Advanced Review

Accounting for risk aversion, income distribution and social welfare in cost-benefit analysis for flood risk management

Jarl Kind,[1*] W.J. Wouter Botzen[2,3] and Jeroen C.J.H. Aerts[2]

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Most cost-benefit analysis (CBA) textbooks and guidelines recognize the objective of CBAs to improve social welfare—a function of well-being of all individuals, conceptualized by utility. However, today's common practice to value flood risk management benefits as the reduction of the expected annual damages does not comply with this concept of social welfare, since it erroneously focuses on money instead of well-being (utility). Diminishing marginal utility of money implies that risk aversion and income differences should be taken into account while calculating the social welfare benefits of flood risk management. This is especially important when social vulnerability is high, damage compensation is incomplete and the distribution of income is regarded as unfair and income is not redistributed in other ways. Disagreement, misconception, complexity, untrained professionals, political economy and failing guidance are potential reasons why these concepts are not being applied. Compared to the common practice, a theoretically more sound social welfare approach to CBA for flood risk management leads to different conclusions on who to target, what to do, how much to invest and how to share risks, with increased emphasis on resiliency measures for population segments with low income and high social vulnerability. The social welfare approach to CBA, illustrated in this study in the context of floods, can be applied to other climate risks as well, such as storms, droughts and landslides.

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INTRODUCTION

Increasing Flood Risk and Cost of Adaptation

Floods are an important climate hazard, causing substantial human suffering and economic loss. Doocy et al.[1] estimate that globally due to floods on average per year, 19,000 persons get killed, 12,000 seriously injured, and 150,000 lose their homes. Those impacts will increase with socioeconomic development. For example, Neumann et al.[2] estimate the world population in the coastal zone to grow from 0.6 billion

*Correspondence to: jarl.kind@deltares.nl

[1]Department of Flood Risk Management, Deltares, Utrecht, The Netherlands

[2]Institute for Environmental Studies, VU University Amsterdam, Amsterdam, The Netherlands

[3]Utrecht University School of Economics, Utrecht, The Netherlands

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persons at present, to 1.0 to 1.4 billion in 2060, of which 80 percent in developing countries.

Likewise, economic flood losses are high and increasing. Average global yearly losses are US$ 15 billion, of which US$ 5 billion insured.[3] Hallegatte et al.[4] estimate that due to socioeconomic development, average annual flood damages of US$ 6 billion for the 136 largest coastal cities will increase to US$ 52 billion by 2050. Adding the effects of climate change and soil subsidence, those annual damages will exceed US$ 1 trillion by 2050, if no adaptation takes place.[4]

Estimated investments to limit the impacts of floods are substantial, reaching tens of billions US$ per year. For example, Hinkel et al.[5] estimate the cost of protecting the global coastline with dikes to reach US$ 12 billion to US$ 71 billion per year by the end of the century under different IPCC climate scenarios. Narain et al.[6] estimate the global cost for coastal protection at an average of US$ 28 billion per year for 2010–2050.

Actual investments in flood risk management will depend on how policy decisions are made. This also depends on how costs and benefits of flood risk management are evaluated, which is complicated because of uncertainties in the values of present and future flood risk.

CBA, Uncertainty and Robust Decisions

Increasing risks, high costs and limited funds justify rational approaches to flood risk management, where investments are prioritized to maximize social benefits. Historically, cost-benefit analysis (CBA) is the most commonly practiced rationalization method.[7,8] CBAs often depend on probabilities for uncertain parameters to estimate values of projects' worth and to conclude whether projects are economically justifiable.[9]

For climate change, however, there are serious concerns about quantifying the uncertainties of the impacts, which is difficult or impossible. As a result, there is a growing interest in relative new, nonprobabilistic, robust decision methods, to assist in formulating adaptation strategies which reduce climate impacts and alleviate poverty, and which perform well under conditions of deep uncertainty—for which probabilities cannot reliably be estimated. Several documents provide lessons and guidance on those methods.[10–19] Still, there are good opportunities to combine the strengths of CBA and robust decision methods. See for example Lempert,[9] who proposes to assess under which conditions (scenarios) certain strategies are economically preferable over others, without *a priori* specifying the joint probability of those conditions.

CBA, Risk Assessment, Social Vulnerability and Equity

Lesser attention is being paid to another difficulty when applying CBA to flood risk management, which is the common practice of valuing benefits as the reduction of expected annual damages (EADs; e.g., Refs 20,21). This practice originates from the risk-based approach, in which risk is defined as consequence multiplied by probability.

The difficulty with this practice is that it only looks at expected monetary values. It is risk neutral since it equally values low-probability/high-consequence events and high-probability/low-consequence events when the expected value of the damage (henceforth *expected damage*) is the same. An example is event A with a probability of 1/1000 per year and damage of US$ 100,000, and event B with a probability of 1/5 per year and damage of US$ 500. This practice thus ignores risk aversion.[22–24] Neither does it relate potential flood losses to the level of household income or wealth, which are important determinants of social vulnerability (e.g., Refs 25,26) and relevant for discussions on equity. Although often called 'CBA,' this practice does not receive general support from welfare economics (e.g., Refs 27–29). It also leads to critical questions regarding the fairness of flood risk policies, as is apparent from recent debates in the UK (e.g., Refs 30–32).

The Present Study

In this study, we review the existing welfare economics literature and concepts and derive broader implications for CBAs for the reduction of climate related risks, by using flood risk management as an example. This flood context is not unique—the concepts are equally applicable to CBAs for other climate-related risks, such as storms, droughts or landslides. We promote a framework for valuing risk reduction benefits, which includes two important and often missing aspects of social welfare—risk aversion and equity (also called distributional) weights—and which directly links to social vulnerability. Its relevance for flood risk management is demonstrated in a case study, where we show that decisions based on the social welfare risk-framework—i.e., who to target, what to do, how much to invest and how to share risks?—can be very different from those based on the common practice.

CBA FOR FLOOD RISK MANAGEMENT AND THE VALUE OF MONEY

Most CBA textbooks and guidelines acknowledge the objective of CBAs to improve or maximize social welfare, which is determined by the individual well-being of all members in a society. Economists developed the concept of utility to operationalize well-being, where well-being is related to income, consumption, or wealth (all 'money'), but not in a linear way. For example, for incomes up to US$ 75,000 per person per year, Kahneman and Deaton[33] find log-linear relationships between well-being and income, which means that an additional US$ 1000 will generate double the amount of additional well-being for a person earning US$ 20,000 than for a person earning US$ 40,000. This is the well-known 'diminishing marginal utility of income.' It is illustrated in Figure 1, in which a utility function relates individual well-being to income. The function is concave, indicating that the marginal utility of income decreases. The bars illustrate that increments in well-being (*y*-axis) obtained from an equal change in income (*x*-axis), depend on the initial income level (*x*-axis).

Diminishing marginal utility of income is important for CBAs in three ways. First, in combination with the rate of pure time preference, it is an important determinant of the value of the social discount rate (the Ramsey equation, e.g., Ref 35), that is used to convert future monetary amounts to present day values. An important reason for discounting future values is the expected per capita income increase, and hence an additional dollar for a current poorer society has a higher value than for a future richer society. Second, it explains why individuals are risk averse: an additional dollar has a higher value during bad times, when income or consumption is low (e.g., because of floods) than during good times (when no floods occur). Third, it is consistent with using equity weights in CBA, where dollars for poor people receive higher values than for rich people.

