes at least one equity reference in these sections. We tracked the use in each section to track how notions of equity are employed in studies that are quantitative and qualitative, and that include different kinds of equity measurements (including none). These results aren't reported in the manuscript.

Instead, we limit our summary statistics to proportions of studies employing various explicit notions of equity. This data is included in a Zenodo respository and is available for reanalysis[118].

Classifying indicators and stated equity measurements

We analyzed all 99 quantitative studies to determine if they include equity indicators as defined in the main manuscript. Studies that include equity indicators are extensively analyzed for the way these measurements are designed. As mentioned in the main manuscript, any study that includes a measurement of the distribution of an outcome and is interpreted as indicating equity is also analyzed in detail.

For each measurement analyzed in detail, we track:

- The moral principle, if any, is stated to guide the way fairness is operationalized
- What is being distributed (outcome types)
- More detailed text about what is being distributed
- The scale at which equity is evaluated (aggregation units). This scale refers to the unit at which the equity measurement is based. Importantly, this category doesn't indicate what the underlying spatial resolution is for determining the values at this scale.
- More detailed text about the scale at which equity is evaluated
- Other characteristics that the outcome being distributed is compared to
- Data sources that are cited
- How the distribution is assessed
- How the way the distribution is assessed is linked to equity implications
- More details about indicating equity implications
- Whether a measurement scale about equity is explicitly stated
- Equity rationale

Data analysis

We relied on the pandas (version 1.5.2)[119] and plotly (version 5.9.0)[119] libraries in the Python programming language to perform our analysis. We used pandas to shape raw analysis data into the correct form for use in plotly to produce Figures 2 and 3. Otherwise, we used pandas to implement filtering steps described in the "Search protocol" section.

Data availability: All data, code, and materials used in the analysis are freely and permanently available at https://doi.org/10.5281/zenodo.8139215. This analysis was tested and confirmed for reproducibility by Sitara Baboolal on July 11th, 2023. If you have any issues reproducing the results, please contact the corresponding author on the GitHub repository.

Code availability: All data, code, and materials used in the analysis are freely and permanently available at https://doi.org/10.5281/zenodo.8139215. This analysis was tested and confirmed for reproducibility by Sitara Baboolal on July 11th, 2023. If you have any issues reproducing the results, please contact the corresponding author on the GitHub repository.

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Author contributions:

Conceptualization: ABP, CH, CK, KK

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Investigation: ABP

Formal analysis: ABP

Project administration: ABP

Visualization: ABP, CH

Funding acquisition: CK, KK

Supervision: CK, KK

Writing – original draft: ABP

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Figures

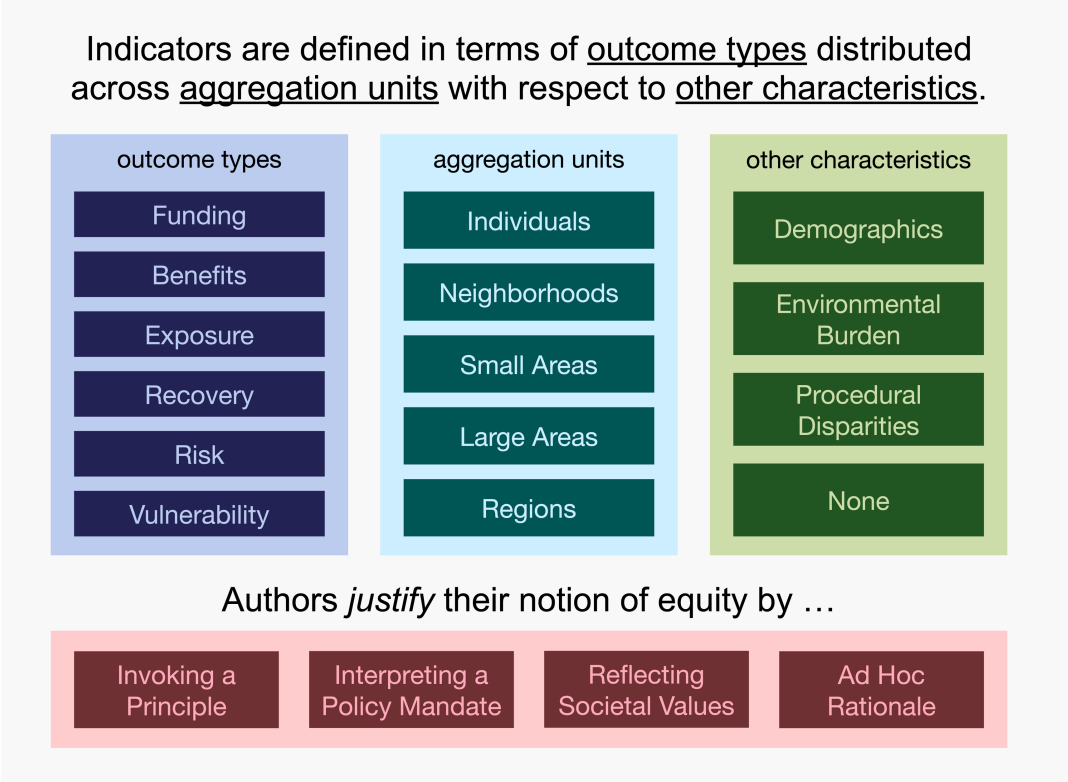

Figure 1: Taxonomy of equity indicators. An equity indicator is defined by answers to four questions: (I) what outcome is distributed? (II) across which scale? (III) with respect to what other characteristics? and (IV) why do the measured quantities indicate equity? (IV) consists of the underlying reason for why measured quantities map to a specific interpretation about equity.

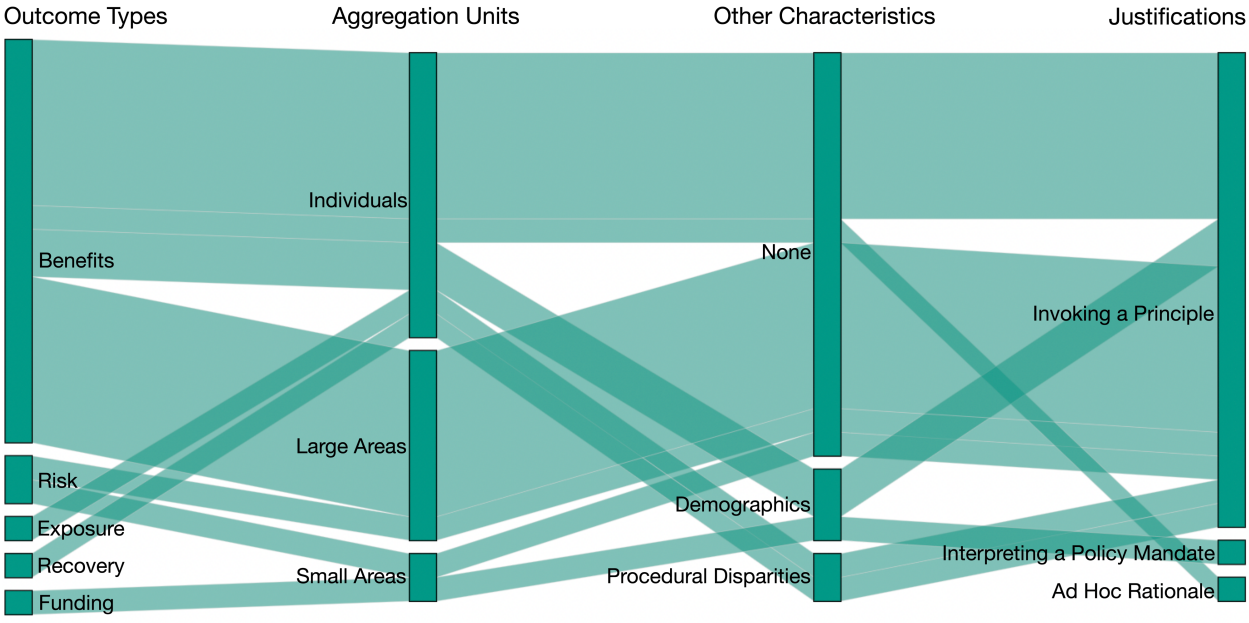

Figure 2: Mapping of all 22 analyzed indicators to the taxonomy. Each indicator is represented by a single line that spans from "outcome types" to "justifications". In aggregate, these create the appearance of bars. Each bar length, and the thickness of each bar, is proportional to the number of indicators in each measurement component group compared to all indicators. For reference, there is one indicator that uses "Funding" for "outcome type". As an example, there are seven indicators that measure benefits at the individual scale, do not include other characteristics, and invoke a principle. Although the "Individuals" bar represents 12 indicators, three of those that consider benefits also consider other characteristics and two consider different outcome types than benefits. Each column is arranged vertically from top to bottom in descending order of the number of indicators in that category.

