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Holistic planning of human, water, and environmental impacts for regional flood management: A case study of aging dam infrastructure

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Abstract. Urbanization and climate change have challenged the structural integrity of flood-control dams through increased storage requirements and internal water pressures. Many existing dams are aging and have been classified as deficient or having potential for life-threatening floods in the event of failure, thereby necessitating rapid and innovative mitigation strategies (e.g., optimized timing of releases, emergency warning systems, property buyouts, additional storage, diversion levees, underground tunnels). Such alternatives are often screened primarily through a cost-benefit analysis (CBA), where measures of flood-risk reduction are quantified according to inundation bounds and implementation costs. Secondary impacts associated with dam-induced flooding, such as environmental triggers (e.g., toxic pollutant releases, wastewater dispersion, soil erosion, habitat disruption) or social vulnerabilities (e.g., medical needs, language barriers, reinforced poverty, housing challenges), are often included at the screening stage as a series of narratives and are therefore largely indeterminant when ranking alternative strategies. This tendency to screen mitigation strategies through the lens of flood inundation may prioritize solutions with strong hydrological benefits while minimizing additional impacts associated with widespread flooding. To address this gap, we compare a reservoir mitigation strategy using traditional CBA metrics with composite socio-environmental risks through geospatial multi-criteria decision analysis (MCDA) and scenario-based hydrologic/hydraulic modelling. We demonstrate a case study of alternative mitigation options associated with the Addicks and Barker Reservoirs in Houston, Texas, USA under Hurricane Harvey rainfall conditions and compare performance outcomes between the traditional CBA approach and the spatial MCDA approach. This study illustrates how preferred flood management strategies may shift when hydrologic outputs are integrated explicitly with socio-environmental factors at the preliminary screening stage. By leveraging the strengths of composite risk indicators and simplified spatial overlay methods, the MCDA framework aids decision-makers in visualizing multi-functional benefits from disparate mitigation options and provides an additional layer of information for optimizing the system.

1 Introduction

A flood-control dam is an engineered structure that mitigates flood risk by storing a large volume of stormwater and then systematically releasing flows through timed operations to minimize downstream impacts. In the United States alone, there are over 91,000 artificial dams, including various flood-control reservoirs, recreational lakes, water supply resources, and hydropower facilities, many of which were constructed with earthen materials following the U.S. Flood Control Act of 1936 (Arnold, 1988; ASCE, 2021). If a flood-control dam overtops or fails completely, known as a breach, catastrophic amounts of uncontrolled water are released into the surrounding area, posing significant risks of property damage and loss of life. Currently, over one-third of the dams within the United States have been classified as 'Significant Hazard Potential', 'High Hazard Potential', or completely 'Deficient', according to the level of structural integrity and the severity of consequences in the event of a breach (ASCE, 2017); thus, the impaired infrastructure systems must be strategically managed to reduce the risk of widespread flooding.

Ongoing research has acknowledged the interdependencies between flood-control dams and compound impacts, where multiple types of physical, environmental, and anthropogenic processes interact within the system to intensify disturbances (Aghakouchak et al., 2020; Huang et al., 2019). For example, reservoir flooding may drive the distribution of sediment and toxic pollutants throughout the environment, negatively impacting ecosystems and human health (Raymond et al., 2020; Zhao et al., 2017). Floods also perpetuate social inequalities by disproportionately impacting vulnerable populations and exacerbating conditions in areas with limited resources for recovery (Fothergill and Peek, 2004). The capacity of a region to address flood risk is contingent on relationships between various co-evolving processes, which are simultaneously shaped by the long-term flood control strategies applied to the region (Sung et al., 2018). To limit such adverse impacts from flood-control reservoirs, there is a need to better understand how socio-environmental properties are connected and interact with hydrological conditions. However, most preliminary flood management frameworks for large-scale infrastructure prioritize economic impacts over socio-environmental concerns, with the latter being difficult to define and summarize numerically (Dassanayake et al., 2015; Werritty et al., 2007).