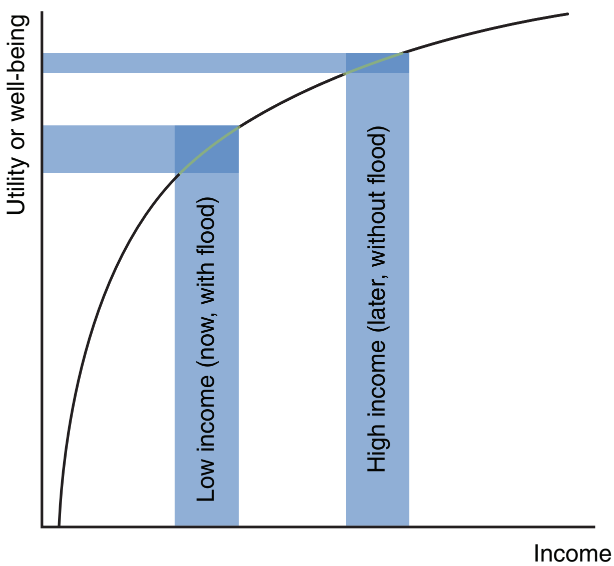

FIGURE 1 | A utility function describing the relation between income and well-being. (Reprinted with permission from Ref 34. Copyright 2014 Cambridge University Press)

Although widely acknowledged, incomplete and inconsistent application of the concept of diminishing marginal utility in CBAs for flood risk management characterizes today's practice.[27–29,36] Since the social discount rate has already been extensively discussed in other studies (e.g., Refs 37,38), we limit our review to risk aversion and equity weights which received less attention, especially in the context of CBAs for flood risk management.

Values for the Elasticity of Marginal Utility

The elasticity of marginal utility determines the curvature of the utility function. Although crucial in discussions on social discount rates, equity weights and risk aversion, there exists no agreed or universal value for this elasticity. Literature suggests different values, depending on factors such as context, culture and period. Especially when used to derive equity weights, some consider the choice of the value to be ethical, to be determined by policy makers (e.g., Refs 39,40). Suggested values tend to be in the range of 0.5–2.0, although higher values are also found (e.g., Ref 34). Average values are about or just above 1, see Table 1. This motivates why examples in this paper assume a range of 0.5–2.0 and a central value of 1.2.

RISK AVERSION AND CBA FOR FLOOD RISK MANAGEMENT

Risk Aversion and Willingness-to-Pay

Fundamental to CBA is that it is based on individuals' preferences, in which costs and benefits of goods and services are valued either in terms of how much individuals are willing to pay for a good or service, or in terms of how much people are willing to accept to give up a good or service.[48] For our purpose, the difference between willingness-to-pay and willingness-to-accept is irrelevant and we base our paper on willingness-to-pay. Risk averse people prefer certainty (e.g., receiving US$ 5) over uncertainty (e.g., 50% chance of receiving US$ 10, and 50% chance of receiving nothing), also when the expected

TABLE 1 | Values for the Elasticity of Marginal Utility

Source	Context	Value/Range
Drupp et al.[35]	Social discount rate	1.35 (standard deviation 0.85)
Pearce et al.[7]	Equity weights	0.5–1.2
Bombardini and Trebbi[41]	Risk aversion	1
Harrison and Ruström[42]	Risk aversion	0.89
Kolstad et al.[34]	Social discount rate	1–3
European Union[40]	Social discount rate	1–2
	Equity weights	by policy maker
Squire and van der Tak[43]	Equity weights	0.5–1.5
Layard et al.[44]	Utility of income	1.26 (95% confidence interval: 1.16–1.37)
Fankhauser et al.[45]	Equity weights	0.5–1.5
HM Treasury[46]	Equity weights	1 (0.7–1.5)
	Social discount rate	1
Asian Development Bank[47]	Social discount rate	1–2

value is the same (US$ 5). If people are risk averse, they are willing to protect themselves against a price that exceeds the reduction of the expected damage (Eq. (1)). The additional willingness-to-pay above the reduction of the expected damage is the risk premium. Such premiums explain for example the existence of commercially viable markets for insurance.

If a measure would eliminate risk, then

$$\textit{Willingness-to-pay for risk elimination} = \textit{expected damage} + \textit{risk premium} \tag{1}$$

If a measure would reduce risk, then the (marginal) willingness-to-pay would be equal to the reduction of the expected damages and the reduction of the risk premium. And on an annual basis, the willingness-to-pay per year for risk reduction is equal to the reduction of the EAD and the reduction of the annual risk premium.

When goods are traded in the market, the (marginal) willingness-to-pay simply equates the market price. For goods which are not traded in the market, such as air quality, public safety, but also flood protection—direct approaches using hypothetical markets are sometimes used to value benefits for individuals, for example, surveys which ask respondents directly for their willingness-to-pay for flood protection (e.g., Ref 49). However, such approaches suffer from several problems, including problems related to the hypothetical characteristics of the valuation, risk communication, risk perception and high survey costs. A recent study explaining why many individuals lack flood protection in the United States, for example, shows that people have difficulties to fully understand and evaluate flood risk, and tend to underestimate potential losses.[50] Under such conditions, the estimated benefits of flood risk management are highly uncertain when direct approaches are used.

The obvious alternative, the engineers' approach of flood risk assessments to estimate the benefits as a reduction in the expected damages, is not supported by welfare economics either, since the reduction of the risk premium is not taken into account. A 'pragmatic approach' to estimate the total benefits to individuals (i.e., willingness-to-pay) is to take the reduction of expected damage as a starting point, and use a multiplier to address the risk premium.[51,52]

Example

With an example we demonstrate the 'pragmatic approach,' in which we use utility function

$$U(C) = \frac{C^{1-\gamma}}{1-\gamma} + 4 \tag{2}$$

for $\gamma \geq 0$, $\gamma \neq 1$, and where U is the utility, C is consumption and γ is the elasticity of marginal utility of consumption.

For $\gamma = 0$, individual well-being is linear in consumption. If $\gamma \geq 0$, the utility function is concave and the additional well-being derived from an additional unit of consumption is lower when consumption increases. We use $\gamma = 1.2$. We add +4 to the utility function to prevent utility to become negative, which is not a methodological problem, but may not be intuitive. Figure 2 illustrates.

Assume that the flood probability is 0.2 per year, that without a flood, consumption is 100 and with a flood, consumption is 10. The expected consumption is $100 \times 0.8 + 10 \times 0.2 = 82$ and the expected damage $0.2 \times (100 - 10) = 18$. These values are found on the x-axis. The utility derived from consumption is on the y-axis. The utility of consumption without flooding, $U(100)$, is 2.01 and of consumption with flooding, $U(10)$, is 0.85. Expected utility is therefore $2.01 \times 0.8 + 0.85 \times 0.2 = 1.78$. The utility of the expected consumption, $U(82)$, is 1.93, which is higher than the expected utility of 1.78; the difference provides the basis for the risk premium.

Imagine a measure which eliminates flood risk. The reduction in expected damage is 18. Because of risk aversion, individuals are willing to pay a higher amount. The willingness-to-pay can be found by using the inverse utility function $U^{-1}(C)$ to determine the monetary equivalent of the expected utility of 1.78. This gives a value of 58, indicated on the x-axis. This means that the willingness-to-pay is equal to $100 - 58 = 42$ and the risk premium $42 - 18 = 24$. The total benefit is 2.3 (=42/18) times the reduction of the expected damage.

To include the risk premium, we define risk-premium multiplier $R_{WTP/ED}$ as willingness-to-pay divided by expected damage; this can be written as

$$R_{WTP/ED} = \frac{willingness\text{-}to\text{-}pay}{expected\ damage}$$

$$= \frac{1 - \left[1 + P\left\{(1-z)^{1-\gamma} - 1\right\}\right]^{1/(1-\gamma)}}{Pz} \quad (3)$$

where P is the probability of flooding and z is the fraction of consumption lost due to flooding.