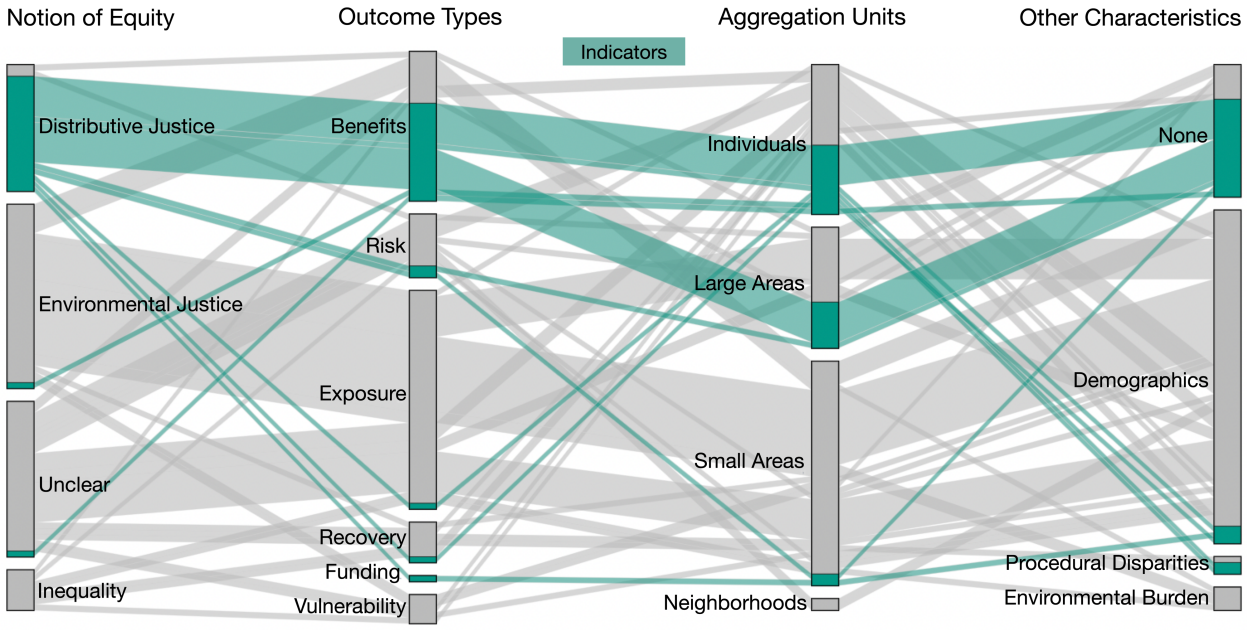

Figure 3: Mapping of all 66 stated equity measurements and 22 indicators to the taxonomy. Instead of the justification category of the taxonomy, this mapping includes the notion of equity used in a study. Each measurement is represented by a single line. In aggregate, these create the appearance of bars. Each bar length, and the thickness of each bar, is proportional to the number of measurements in each group compared to all measurements. For reference, there is one indicator that uses "Funding" for "outcome type". Each column is arranged vertically from top to bottom in descending order of the number of indicators in that category. Indicators are in light green and stated equity measurements are in light gray.

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The file includes:

Supplementary Text
Table S1

Detailed examples of several indicators

Tate, E., Strong, A., Kraus, T. & Xiong, H. Flood recovery and property acquisition in Cedar Rapids, Iowa. Nat. Hazards **80**, 2055–2079 (2016).

Tate et al. defines an indicator which measures (I) the distribution of grant funding for flood acquisitions (adaptation funding) (II) across census block groups (small census areas) (III) as a function of a flood-specific vulnerability index defined by demographic data at the census block group scale (demographics)[85]. The authors are explicit that the allocation of funding is more equitable if it is prioritized for those most in need. This corresponds to higher values of their vulnerability index which is defined in terms of factors that research suggests is most relevant for flood-specific vulnerability. The authors are transparent that this interpretation of equity is meant to reflect their perception of the underlying objectives of different federal grant programs for buyouts and hinges on how the vulnerability index is defined (interpreting a policy mandate).