For example, in recent dam modification studies conducted by the United States Army Corps of Engineers (USACE), mitigation options included structural measures (e.g., additional reservoir storage, levees, tunnels, channel improvements, spillways) as well as non-structural adaptation approaches (e.g., community buyouts, optimized timing of releases, flood warning systems, public outreach, evacuation planning) (USACE, 2019b, 2020, 2021). Preliminary dam modification studies conducted by the USACE employ a cost-benefit analysis (CBA) to refine numerous mitigation options into a focused array of alternatives for further investigation. In flood management, a CBA framework is used to rapidly screen the applicability of many alternatives according to their proposed benefits (i.e., reduction in flood inundation area) and total costs (i.e., implementation and maintenance costs) (Brouwer and Van Ek, 2004). The flood-reduction benefits are typically analysed with hydrologic and hydraulic models that do not integrate environmental or social impacts. Instead, socio-environmental considerations are loosely considered into the early screening stage using qualitative descriptions and generalized narratives, while the CBA is relied upon for quantitative trade-offs (see **Sect. 3.2**) (Dassanayake et al., 2015). In doing so, many CBA-based studies ignore or minimize the intangible costs associated with complex social and environmental losses, due largely to their complex nature in valuation (Dassanayake et al., 2015; Hawley et al., 2012; Scussolini et al., 2017).

As such, we necessitate further effort toward integrating robust hydrological models with socio-environmental datasets within flood management. Stakeholders with a vested interest in flood-control strategies are gaining increased access to high-resolution datasets for defining such intangible indicators of risk. By quantifying and integrating multiple factors associated with flood risk (mostly non-monetary), stakeholders are increasingly able to justify courses of action that may oppose the status quo. The effort to integrate MCDA into GIS has been instrumental for developing the paradigm of spatial decision support, in which GIS technology is made available directly to decision-makers for policy or scenario development (Malczewski, 2006). GIS-based MCDA assigns weights to the criteria and exposes the geography of disparate characteristics under different scenarios using aggregation methods and hierarchical structuring (Fernandez et al., 2016). In GIS-based MCDA, the model is formulated such that all variables have the same physical dimension, although they are measured in different units, using the 'additive utility' assumption (Kabir et al., 2014).

In the context of flood management, spatial MCDAs have been used to evaluate the net impact of mitigation measures, often described in terms of flood extents, (e.g., Fernandez et al., 2016; Hajkowicz and Collins, 2007; De Brito and Evers, 2016),. However, many such spatial MCDAs have not included robust representation of inter-disciplinary variables from the social and environmental sciences (De Brito and Evers, 2016; Fernandez et al., 2016; Malczewski, 2006; Meyer et al., 2009). MCDA studies for flood-control dams have primarily focused on optimization of operations for existing infrastructure (e.g., the timing associated with storage and release of flows) and not the planning of new structures (Fu et al., 2013; Fu, 2008; Labadie, 2004; Teegavarapu et al., 2013; Zamarrón-Mieza et al., 2017). As such, the extension of spatial MCDA to consider large-scale mitigation of flood-control dams is a largely undeveloped area of research (De Brito and Evers, 2016; Zamarrón-Mieza et al., 2017). There are few approaches generally available for the application of spatial MCDA in the social vulnerability assessment to flood risk (e.g., (Kienberger et al., 2009), (Scheuer et al., 2011), (Hadipour et al., 2020)). Such studies within the hydrological literature have excluded robust stormwater modelling in lieu of simplified spatial data overlay techniques for identifying areas of flood exposure (e.g., Kandakoglu et al. (2019), Meerow and Newell (2017), Rincón et al. (2018)). Since GIS-based MCDA is a rather simplified approach to data integration, using streamlined methods for assessing flood exposure may seem intuitive. However, as demonstrated throughout this study, the complex interactions between dam-influenced watersheds during extreme events necessitates a detailed understanding of the hydrological system through well-established modelling techniques.

Indeed, given the large costs associated with new dam infrastructure, decision-makers already employ robust hydro-dynamic modelling at the early screening stage to ensure that the system is adequately understood from a drainage standpoint (e.g., USACE (2013a, 2015, 2021). Reliable HEC-HMS/HEC-RAS models throughout the United States are extremely common (e.g., HCFCD (2019)) due to the necessity of maintaining such models for federal flood insurance mapping and access to relevant funding sources by municipal agencies. Transitioning from a primary focus on flood inundation to holistic

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risk, beyond the use of simplified narratives and quantitative assessments for socio-environmental impacts, is presently lacking within the mainstream flood management community. This study demonstrates how access to high-resolution geospatial datasets and a simplified SAW overlay approach may be seemingly combined with the existing emphasis on HEC-HMS/HEC-RAS modelling to better understand the relationships between mitigation alternatives and holistic flood risk.