$R_{WTP/ED}$ increases with the fractional loss of household consumption, z, which we refer to as 'social vulnerability.' This also means that for a given amount of damage (e.g., US$ 1000), the risk premium and hence risk reduction benefits will be higher for poorer than for richer households. The multiplier is 1 (and the risk premium zero) if the probability P is 1, in case damages for poor and rich households receive equal value. The risk premium is thus to be interpreted as the individuals' valuation of risk, a value which depends on income. However, the risk premium does not replace a procedure of equity weighting to take differences in incomes in CBAs into account (see next section).[a]

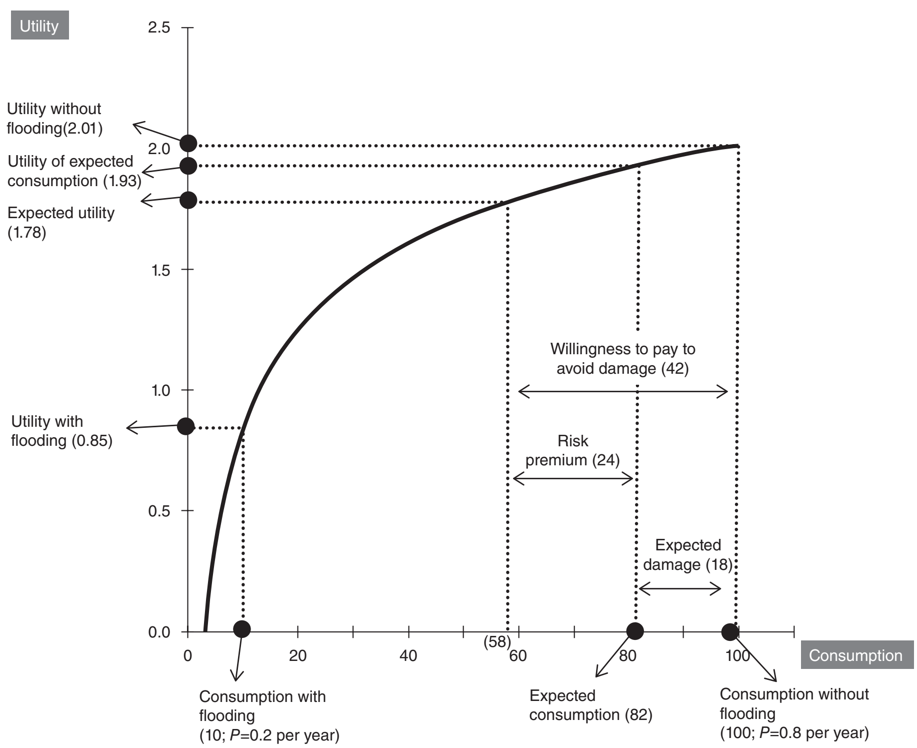

FIGURE 2 | Expected damage, risk premium and willingness-to-pay for eliminating flood losses.

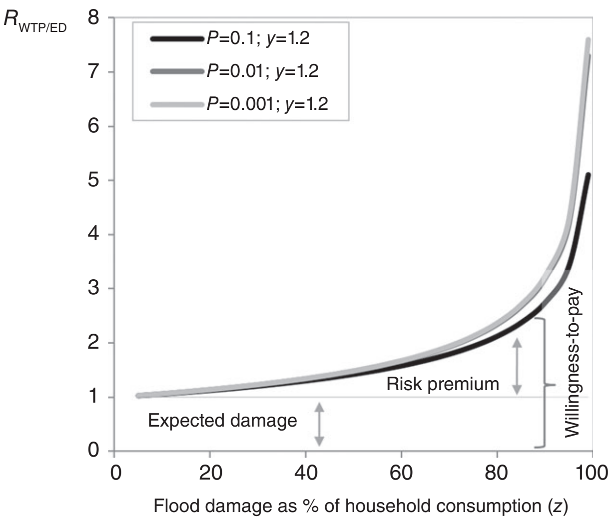

FIGURE 3 | Risk premium multiplier $R_{WTP/ED}$ as function of damage as % of household consumption (z).

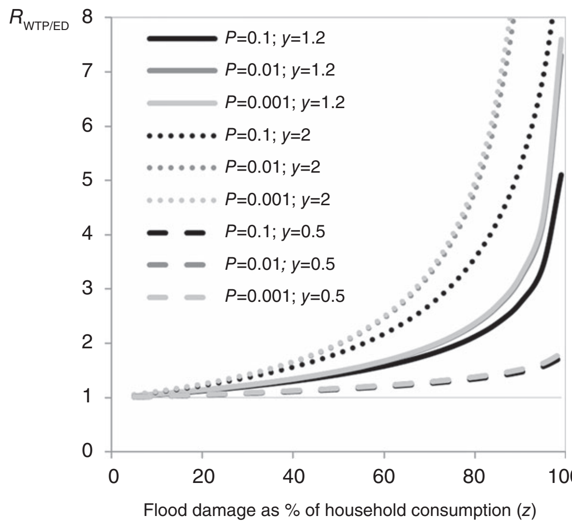

FIGURE 4 | Risk premium multiplier $R_{WTP/ED}$ for different values of flood probability P and elasticity of marginal utility γ.

In Figure 3, three curves for $R_{WTP/ED}$ are plotted for different values of P (0.1, 0.01 and 0.001) and for γ is 1.2. All curves start with a value close to 1 for small values of z. For a relative modest loss of consumption of 30% (z = 0.3), $R_{WTP/ED}$ increases to about 1.2. For z = 0.6, $R_{WTP/ED}$ increases further to about 1.6 and for z = 0.9 up to 2.7 to 3.2, with an average of 3.1. When almost all consumption is lost (z = 0.99), $R_{WTP/ED}$ increases to 5.1 up to 7.6, with an average of 6.7.

Figure 3 also shows that the sensitivity of the multiplier with respect to the flood probability (for $P \leq 0.1$) is limited, a characteristic we use later in the case study. The multiplier is very sensitive with respect to the value of the elasticity γ, as Figure 4 shows.

Special Cases

There are two special cases for the risk premium. A first case is intangible damages which cannot be compensated or redistributed, for example, loss of life, injuries or inconvenience. Those damages are incorporated in CBAs through the values of statistical life, value of statistical injury, and similar,[51–53] which are based on direct inquires of individuals' willingness-to-pay for reduced mortality (and similar) risks, and hence already include the risk premium (Eq. (1)).

Another case is that a zero (or small) risk premium should be applied if flood losses are spread over a large group, or in time, such that the effect on individual's consumption (z in Figures 3 and 4) approaches zero. This could for example be the case if the government compensates flood losses. This is known as the Arrow–Lind theorem.[54] However, if the loss to society would be too large, so that it cannot be spread without reducing consumption significantly, a risk premium should still be applied.

INCOME DISTRIBUTION AND CBA FOR FLOOD RISK MANAGEMENT

Introduction

According to Nobel prize winner Amartya Sen,[55] the economic discipline can be traced back to two different origins. The engineering origin deals with daily life issues, such as administration and logistics, and has a focus on allocative efficiency: the use of scarce resources in such way that maximizes aggregate wealth. The ethical origin is concerned with higher social objectives and focuses on individual well-being, income distribution and social welfare. In most—if not all—countries, national governments set policies which reflect those two origins, by balancing macro-economic growth objectives with social objectives such as income (re-)distribution. It is generally acknowledged that CBAs should be conducted within the contexts of those national policies (e.g., Refs 28,56–59).

However, disagreement exists whether CBAs should also be concerned with income distribution. Some argue that (government) agencies using CBAs to justify new projects or policies, should only demonstrate the allocative efficiency of the proposal, and leave concerns on income distribution to specialized agencies, or higher level government (e.g., Refs 60,61). Hence, projects should not be used to redistribute income and equity weights in CBAs should not be applied. Others argue that adjusting costs and benefits for differences in income is intrinsically consistent with welfare economics and should be accounted for in CBAs, especially if the income distribution is considered unfair, and income is not redistributed in other ways.