Gourevitch, J. D. et al. Spatial targeting of floodplain restoration to equitably mitigate flood risk. Glob. Environ. Change **61**, 102050 (2020).

Gourevitch et al. employs an indicator that measures (I) the distribution of equity-weighted flood damage reduction from floodplain restoration (benefits) (II) across households (individuals) (III) as a function of the appraised value of the structures at risk as a proxy for household income (demographics). The authors are explicit that the distribution is more equitable if lower income households have higher benefits. The authors are transparent that they assume equity-weighting reflects a society's preferences for inequality aversion and leads to investments that promote benefits and reduce costs to lower income households (invoking a principle). This indicator is unique for examining the distribution of an outcome estimated through a social welfare function in terms of demographic characteristics.

Elliott, J. R., Loughran, K. & Brown, P. L. Divergent Residential Pathways from Flood-Prone Areas: How Neighborhood Inequalities Are Shaping Urban Climate Adaptation. *Soc. Probl.* (2021).

Elliott et al. defines an indicator that measures (I) the distribution of distance resettled, and to what degree resettlement occurs with former neighbors, after flood acquisitions (benefits) (II) for households (individuals) of (III) different ethnicities and incomes (demographics). The authors are explicit that the outcome is more equitably distributed if households are able to maintain social ties to their community after accepting a buyout regardless of their race and ethnicity, and are transparent that this interpretation is grounded in theories of both environmental justice and sociology[6,8,10,42]. The authors define typologies of resettlement that correspond to various degrees of maintaining what they call the social value of home and community and estimate which types of residents fit into different typologies in order to make claims about equity in co-benefits (or harms) from buyouts.

Mobini, S., Becker, P., Larsson, R. & Berndtsson, R. Systemic Inequity in Urban Flood Exposure and Damage Compensation. *Water* **12**, 3152 (2020).

Mobini et al. measures (I) the distribution of approved flood damage claims for houses in Sweden (recovery) (II) for households (individuals) with respect to (III) whether houses have separate or connected sewage systems (procedural disparities). The authors state that citizens should have equal opportunity to have their flood risk managed and cite theories in distributive justice to support this notion (invoking a principle). This indicator is unique because it

incorporates the procedural concern that different claims approval processes for homes with different types of sewage systems could lead to what they call inequitable differences in the ability of flood-damaged homes to recover from a flood. The authors are silent on whether procedural disparities are due to varying risk levels that the different sewage systems may correspond to, but because the indicator is transparent it is easier for readers to interpret the measured quantities for themselves and form their own equity implications.

Table S1.

Enumeration of equity indicators within our analysis sample for the different categories within the taxonomy. Each field (left column) is mapped to each example of how the field was represented in corresponding indicators.

Field	Enumeration of Equity Indicators Encountered in Analysis
I. Outcome types	
Exposure	Filed damage claims after a flood
Risk	Expected annual losses
Benefits	Modeled difference in losses with and without an intervention; Modeled farm profits under different adaptation strategies; Retaining connection to neighbors after buyouts
Recovery	Approved damage claims after a flood
Adaptation Funding	Allocation of buyout funds
II. Aggregation Units	
Individuals	Buildings; Households
Small Census Areas	Census block groups; Census sectors
Large Areas	Districts; Cities
Regions	“Macroareas”
III. Other Characteristics	
Demographics	Structure value as proxy for income; Race and ethnicity
Procedural Disparities	Different claims filing processes for houses with different sewage systems

IV. Justification for a Notion of Equity (Equity Rationale)	
Invoking a Principle	Aggregation under different moral principle motivated ethical frameworks - egalitarianism, utilitarianism, envy-free, sufficientarianism, prioritarianism, Rawlsian*;* Welfare; "All citizens should have equal opportunity to have their flood risk managed"; Theories in environmental justice and sociology
Interpreting a Policy Mandate	Allocation preference towards communities more vulnerable to impacts from floods
Ad Hoc Rationale	Median benefit-cost ratio > 1 across homes means the majority of people experience benefits