To be used at the screening level, such a framework should be practical and intuitive for a broad range of decision-makers using readily-accessible data and common modelling applications. By combining MCDA with HEC-HMS/HEC-RAS inundation outputs, which are the primary modelling schemes used in USACE reservoir planning (USACE, 2016), we highlight how standard screening studies may be expanded using programs that are familiar to reservoir decision-makers. We extend the popular MCDA framework to not only improve flood control policy associated with dam infrastructure but also to elucidate how complex engineered solutions impact the tripartite coupling of human-water-environmental systems in an urban setting. We discuss how alternative dam management strategies may impact the surrounding community and how socio-environmental factors may compound the overall impacts associated with watershed systems during extreme event conditions. By including the weight of such factors, community values are incorporated, and stakeholders can visualize how local priorities translate into socio-environmental impacts, thereby shaping management through data-informed metrics.

2 Methodology & Case Study

The approach presented here is rooted in the concept of spatial risk, where risk is the areal product of flood exposure (i.e., location of flood occurrence) and adverse impact, defined as the degree of exposed hazards and vulnerabilities associated with flooding. While numerous definitions of risk abound throughout the literature, we adopted the general concepts described by Kron (2005), defined in **Eq. 1**, to translate social and environmental challenges into spatial indices for flood management. Here, vulnerability describes the degree of susceptibility, or disadvantage, a given locale may experience from flooding. Hazard represents a shock that may be triggered by flooding, and which poses a negative consequence to regional health. Together, vulnerability and hazard determines the extent to which flood exposure constitutes a threat by adversely impacting local civilizations and ecosystems (Cabrera and Lee, 2020).

$$Risk = Exposure \cap \sum(Vulnerability, Hazard) \tag{1}$$

Numerous spatial hazards and co-occurring vulnerabilities were present throughout the ABRS inter-linked watershed system during Hurricane Harvey, as depicted in **Fig. 1** (further described in **Sect 2.1.3**). When the ABRS reservoirs were released at unprecedented levels, downstream flooding triggered various social and environmental factors, resulting in compound damages throughout the system. The MCDA framework, presented in **Fig. 2**, amalgamates flood exposure, vulnerability, and hazard into a spatial representation of total risk, thereby allowing for systematic ranking of alternatives. Stakeholder-derived weights were obtained using the Analytical Hierarchy Process (AHP), which is a common decision-making technique for deriving the relative priority of disparate criteria according to a hierarchical aggregation of stakeholder responses. Within MCDA, the AHP has been widely used to weight criteria using pairwise comparison, where stakeholders

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are presented with a matrix of all possible criteria pairs and are asked to identify preference using a nine-point scale (Panjwani et al., 2019). The eigenvalue method was used to compute relative criteria weights for each stakeholder response matrix, which were then aggregated across the full participant cohort to derive average group weightings (Saaty, 2002). Flood inundation (i.e., *exposure*) was estimated using standard drainage models (i.e., HEC-HMS, HEC-RAS) and hydraulic geometries for eight alternative mitigation strategies presented by the USACE (2020) screening analysis for the ABRS system.

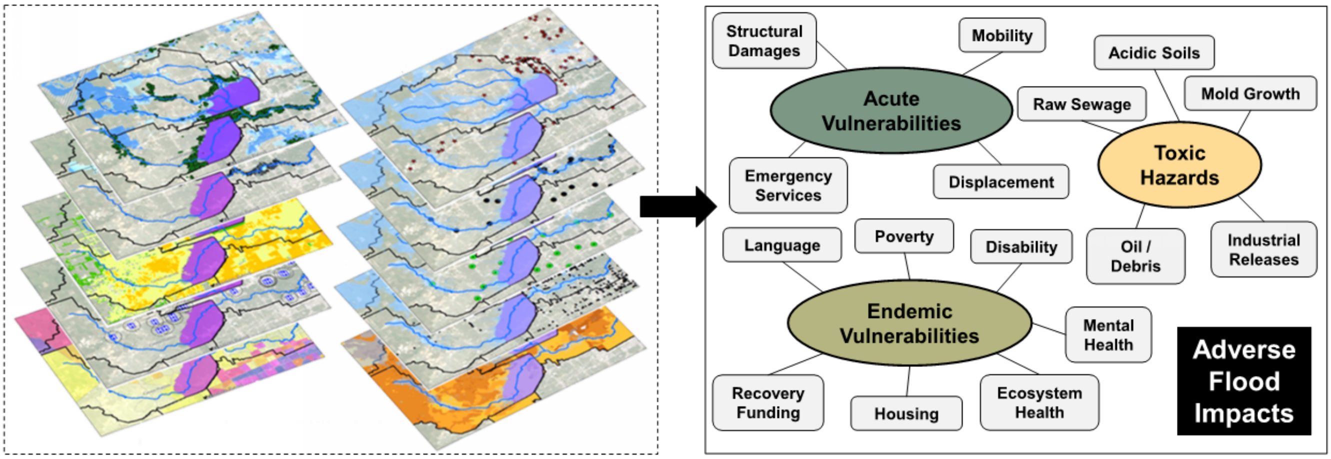

Figure 1. Geospatial data layering for adverse socioenvironmental flood impacts, comprising a mixture of local hazards and vulnerabilities associated with Hurricane Harvey flooding in the ABRS system.