Methodologies to use equity weights in CBAs were developed and promoted in the past, including by organizations like the World Bank and the United Nations,[43,58] where higher weights were assigned to cost and benefits for low income groups, and lower weights for high income groups. In reality, however, equity weighted CBAs have seldom been carried out.[36,47,62]

Within the context of CBAs for policies to reduce or mitigate future climate change, there is a revival on the debate of using equity weights (e.g., Refs 34,45,63,64). This is especially true when dealing with moral concerns related to the economic valuation and aggregation of costs and damages in rich and poor countries. Maybe the clearest example is the value of statistical life, which is based on individual's willingness-to-pay for reduced mortality risk, and hence depends on income. Without correcting for income differences, lives lost in rich countries would be valued much higher than those in poor countries.[65] Also the IPCC states (with 'medium confidence') that '*(e)thical theories based on social welfare functions imply that distributional weights, which take account of the different value of money to different people, should be applied to monetary measures of benefits and harms*' and that '*(s)uch weighting contrasts with much of the practice of cost-benefit analysis*' (Ref 34, p. 211).

When the existing income distribution is considered fair, when income is redistributed through other means, or when flood damages are compensated, using equity weights in CBAs for flood risk management may not be needed. However, especially in developing countries, areas with the highest flood risks are often populated by socially vulnerable groups with relative low incomes (e.g., Refs 20,66–68), and compensation of flood damage and direct income transfers are often limited. CBAs which ignore income differences, can reach different conclusions (e.g., that investments are not justified because the damages are too low, e.g., Ref 67) compared to CBAs which do take such differences into account.

Social Welfare

When the focus of a CBA is on social welfare, an important question is how social welfare is measured. Social welfare depends on the well-being of individuals, which is expressed in terms of utility. The problem, however, is that utility is an ordinal measure, which can be used to explain individuals' rational choices,[69] but cannot be used to aggregate individual's well-being into a single measure of social welfare. There is no generally accepted solution for this problem,[57,64,70,71] and hence CBAs are not free of moral judgments.[64]

Often implicitly, most CBAs use therefore two assumptions to avoid the aggregation problem[59,70,71]: (1) a utilitarian social welfare function is used and (2) equal marginal utility of income for all individuals is assumed. Only on this basis, the change in social welfare is equal to the summed changes in individuals' net incomes, as we explain below.

Social welfare functions define social welfare, W, as function of the utility U of all people N in society, that is

$$W = W(U_1, U_2, \ldots, U_N) \tag{4}$$

The partial derivative of social welfare with respect to the utility of individual i, $(\partial W/\partial U_i)$, denotes how much weight society assigns to an increase in well-being for individual i. We use ω_{Ui} to represent the 'utility weight' for individual i. Utilitarian social welfare functions use ω_{Ui} of 1 for all individuals, while for example in egalitarian social welfare functions, ω_{Ui} decreases with income (e.g., Refs 72,73). It is generally acknowledged that the choice of those weights is subjective; different individuals and political parties will favor different weights. Most countries use utilitarian social welfare functions, in which equal increases in well-being for rich and poor persons receive equal social values.

A change in social welfare due to a change in net income (rather than utility) for different individuals, ∂Y_i, does not only depend on the utility weights, ω_{Ui}, but also on the marginal utility of income, $\partial U_i/\partial Y_i$, denoted as ω_{Yi}. We therefore write the (change in) social welfare, ∂W, as:

$$\delta W = \left(\frac{\delta W}{\delta U_1}\cdot\frac{\delta U_1}{\delta Y_1}.\delta Y_1 + \frac{\delta W}{\delta U_2}\cdot\frac{\delta U_2}{\delta Y_2}.\delta Y_2 + \ldots, + \frac{\delta W}{\delta U_N}\cdot\frac{\delta U_N}{\delta Y_N}.\delta Y_N\right) \tag{5}$$

or,

$$\delta W = (\omega_{U_i}.\omega_{Y_1}.\delta Y_1 + \omega_{U_2}\omega_{Y_2}.\delta Y_2 + \ldots, + \omega_{U_N}\omega_{Y_N}.\delta Y_N) \tag{6}$$

The second assumption for the aggregation of individual changes in income into social welfare is that all individuals have equal marginal utility of income. In this case, ω_{Yi} is the same for everyone and may be left out of (Eq. (6)). In combination with a utilitarian social welfare function, the change in social welfare ∂W is then equal to the summed changes in individuals' net incomes.

The assumption that the marginal utility of income is the same for everyone means that a dollar increase in income has the same value for all. This would be the case if the elasticity of the marginal utility is zero, or if incomes and tastes for money are more or less equal. In other cases, the assumption is not in line with welfare economics and a correction in the CBA could be made to correct for income differences.

Illustration

We illustrate how equity weights ω_{Yi} can be derived on basis of utility function

$$U(Y) = \frac{Y^{1-\gamma}}{1-\gamma} \tag{7}$$

for $\gamma \geq 0$, $\gamma \neq 1$, and where U is the utility, Y is income and γ is the elasticity of marginal utility of income.

For $\gamma > 0$, the marginal utility of income decreases. Table 2 shows as an example the increase in utility of a US$ 1 increase in income, $U(\partial Y)$, for three groups, with average income of US$ 100, high income of US$ 500 and low income of US$ 50; and with γ equal to 1.2. The incremental utility equals 0.0040 for the average income group, 0.0006 for the high income group and 0.0090 for the low income group. Equity weights ω_{Yi} are normalized as the weights attached to the increase in income for different income groups relative to that of the average income group. The result is a weight of 0.15 (0.0006/0.0040) for the high and of 2.28 (0.0090/0.0040) for the low income group.

TABLE 2 | Incremental Utility of a US$ 1 Increase in Income for Different Income Groups and Resulting Equity Weights

Income and Utility	Average Income	High Income	Low Income
Y_0	US$ 100	US$ 500	US$ 50
Y_1	US$ 101	US$ 501	US$ 51
∂Y	US$ 1	US$ 1	US$ 1
$U(Y_0)$	−1.9905	−1.4427	−2.2865
$U(Y_1)$	−1.9866	−1.4421	−2.2775
$U(\partial Y)$	0.0040	0.0006	0.0090
Equity weight ω_{Yi}	1.00	0.15	2.28

For a CBA of flood risk management, this means that a US$ 1 damage for a low income household would be valued as US$ 2.28 whereas for a high income household this would be US$ 0.15.

A full distributional analysis of the costs and benefits of projects on different income groups is often not possible. Guidelines and handbooks on CBA (e.g., Refs 7,40,47) therefore use an approximation (Eq. (8)) to determine equity weights for marginal changes in income, which is based on the first derivative of the utility function, $U'(Y) = Y^{-\gamma}$. The equity weight for a person with income Y_i for a marginal increase in income then equals:

$$\omega_{Yi} = \left(Y_i/Y_{avg}\right)^{-\gamma} \tag{8}$$

FRAMEWORKS FOR VALUING THE BENEFITS OF FLOOD RISK REDUCTION

In this section, we first describe four frameworks to value the benefits of flood risk reduction, which are based on the literature review, and which are with and without risk premiums, and with and without equity weights. Second, we review existing CBA guidelines, issued by countries and institutions to promote internal consistency in the appraisal of projects, with respect to the compliance with those frameworks. The frameworks are summarized in Table 3. All assume utilitarian social welfare functions.

The Expected Value framework characterizes today's engineers' practice in CBAs for flood risk management. Benefits are based on results of flood risk assessments and valued as the reduction in EADs. It only deals with policy concerns over allocative efficiency, in which aggregated wealth is being maximized. This framework is not well-founded in welfare economics, but could be applied if there is sufficient compensation of flood damage, or if damages are relative small compared to income and the income distribution is fair or if income is redistributed through other means. The Certainty Equivalent framework is concerned with allocative efficiency and social vulnerability, and adds the risk premium to the expected damage. This risk premium increases more than proportional with the fraction of household income lost and therewith direct relates to social vulnerability. This framework could be used

TABLE 3 | Four Frameworks to Value Benefits of Flood Risk Reduction

<table>
<tr><th></th><th colspan="3">Expected Value</th><th colspan="2">Certainty Equivalent</th><th>Equity Weighted Expected Value</th><th>Social Welfare</th></tr>
<tr><td>Policy concerns</td><td colspan="3">Allocative efficiency</td><td colspan="2">Allocative efficiency
Social vulnerability</td><td>Allocative efficiency
Equity</td><td>Allocative efficiency
Social vulnerability
Equity</td></tr>
<tr><td>Concepts used in the valuation</td><td colspan="3">Expected damage</td><td colspan="2">Expected damage
Risk premium</td><td>Expected damage
Equity weights</td><td>Expected damage
Risk premium
Equity weights</td></tr>
<tr><td>Monetary metric</td><td colspan="3">Expected Annual Damage</td><td colspan="2">Certainty Equivalent Annual Damage</td><td>Equity Weighted Expected Annual Damage</td><td>Equity Weighted Certainty Equivalent Annual Damage</td></tr>
<tr><td colspan="8">When to apply:</td></tr>
<tr><td>Damage compensation</td><td>Sufficient[1]</td><td colspan="2">Insufficient</td><td colspan="2">Insufficient</td><td>Insufficient</td><td>Insufficient</td></tr>
<tr><td>Damage as % of income</td><td></td><td colspan="2">Low</td><td colspan="2">High</td><td>Low</td><td>High</td></tr>
<tr><td>Income distribution</td><td></td><td>Fair</td><td>Unfair</td><td>Fair</td><td>Unfair</td><td>Unfair</td><td>Unfair</td></tr>
<tr><td>Other ways to redistribute income</td><td></td><td></td><td>Sufficient</td><td></td><td>Sufficient</td><td>Insufficient</td><td>Insufficient</td></tr>
</table>

[1] Unless the damage is too large for the economy as a whole. In that case, one of the other frameworks should be applied.

when compensation is insufficient, social vulnerability is high and the income distribution is fair or income is transferred through other means. Benefits are valued in terms of the certainty equivalent annual damage (CEAD). The Equity Weighted Expected Value framework incorporates concerns over equity in the flood risk assessment, by applying equity weights to the expected damages. It can be used when compensation is insufficient, social vulnerability is low and the income distribution unfair and income is not transferred through other means. Benefits are valued in terms of the equity weighted EAD (EWEAD). The Social Welfare framework integrates all three concerns over allocative efficiency, equity and social vulnerability. It is the preferred framework when no compensation exists, social vulnerability is high and the income distribution is regarded as unfair and income is not transferred through other means. Benefits are valued in terms of the equity weighted CEAD (EWCEAD).

Table 4 provides the authors' assessment of the compliance of those frameworks with CBA guidelines from different countries and organizations.

Guidelines which do not discuss risk preferences and do not discuss or do not allow equity weighting are considered to be consistent with the Expected Value framework.[74,76,79–81,83] Several guidelines however allow alternative assumptions for risk neutrality, for reasons which are in essence comparable to those for risk premiums, although none of these guidelines makes clear how the alternative assumptions on risk preferences should be implemented. We assess those guidelines to be compatible with the Certainty Equivalent framework,[40,47,62,75,78,82,84] or the Social Welfare framework. Guidelines from the UK (only Ref 21), European Union,[40,82] IPCC[34] and OECD[7] are compatible with the Social Welfare framework, since they allow for both risk aversion and equity weighting. These guidelines describe procedures for equity weighting similar to the short-cut of Eq. (8). An exception is Defra,[77] which prescribes a direct correction in the flood risk assessment, by adjusting the stage-damage function for the most vulnerable groups, in such way that their flood damages are given higher values.

CASE STUDY NEW ATLANTIS

Introduction

In this case study, we demonstrate if and how the different frameworks would lead to different CBA-based policy decisions on flood risk management. The case is hypothetical but could be any town in an urbanized delta, where floods result from storm surge, high discharges of canals or rivers, extreme rainfall, or a combination of these; where the level of flood risk varies across town and with relative rich and poor districts. We believe that this holds for many towns vulnerable to floods, for example Boston, Dhaka, Ho Chi Minh City, Jakarta, London, Miami, New Orleans, New York or Rotterdam.

TABLE 4 | Assessment of the Compliance of the Frameworks with Different CBA Guidelines

Category	Guideline	Risk Preference		Equity Weights		Framework(s)
		Default	Exemptions from Default Relevant for Flood Risk Management	Default	Reason or Remark	
Countries	Canada[74]	—		Not allowed	Controversy	EV
	Netherlands[75]	Case dependent	Except for concentrated risks, e.g., floods	Not allowed	Socially fair income distribution assumed	CE
	New Zealand[76]	Neutral		Not allowed	Complexity	EV
	United Kingdom[46]	Neutral	'Variability adjustment' when risks are large relative to income	Compulsory	Justification should be provided when not used	SW
	United Kingdom-floods[21,77]	—		Compulsory	Justification should be provided when not used	EWEV
	United States[78]	Neutral	Explanation for alternative assumption needed	Not allowed	Separate description of distributional effects	CE
	United States floods[79]	—		—		EV
	Queensland (AU)[80]	—		—		EV
IFIs and donors	ADB[47]	Neutral	Except for nonmarginal or pro-cyclical projects	Not promoted	Controversy, complexity	CE
	CARE[81]	—		—		EV
	European Union[40,82]	Neutral	Explanation for alternative assumption needed	Possible	Stakeholder matrix preferred	CE, SW
	IDB[83]	—		—		EV
	World Bank[62,84]	Neutral	Projects which are extremely large; projects affecting particular groups	Not promoted		CE
Other	IPCC[34]	Case dependent		Preferred		SW
	OECD[7]	Case dependent		Possible		SW

—, the concept is not mentioned in the guideline; CV, Certainty Equivalent framework; EV, Expected Value framework; EWEV, Equity Weighted Expected Value framework; SW, Social Welfare framework.

Our town is New Atlantis, with 70,000 inhabitants living in four districts: Central, Beach, Hills, and Canal (Figure 5). Decisions on flood risk management are made on the level of these districts. The average per capita income for the town is US$ 28,000 per year. Central is the historical centre, located on a riverbank. Flood inundation depths are limited and damages modest. Buildings are relatively old and home to people with below average income. Beach is located near the sea. Incomes are highest, buildings

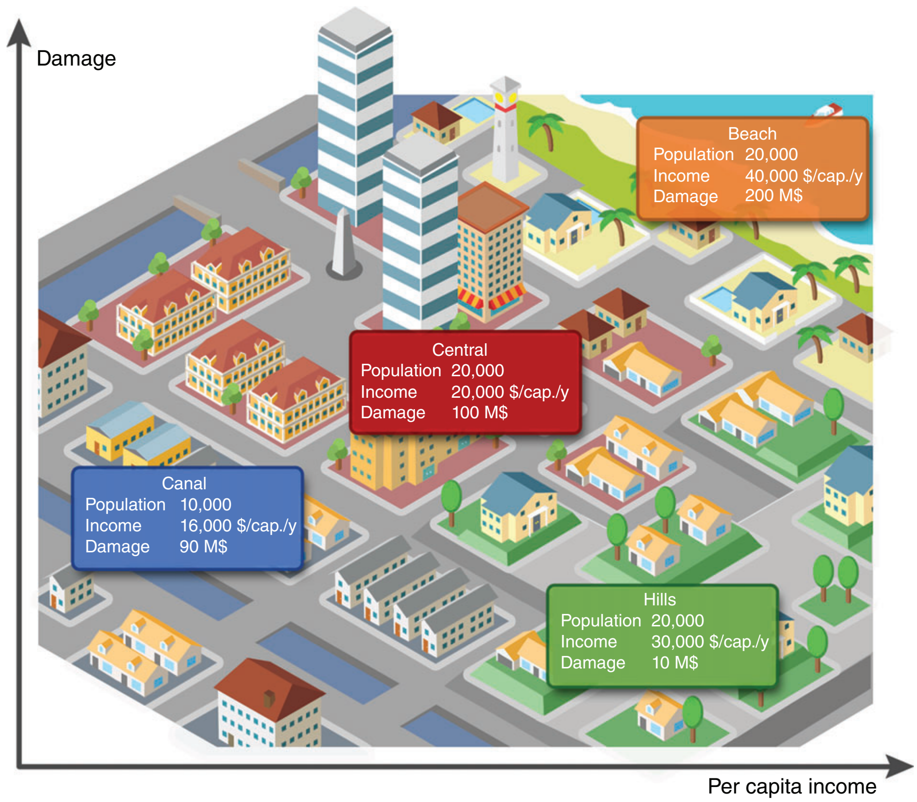

FIGURE 5 | Key figures for districts of New Atlantis.

are modern but not well protected and potential flood damage due to surge is high. Canal is a well-drained area developed in the 1950s, adjacent to the city centre. The area is inhabited by a smaller population with below average incomes. Buildings are functional and simple and damages are modest in financial terms, even with deep inundation levels. Hills is a new district in a green lushly area, located on relative higher grounds. The area is populated by households with above average incomes. The potential damage, mainly caused by pluvial floods, is limited.