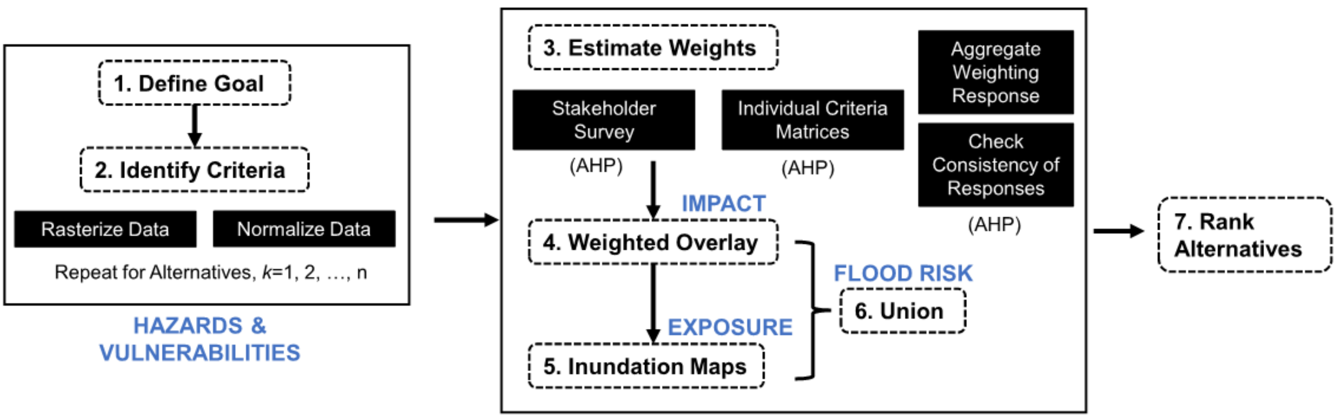

Figure 2. Spatial MCDA workflow for reservoir case study mitigation alternatives.

2.1 Case Study Background

Urbanization and climate change have amplified water pressures within aging dams, which are not equipped to handle intense increases in flow. Such prospects were evidenced by the Addicks and Barker Reservoir System (ABRS), a pair of earthen dams that were originally built in the 1940s in a largely unpopulated region of Houston, Texas, USA. As local development increased, the ABRS exhibited various structural deficiencies and were classified in 2010 as 'Level 1 – Urgent & Compelling (Unsafe)' dams due to an extremely high risk of impending failure (BMI, 2013; USACE, 2010). During Hurricane Harvey

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(2017), the ABRS system was challenged by unprecedented amounts of rainfall and large volumes of overflow from an upstream watershed divide, resulting in emergency-induced stormwater releases and widespread flooding (HCFCD, 2020; USACE, 2017). The deluge persisted for several weeks, damaging thousands of homes and businesses, and adversely impacting vulnerable populations (e.g., uninsured neighborhoods, low-income households, people with disabilities). The flood waters also triggered distribution of various toxic pollutants throughout the environment, resulting in long-term health challenges and environmental consequences (Raymond et al., 2020; Zhao et al., 2017). Such socio-environmental impacts represent a holistic severity of adverse consequences associated reservoir-induced flooding, thereby exacerbating the total damages realized by a particular storm event (De Brito and Evers, 2016). While these issues have been studied at-large as individual occurrences, there exists a limited understanding of the interactions and feedbacks between them. As such, the practical integration of environmental and social factors into mitigation planning for regional flood risk, including high-risk dam systems, has not reached full potential (Girons Lopez et al., 2017).