To facilitate the example, flood probabilities are assumed to be 1/100 per year for all districts.

The Need for a Flood Risk Management Plan

The national government has allocated US$ 80 million to reduce flood risks in New Atlantis. The Mayor's office has started a process to formulate a plan which maximizes flood risk reduction benefits within the budget. Exploratory studies in the districts identified potential flood defense measures, to decrease flood probabilities from 1/100 to 1/200 per year (other types of measures are introduced in a later section). Costs of these measures turned out to be the same for all districts—US$ 40 million. Now the task of the Mayor is to select two districts where measures can actually be implemented. The question is, which districts should the Mayor choose in order to maximize benefits? We will show that this depends on the CBA framework.

At this point, we make a few additional assumptions which facilitate the case further. We already mentioned the assumptions of equal costs, flood probabilities and effectiveness of flood defense measures for all districts. We only consider direct, tangible household damages, which we assume to be independent of the flood probability (for a more inclusive assessment of the social welfare impacts of floods, we refer to Ref 85). We only look at one moment in time. We assume households with homogenous risk preferences. In the districts, we assume homogenous households with respect to size, income, damage and flood probability. We assume no damage compensation and no flood insurance, and further assume the risk premium to be independent of the flood probability (see the earlier section on risk aversion). We note that main conclusions of the case will hold when these assumptions are relaxed, but computations will be more complex.

Different Values of Flood Risk

Table 5 provides the different values of flood risk. Flood risk based on the EAD is highest in Beach and

TABLE 5 | Flood Risk According to Four Different Metrics

District	Population	Income	Total Income	Flood Probability	Flood Damage	Expected Annual Damage (EAD)	Social Vulnerability (z) (damage as fraction of income)	Certainty Equivalent Annual Damage (CEAD)		Equity weight	Equity Weighted Expected Annual Damage (EWEAD)		Equity Weighted Certainty Equivalent Annual Damage (EWCEAD)	
	No.	US$ per cap/year	Million US$/year	1/year	Million US$	Million US$/year		Million US$/year	As % of EAD		Million US$/year	As % of EAD	Million US$/year	As % of EAD
Beach	20,000	40,000	800	1/100	200	**2.00**	0.25	**2.36**	118	0.65	1.30	65	1.54	77
Central	20,000	20,000	400	1/100	100	**1.00**	0.25	1.18	118	1.50	**1.50**	150	**1.77**	177
Canal	10,000	16,000	160	1/100	90	0.90	0.56	**1.43**	162	1.96	**1.76**	196	**2.80**	311
Hills	20,000	30,000	600	1/100	10	0.10	0.02	0.10	100	0.92	0.09	92	0.09	93
Total	70,000	28,000	1960			4.00		5.08	127		4.65	116	6.20	155

Per district, the calculations use aggregates of income and damage, rather than damage and income per capita or household. This is justified since we assumed homogenous households within the districts. If incomes and damages per household differ within the districts, the calculations should be made on a more disaggregated level.
Two highest risk values are indicated in bold.

Central. Due to the additional risk premiums, flood risk measured by the CEAD is higher than the EAD. The largest risk premium is for Canal, where social vulnerability (z = 0.56) is highest; Beach and Canal have the highest risks based on CEAD. The EWEAD is based on the EAD, but corrects for differences in income. This leads to the highest flood risks in Central and Canal. When both risk premiums and differences in incomes are taken into account, the EWCEAD leads to further increases in flood risks for Central and Canal, which remain highest.

Four 'Optimal' Flood Risk Management Plans

The assumptions we made earlier mean that in the optimal plans districts are chosen with the highest flood risks. This can be easily verified. For example, if we take the EAD to value flood risk, if the discount rate would be 4% per year and the investment US$ 40 million, the net present value (in million US$) of a flood defense scheme, calculated over an infinite time horizon as function of the EAD, would be (1/100 – 1/200) EAD/0.04 – 40, or 12.5 EAD – 40, for all four districts. Hence, the higher the EAD, the higher the net present value of the scheme. In our example, with equal investment costs, flood probabilities and effectiveness of measures, it is thus not necessary to calculate net present values to select the districts in the optimal plans.

We formulate four basic optimal flood risk management plans, based on our frameworks, with different objectives. The objective of plan '*Damage*' is to minimize aggregated flood damages; the plan is based on the Expected Value framework with EADs. '*Vulnerability*' has an additional focus on the social vulnerability of individual households; it is based on the Certainty Equivalent framework with CEADs. In '*Income*,' aggregated flood damages are also minimized, after being adjusted for income differences; the plan is based on the Equity Weighted Expected Value framework with EWEADs. '*Welfare*' is based on the Social Welfare framework with EWCEADs, in which concerns over efficiency, social vulnerability and income distribution are integrated.

Table 6 shows the basic optimal plans, with flood defense measures in two districts.

In '*Damage*,' flood defenses are implemented where absolute damages are highest—Beach and Central. This leads to a reduction in the EAD from US$ 4.0 million per year without the plan, to US$ 2.5 million per year (2.0/2 + 1.0/2 + 0.9 + 0.1) with the plan, a benefit of US$ 1.5 million per year. In '*Vulnerability*,' flood defenses are for Beach and

TABLE 6 | Four Versions of the Basic Optimal Flood Risk Management Plans

	'Damage'	*'Vulnerability'*	*'Income'*	*'Welfare'*
Beach	Flood defense	Flood defense		
Central	Flood defense		Flood defense	Flood defense
Canal		Flood defense	Flood defense	Flood defense

Canal. The shift from Central to Canal is due to Canal's high social vulnerability (z = 0.56). The CEAD reduces from US$ 5.08 million per year to US$ 3.18 million per year (2.36/2 + 1.18 + 1.43/2 + 0.1), hence annual benefits are US$ 1.89 million. '*Income*' provides flood defenses for Central and Canal, which is due to their low incomes and hence high equity weights (1.50 and 1.96). The EWEAD reduces from US$ 4.65 million per year to US$ 3.03 million per year (1.30 + 1.50/2 + 1.76/2 + 0.09), hence benefits are US$ 1.63 million per year. '*Welfare*' also provides flood defenses for Central and Canal. The plan reduces the EWCEAD from US$ 6.20 million per year to US$ 3.92 million per year (1.54 + 1.77/2 + 2.80/2 + 0.09), hence benefits equal US$ 2.28 million per year. Note that the benefits are highest when the EWCEAD is used.

This example shows already that using risk aversion and equity weights can have significant impacts on CBA-driven conclusions, especially since it assigns higher benefits to areas where social vulnerability is high and incomes are low. It changes the optimal plan, away from Beach with high damage and high per capita income, toward Canal with lower damage and low per capita income. This is a remarkable change, considering that both potential damages and existing flood risk (measured by the traditional EAD) are more than two times higher in Beach than in Canal.

Damage Reduction, Risk Transfer and Optimal Flood Risk Management

So far, we only considered flood defense measures. We now extend the case with two additional types of measures and introduce three new versions of the optimal plans. In '*Vulnerability-2*' and '*Welfare-2*,' we introduce damage reduction as additional measure. In '*Welfare-3*,' we introduce both damage reduction and risk transfer. The optimal versions of these plans are summarized in Table 7.

In '*Vulnerability-2*,' it is optimal to provide flood defense for Beach and damage reduction for Canal. This plan was developed after the request of Canal community, given its high social vulnerability, to finance measures to reduce the consequences of floods, rather than to raise the level of flood protection, as in the original '*Vulnerability*.' We assume that within the budget of US$ 40 million, measures can be taken to reduce damage by 45%. Table 8 presents the flood risk for Canal for '*Vulnerability-2*.' It first shows that the EAD with '*Vulnerability-2*' of US$ 0.50 million per year is higher than the EAD with '*Vulnerability*' of US$ 0.45 (=0.9/2) million per year, so that CBAs based on the Expected Value framework would reject Canal's proposal. With the risk premium (in the CEAD), the benefits of damage reduction in '*Vulnerability-2*' of US$ 0.82 million (1.43–0.61) exceed the benefits of a reduction of the flood probability of US$ 0.71 million (1.43/2) by US$ 0.11 million per year. This is due to the lower social vulnerability in Canal with '*Vulnerability-2*' (z reduces from 0.56 to 0.31). CBAs based on the Certainty Equivalent framework of CEAD would accept Canal's proposal.

'*Welfare-2*' provides flood defenses for Central and damage reduction for Canal, since it simply combines the conditions under which a shift from flood defense to damage reduction occurs for Canal (from '*Vulnerability*' to '*Vulnerability-2*') and the conditions under which the shift from Beach to Central occurs (from '*Damage*' to '*Income*' to '*Welfare*').

'*Welfare-3*' provides flood defenses for Beach and Central, and damage compensation (risk transfer) for Canal. It was developed after the community of Beach offered to provide damage compensation to Canal would a flood occur, if Canal would agree to have US$ 40 million invested in flood defenses for Beach rather than damage reduction for Canal. Hence, apart from the risk transfer agreement, plan '*Damage*,' the optimal plan according to the EAD, is implemented. Table 9 shows the EWCEAD for the initial

TABLE 7 | Three Versions of Extended Optimal Flood Risk Management Plans

	'Vulnerability-2'	*'Welfare-2'*	*'Welfare-3'*
Beach	Flood defense		Flood defense
Central		Flood defense	Flood defense
Canal	Damage reduction	Damage reduction	Risk transfer

TABLE 8 | Values of Flood Risk after Implementation of Measures Which Reduce Flood Damages by 45% in Canal ('*Vulnerability-2*')

								Certainty Equivalent Annual Damage (CEAD)			Equity Weighted Expected Annual Damage (EWEAD)		Equity Weighted Certainty Equivalent Annual Damage (EWCEAD)	
District	Population No.	Income US$ per cap/year	Total Income Million US$/year	Flood Probability 1/year	Flood Damage Million US$	Expected Annual Damage (EAD) Million US$/year	Social vulnerability (z) (damage as fraction of income)	Million US$/year	As % of EAD	Equity weight	Million US$/year	As % of EAD	Million US$/year	As % of EAD
Canal	10,000	16,000	160	1/100	49.5	0.50	0.31	0.61	124	1.96	0.97	196	1.20	243

Per district, the calculations use aggregates of income and damage, rather than damage and income per capita or household. This is justified since we assumed homogenous households within the districts. If incomes and damages per household differ within the districts, the calculations should be made on a more disaggregated level.

TABLE 9 | Values of Flood Risk after Risk Transfer from Canal to Beach ('*Welfare-3*')

								Certainty Equivalent Annual Damage (CEAD)			Equity Weighted Expected Annual Damage (EWEAD)		Equity Weighted Certainty Equivalent Annual Damage (EWCEAD)	
District	Population No.	Income US$ per cap/year	Total Income Million US$/year	Flood Probability 1/year	Flood Damage Million US$	Expected Annual Damage (EAD) Million US$/year	Social vulnerability (z) (damage as fraction of income)	Million US$/year	As % of EAD	Equity weight	Million US$/year	As % of EAD	Million US$/year	As % of EAD
Beach	20,000	40,000	800	1/100	200	**2.00**	0.25	**2.36**	118	0.65	**1.30**	65	**1.54**	77
Beach Risk transfer						0.90	0.11	0.97	107	0.65	0.59	65	0.63	70
Central	20,000	20,000	400	1/100	100	**1.00**	0.25	**1.18**	118	1.50	**1.50**	150	**1.77**	177
Canal	10,000	16,000	160	1/100	90									
Hills	20,000	30,000	600	1/100	10	0.10	0.02	0.10	100	0.92	0.09	92	0.09	93
Total	70,000	28,000	1960			4.00		4.61	115		3.48	87	4.03	101

Per district, the calculations use aggregates of income and damage, rather than damage and income per capita or household. This is justified since we assumed homogenous households within the districts. If incomes and damages per household differ within the districts, the calculations should be made on a more disaggregated level.
Two highest risk values are indicated in bold.

TABLE 10 | Summary of Optimal Flood Risk Management Plans and Assessment of Those Plans on Basis of Different Metrics for Flood Risk

	'*Damage*'	'*Vulnerability*'	'*Vulnerability-2*'	'*Income*' and '*Welfare*'	'*Welfare-2*'	'*Welfare-3*'
Beach	Flood defense	Flood defense	Flood defense			Flood defense + Risk transfer from Canal
Central	Flood defense			Flood defense	Flood defense	Flood defense
Canal		Flood defense	Damage reduction	Flood defense	Damage reduction	Risk transfer to Beach
	Benefits of the optimal flood risk management plans (in US$ million per year):					
EAD	**1.50**	1.45	1.41	0.95	0.91	**1.50**
CEAD	1.77	1.89	**2.00**	1.30	1.41	**2.24**
EWEAD	1.40	1.53	1.44	**1.63**	1.54	**2.58**
EWCEAD	1.65	2.17	2.37	2.28	**2.48**	**3.83**

Benefits of optimal plans are indicated in bold.

situation, but with the risk transfer. Since the EWCEAD in Beach and Central are highest, the optimal plan would implement measures in those two districts.

Lessons from the Case

The upper part of Table 10 summarizes all plans. An optimal plan based on the EAD ('*Damage*') provides flood defenses to Beach and Central, where the reduction in the EADs is highest. By additionally taking the risk premium into account, '*Vulnerability*,' based on the CEAD, shows that it is efficient to replace the flood defense scheme for Central by a scheme for Canal, where social vulnerability is higher. '*Vulnerability-2*' shows again that due to high social vulnerability in Canal, it is optimal to replace flood defenses by damage reduction, even if this increases the value of residual flood risk as measured by the traditional EAD. '*Income*' and '*Welfare*' show that when differences in income are taken into account, the scheme in Beach, with above average per capita income, is replaced by a scheme in Central, with below average income levels. '*Welfare-3*' introduced the possibility of full damage compensation for Canal, in this example, by Beach. In this case, the optimal plan turned out to be flood defenses for Beach and Central, as in '*Damage*,' and risk transfer for Canal.

The lower part of Table 10 provides the benefits of the plans, based on the different metrics of flood risks. Apart from '*Welfare-3*,' relative rankings turn out to be very different. '*Damage*,' optimal for EAD, is the worst plan on basis of EWEAD and EWCEAD. And '*Welfare-2*,' optimal for EWCEAD, is the worst plan on basis of EAD. Damage reduction in Canal, in '*Vulnerability-2*' and '*Welfare-2*,' is optimal in terms of CEAD and EWCEAD, but not in terms of EAD and EWEAD. The important exception is '*Welfare-3*,' based on the Social Welfare framework (EWCEAD) and additionally providing risk transfer, which is optimal from all frameworks and metrics. Note that the social welfare benefits (in terms of a reduction of the EWCEAD) of the risk transfer is US$ 2.18 million per year (i.e., 3.83–1.65; compare '*Welfare-3*' with '*Damage*'), which exceed the benefits of the flood defenses of (in EWCEAD) US$ 1.65 million per year ('*Damage*'). This means that in this example, in terms of social welfare, changing the distribution of the existing risk is more valuable than reducing the risk itself.