The ABRS is a large-scale earthen dam system built in the late 1940s and operated by the United States Army Corps of Engineers (USACE). The ABRS comprises several watersheds in the Houston region that are hydrologically-connected via the Addicks and Barker flood management dams and their downstream releases into Buffalo Bayou, as well as cross-basin overflow from Cypress Creek that enters the reservoir watersheds during extreme events. The Addicks and Barker reservoirs have been classified as two of the most-hazardous and deficient dams in the United States due to their aging structural components and ongoing urbanization in the surrounding area (USACE, 2010). (Reference **Appendices A-B** for further details regarding the complex history and hydrologic properties of the ABRS system). Here, we investigate several alternative mitigation solutions for addressing reservoir-induced flooding within the ABRS system in Houston, Texas, USA under Hurricane Harvey rainfall conditions. We consider the case study of reservoir-induced flooding during Hurricane Harvey as an opportunity to further investigate hydrologic complexities associated with dam management and how these processes impact the surrounding community during extreme event conditions. Unique hydrological phenomena, such as cross-basin overflow and emergency-induced reservoir releases, are integrated into a GIS-based decision-making framework to quantify the magnitude of environmental and social risk within flood management.

2.1.1 Alternative Mitigation Strategies

The extent of flood damages during Hurricane Harvey inspired widespread discussions regarding regional drainage with specific attention to mitigation of the ABRS reservoirs (USACE, 2020). In 2020, an interim feasibility report was released where eight mitigation strategies were screened on the basis of CBA and narrowed to a focused array of five alternatives for further analysis (USACE, 2020, Tables 3 & 9). Alternative mitigation strategies identified by the USACE included dredging a large underground tunnel, adding an additional reservoir to capture cross-basin overflow, widening receiving channels, increasing storage capacity, and buying-out properties. Such strategies are reminiscent of the original 1940 project plan, where additional open space, storage, and routing improvements provided an added layer of protection but were later abandoned due to limitations in funding and land availability (see **Appendix A**).

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Alternative **A1** was included as a baseline strategy for comparison against the various mitigation alternatives. Two of the structural alternatives included adding an additional reservoir to capture cross-basin overflow from Cypress Creek (**A2**) and diverting water from Cypress Creek through a diversion levee at the Addicks-Cypress watershed divide (**A4**). Non-structural solutions included a governmental buy-out of properties within the reservoir pooling level (**A3** in the Addicks watershed, and **A5** in the Buffalo Bayou watershed). Alternative **A6** was included as a hybrid approach for increasing storage capacity within the existing ABRS footprint (structural) and optimizing the timing of releases into Buffalo Bayou (non-structural). [Note: Alternative A6 in the USACE (2020) report only considered increased system storage by expanding capacity in the ABRS reservoir footprints. Here, we combined increased storage with the potential for optimizing downstream releases to accommodate the influence of dam operations on the overall hydrology during an extreme event, further described in the Supplementary Information, *Text S1-S2*]. To increase overall conveyance capacity, additional structural alternatives included widening and deepening the receiving channel (**A7**) or drilling an underground tunnel to route water away from the reservoirs and directly to Galveston Bay (**A8**). These alternative mitigation strategies are depicted spatially in **Fig. 3**.

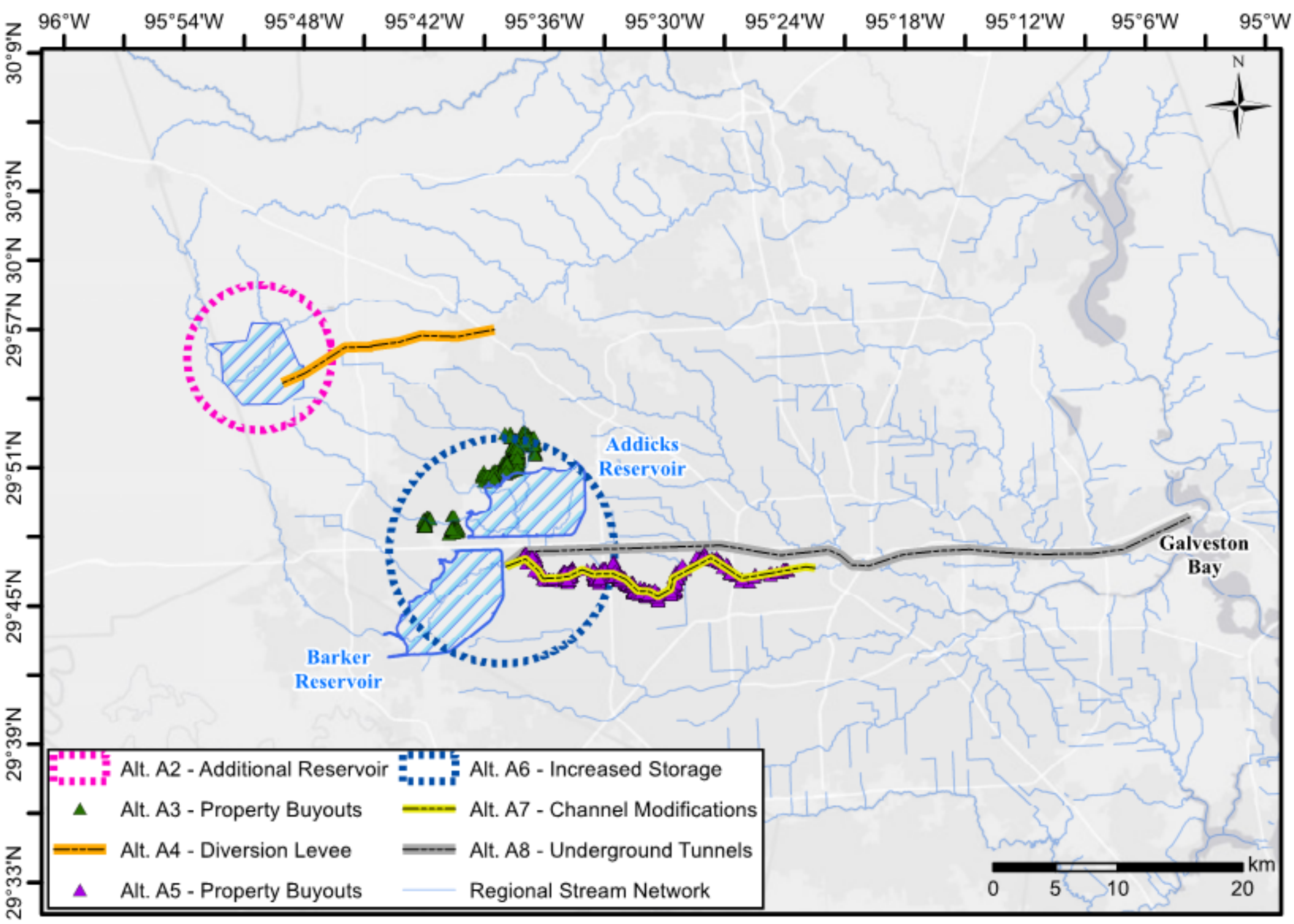

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Figure 3: Addicks and Barker Reservoir System (ABRS) of regional inter-connected watersheds in Houston, Texas, USA, including spatial depictions of proposed alternative mitigation strategies in the interim dam modification feasibility study (USACE, 2020), Alternatives A1-A8. Alternatives A2-A4 correspond to mitigation options within the Addicks watershed, while Alternatives A5-A8 include mitigation for the Buffalo Bayou watershed. *[Note: Geospatial sources for the alternative strategies include: A2, A7, A8 (USACE / Community Impact Newspaper, 2020); A4 (USACE, 1940); and A3, A5 (HCFCD, 2021).]*

2.1.2 Cost-benefit Analysis

Cost-benefit analysis is the primary framework used by the USACE to evaluate the cost effectiveness of disparate water resources projects (IWR, 2009). In such studies, net costs are presented as the added measure cost (AMC) for both low- and high-estimates of total construction, real estate acquisition, and annual maintenance of the mitigation alternative over the life of the project. Net benefits are described in terms of expected annual damages (EAD), computed as the probabilistic damages associated with a specific flood event for each management plan using hydrologic and hydraulic modelling and economic data along the modelled reach (USACE, 1989). In the USACE (2020) screening report, each mitigation strategy was evaluated for overall costs and benefits and compared to the baseline scenario for the 50-year return period. A discount rate of 2.75% was used to equate monetary values over time, known as the net present value (NPV), by considering society's opportunity costs of current consumption. Cost effectiveness was then calculated using the benefit-cost ratio (BCR) (**Eq. 2**) to rank the mitigation strategies and identify which alternatives should be considered for further evaluation.

$$BCR_k = \frac{NPV_{benefits,k}}{NPV_{costs,k}}, \text{for } k = 1, 2, \ldots, 8\,. \tag{2}$$

The cost-benefit statistics from the USACE (2020) report (e.g., AMC, EAD, BCR) are summarized in **Table 1**. In the screening study, a total of eight (8) mitigation alternatives (e.g., the preliminary array) were reduced to a focused array of three (3) mitigation strategies (plus the baseline scenario) according to the CBA approach. This focused array was recommended throughout the report for further evaluation, while the remaining alternatives were discarded. It is noted that the BCR statistics were not provided for all alternatives, including the options that were removed from the preliminary array. Instead, the alternatives that were excluded from the focused array (**A3-A6**, **A8**) were screened according to a very high-level, generalized assessment of evaluative criteria, as further described below and summarized in **Table 2**.