DISCUSSION AND CONCLUSIONS

To summarize, we propose in this study three metrics for valuing the benefits of flood risk reduction, as alternative for the traditional engineering approach of measuring these benefits as the reduction in the EAD. The alternative metrics are the CEAD, the EWEAD and the EWCEAD. Those metrics include risk aversion and/or equity weigths and are well founded in welfare economics. For choosing one of those metrics in a CBA of flood risk management, one should consider (see Table 3): (1) the level of damage compensation, (2) the level of social vulnerability, (3) the fairness of the income distribution, and (4) whether income is being redistributed through other ways.

The case study clearly demonstrates that accounting for risk aversion and equity weights can significantly alter policy conclusions based on CBAs. Conclusions do not only change with respect to whom to target, but also with respect to what to do—the type of flood risk management measures which are most desirable. The case illustrates that while the traditional enginering approach (based on

EADs) is not able to assign any benefits to a risk transfer scheme, the benefits of risk transfer in a Social Welfare framework (based on EWCEADs) can outweigh the benefits of flood defenses. The case also demonstrates that if equity and social vulnerability issues are tackled through other means, optimal flood risk management can still be guided by allocative efficiency (the EAD), unless the damage is also large for the economy as a whole.

In the literature on the economics of climate change mitigation, we find shared concerns about the distribution over rich and poor countries of damages caused by climate change, and the costs for mitigation.[34] Here, ideas about integrating risk aversion and income distribution are increasingly shared. However, whereas climate mitigation requires international cooperation, coordination and planning procedures, adaptation to climate change is mostly a national, regional or local concern. Today, there exists a wide variety of CBA guidelines to support decision making on infrastructure investments, which includes infrastructure for flood risk management. If at all, those guidelines provide opposing views and recommendations on the application of equity weights and risk aversion. For example, guidelines from the OECD, the European Union and UK[7,40,46,77] favor the use of equity weights, whereas guidelines from the Asian Development Bank and the Netherlands do not favor, or explicitly prohibit equity weighting.[47,75]

The literature also suggests some additional explanations why risk aversion and equity weights are not being used in practice. There may be misconceptions about the purpose of a CBA. For example, the OECD (Ref 7, p. 283) mentions the misconception caused by using money as numeraire to measure individuals' preferences, leading to the perception that money needs to be maximized, rather than well-being (in terms of Figure 1: optimizing on the x-axis instead of on the y-axis). The complexity of incorporating basic economic principles into CBAs may be another cause,[7,62,86] while at the same time CBAs are carried out by 'do-it-yourself' economists—professionals without formal training in economics (Ref 7, pp. 286–287). Lacking objectivity in the choice of the utility functions and parameter values, such as the elasticity, are other potential causes.[28,39,47,86]

Kaufman[86] suggests a systematic failure to distinguish 'baseline uncertainty' from 'effectiveness uncertainty' to explain why risk aversion is not taken into account. With baseline uncertainty, Kaufman refers to the existing uncertainty about probabilistic outcomes—such as flood risk—which may be reduced by a project, and with effectiveness uncertainty to the extent that benefits and costs of projects are unknown, uncertainty caused by a project. Most CBA guidelines recommend by default risk neutrality with respect to effectiveness uncertainty, especially when projects are part of larger portfolios of publicly financed projects, and do not, or provide insufficient guidance regarding baseline uncertainty. The recommendation to assume risk neutrality with respect to effectiveness uncertainty is then mistakenly interpreted to assume risk neutrality with respect to baseline uncertainty (e.g., flood risks) as well.

An important argument against the use of equity weights is the argument that projects are inefficient means for redistributing income (e.g., Refs 47,60,87). More direct interventions, like lump-sum transfers, subsidies and income taxes, would be preferable for this purpose. However, redistributive instruments may incur significant costs as well, estimated up to 50% in industrialized countries.[87] In developing countries, where targeting of public funds to poorer segments of the population is often imprecise (e.g., Ref 88), the cost of direct redistributions may be even significant higher. And even if direct transfers to low income groups are feasible, in practice there may be little willingness to make transfers to such groups who often have limited political power.

Another complication is that even if CBA guidelines from international finance and donors organizations would favor the use of equity weights, it is questionable if this would be acceptable by the receiving countries, since the use of equity weights can be interpreted as donors getting involved with income policies in those countries.

Some CBA guidelines, such as in The Netherlands, do not allow equity weights, arguing that in a well-functioning democracy, existing distributions of income and wealth can be assumed to be socially desirable distributions. In this case, the social welfare function would correct for higher marginal values of income for low income groups, in such a way that the social value (i.e., the product of and ω_{Ui} and ω_{Yi}) of a dollar is the same for everyone.[75,b] Intuitively, the argument is appealing: in societies where the income distribution is considered fair (or desirable because it gives incentives for people with a high productivity to use that productivity), it would be problematic if CBAs conclude that social welfare improves if (*sec*) income is redistributed. The argument, however, implies elitists[72] (rather than neutral or egalitarian) utility weights, that is, weights which increase with income, and hence implies a departure of the use of a utilitarian social welfare function in the Netherlands. The argument that the existing income distribution in the Netherlands coincides with the socially desirable income distribution, appears to be rather weak. For example, in 2009, TNS-Nipo research indicated that the majority (60%)

of the Dutch population was in favor of a more equal income distribution.[89] However in 2015, the income distribution is more unequal than in 2009 and 2010.[90]

As we have shown in our case study, to account for risk aversion and distributional concerns, averages do not do. A possible challenge for implementation in CBAs for flood risk management is the detailed, geo-referenced data that is needed on the impacts of floods on individual household consumption or income.[85] Flood damage models are often based on average depth–damage curves and average maximum flood damages.[91] To account for risk aversion and equity weights, those should be augmented with stochastic information to account for distribution and uncertainty. Data on income distribution may be available from various sources, including census bureaus and poverty maps. The collection and processing of such data require additional efforts.

To overcome the problem of subjective choices in utility functions and values for the elasticity, a potential solution for agencies issuing CBA guidelines is to provide detailed guidance on those issues, rather than to disregard the concepts of risk aversion and equity weights at the expense of poor and socially vulnerable population segments. Such guidance could be comparable to the guidance many regulators provide with respect to the use of discount rates, the value and structure of which is often debated, but where clearly some value is better than zero or no value at all.

As a last remark, we note that CBAs based on social welfare should also take into account who pays for flood risk management, this has not been discussed in this paper. The described procedure for equity weights for benefits however is equally applicable for the cost of measures.

NOTES

[a] This is in line with Kroll and Davidovitz[92] who state that existing economic models fail to distinguish risk aversion from inequality aversion. In this paper, we use expected utility theory in the context of deriving individuals' willingness-to-pay. We propose additionally using equity weighting for aggregating willingness-to-pay into social welfare.

[b] In climate-economics models, used to recommend optimal global climate change mitigation strategies, Negishi weights are often used for ω_{Ui} which freeze the current global income distribution.[64] In the optimal mitigation strategy, Negishi weights are equal to the reciprocal of ω_{Yi} and hence increase with income, which means that higher values are attached to incremental well-being for richer countries. Without Negishi weights, the models would recommend large scale income transfers from rich to poor countries, a recommendation which could be politically infeasible and is hence not allowed for in the model. Negishi weights constrain the models to recommend such solutions. In the reviewed literature and to our best knowledge, Negishi weights are not used or recommended in CBAs for national or local climate adaptation. Rather, adaptation CBAs (like those for flood risk management) are mostly used to appraise proposed strategies or projects. Part of these can be income redistribution, depending on political feasibility. Unlike mitigation, there is no need for CBAs for national climate adaptation projects to constrain the social welfare function to prevent an optimal yet politically infeasible redistribution of income.

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