Table 1. Summary of benefit-cost analysis statistics used in the USACE (2020) report to screen preliminary mitigation strategies into a focused array of alternatives for detailed investigation.

Mitigation Alternative (A_k)*	**A_k†**	***AMC*** *low*	***AMC*** *high*	***EAD***	***BCR***	**Focused Array**
No action, baseline scenario	A_1	N/A	N/A	$ 18.3 M	N/A	YES
Adding additional reservoir	A_2	$ 2.14 B	$ 2.88 B	$ 1.00 M	0.1	YES
Property buyouts	A_3, A_5	$ 2.30 B	$ 2.30 B	$ 500 M	/x/	YES
Diversion to adjacent watershed(s)	A_4	$ 0.25 B	$ 350 M	$ 2.80 M	/x/	NO
Increased storage in existing reservoirs	A_6	$ 1.30 B	$ 1.80 B	$ 1.60 M	/x/	NO
Improvements to receiving channel	A_7	$ 1.00 B	$ 1.25 B	$ 2.80 M	0.3	YES
Underground tunnels	A_8	$ 6.50 B	$ 12.0 B	$ 5.15 M	/x/	NO

*: As described in the USACE (2020) report; †: As described in the case study; /x/: Not provided in USACE (2020) report.

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A qualitative approach was used within the ABRS screening study to consider the magnitude of costs and adverse socio-environmental impacts among the preliminary alternatives (USACE, 2020, *Sect. 4.8*). In the screening analysis, costs were described using a 3-point scale (high, medium, or low), where magnitude was relative to the composite alternative costs in the preliminary array. Environmental concerns were represented by considering whether an alternative may adversely impact local threatened/endangered (TE) species, categorized as a binary variable (yes or no) (USACE, 2020, *Sect. 4.10*). The analysis considered social criteria by noting whether a mitigation alternative may disproportionally impact environmental-justice (EJ) populations, categorized as a binary variable (yes or no). Median values for select socio-economic variables (e.g., population, income, education levels, and race/ethnicity) were presented at the watershed-scale and compared to median socio-economic metrics for the state (Texas) and country (United States) (USACE, 2020, *Sect. 2.8*). By comparing socio-economic metrics at the watershed-level with the state- and national-level data, the report noted no relative disadvantages between the ABRS and the overall populace. A further metric of comparison was added to represent an offset in life risk associated with flooding (USACE, 2020, *Table 52*), described by USACE guidelines for incorporating risk-informed metrics into screening assessments (USACE, 2019a).

Table 2. Qualitative summary of mitigation alternatives according to their magnitude of potential impacts to threatened/endangered (TE) species, environmental justice (EJ) populations, total costs, and life risk reduction. The data in this table were used as an early screening tool in the USACE (2020) resilience study to reduce the preliminary array of mitigation options into a focused array for detailed evaluation.

A_k	Impacts to TE Species	Impacts to EJ Populations	Magnitude of Costs	Life Risk Reduced[Δ]	Focused Array
A_1	N/A	N/A	-	/x/	YES
A_2	Low	No	Moderate to High	112 to 202	YES
A_3, A_5	/x/	No	Low	1200	YES
A_4	Low	No	Low	/x/	NO
A_6	Moderate - High	No	High	/x/	NO
A_7	Moderate	No	Low	96 to 167	YES
A_8	Low - Moderate	No	High	/x/	NO

/x/: Not provided in USACE (2020) report; [Δ]: Range between night/daytime flooding scenarios.
[Note: The USACE (2020) report included additional criteria in the initial screening assessment (e.g., potential for system-wide impacts, according to hydrological and hydraulic modelling; potential for impacts to critical infrastructure; required mitigation acres on a categorical scale from low-high). However, as these criteria were incorporated into the benefit-cost analysis throughout the report, we did not include them here.]

It is unclear how the statistics in **Table 2** were used for comparing alternatives and defining the focused array, as no formal trade-offs analysis was presented in the USACE (2020) report. Rather, a brief narrative was provided for justifying how Alternatives A_4, A_6, and A_8 did not result in ideal balancing of mitigation costs and benefits. As the BCR ratios were not provided for these alternatives, we lacked a firm basis for understanding such decisions quantitatively. Instead, socio-demographics were assessed at a regional-scale and did not consider the unique spatial connections amongst social vulnerability factors. Similarly, environmental impacts were described qualitatively in terms of the habitat quality, while regional pollution hazards were largely indeterminate. This lack of CBA information within the USACE (2020) report served as the basis for our overall case study. We aimed to establish a more transparent foundation for deciding which alternatives should be considered for further analysis by leveraging high-resolution datasets and stakeholder values, in addition to cost-benefit metrics, as discussed in **Sect. 3.4**.

2.1.3 Regional Impact Factors

Flooding associated with Hurricane Harvey damaged over 154,000 homes in the greater-Houston region, of which at least 46,800 were located within the ABRS inner-connected watershed system (HCFCD, 2018). The floodwaters inundated highly industrialized regions of Houston for several days, impacting various industrial facilities, toxin disposal sites, and wastewater treatment plants. This triggered the release of over one-million gallons of environmental toxicants into the environment, many of which were known carcinogens (Miller and Craft, 2018; Ratnapradipa et al., 2018). Moreover, the diffusion of acidic soils and changes in water salinity triggered widespread ecosystem degradation (Folabi, 2018; Kiaghadi and Rifai, 2019). Studies revealed that the long-term health impacts associated with flood-dispersed pollutants were significant (Du et al., 2017; Horney et al., 2018; Kapoor et al., 2018; Schwartz et al., 2018; Stone et al., 2019), which led to an exacerbation of environmental inequalities from disparate exposure patterns (Ratnapradipa et al., 2018).

Research also highlighted various social factors that caused people to experience the effects of flooding and recovery differently, despite being impacted by the same storm. For example, Hurricane Harvey displaced many low-income populations and exacerbated the inability of residents to obtain affordable housing after one-quarter of public housing units were damaged, resulting in endemic poverty issues and long-term housing challenges (Dickerson, 2017). Moreover, the flood extents disproportionally impacted federally-subsidized housing units compared with wealthier neighbourhoods (Chakraborty et al., 2021). Studies also revealed a disproportionate exposure to flooding for disabled individuals, including those with ambulatory and cognitive difficulties (Chakraborty et al., 2019). Mobility issues associated with flooding reduced access to emergency services, which posed additional hazards to vulnerable populations, and led to several fatalities during Hurricane Harvey (Bodenreider et al., 2019; Jonkman et al., 2018). Studies also demonstrated an increased likelihood for marginalized groups to experience post-traumatic stress following the flood event (Flores et al., 2020; Griego et al., 2020). Language and cultural barriers were shown to impact how residents were able to prepare for the storm, evacuate, and obtain post-disaster funding for recovery efforts (Ratnapradipa et al., 2018). Moreover, less than 20% of the damaged homes during Hurricane Harvey possessed active flood insurance, as many structures were located outside of the federally-demarcated zones where insurance is voluntary (Klotzbach et al., 2018), thereby delaying flood recovery efforts and necessitating additional sources of post-disaster aid (Griego et al., 2020).

In addition to such ubiquitous hazards and vulnerabilities, community members also raised concerns about ancillary impacts associated with the USACE (2020) alternatives. Ancillary impacts are defined as adverse socio-environmental effects, observed locally, resulting from specific infrastructure decisions. For example, in considering an additional reservoir to capture cross-basin overflow (**A2**), nonprofit agencies stressed the negative connotation of disrupting prairie lands that provide natural stormwater mitigation and habitat preservation throughout the region (Arrajj, 2018; TPL, 2018). Alternatives **A3** and **A5** included relocating tens of thousands of homes within highly-established neighborhoods that have strongly resisted buyout efforts in the past (Campbell et al., 2020) and which would pose tremendous social opposition effects. Studies also showed a negative social connotation from cross-basin diversion (**A4**), as communities along Cypress Creek would face increased

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vulnerabilities (Dunbar et al., 2019). Finally, the proposed strategy of channelizing Buffalo Bayou (**A7**) revealed numerous community concerns regarding environmental habitat disruption (i.e., endangering the highly-threatened Alligator snapping turtle, Munscher et al., 2020) and diminished social amenities and recreational opportunities along the cherished natural stream (Campbell et al., 2020).

The composite impact factors associated with the ABRS system are depicted spatially in **Fig. 4**. The following sections describe how each of the impact factors were weighted by local stakeholders (**Sect. 2.2**), compared to regional flood inundation bounds (**Sect. 2.3**), and then used to derive holistic risk maps (**Sect 2.4**) for amalgamating social, environmental, and hydrological properties in the proposed framework.

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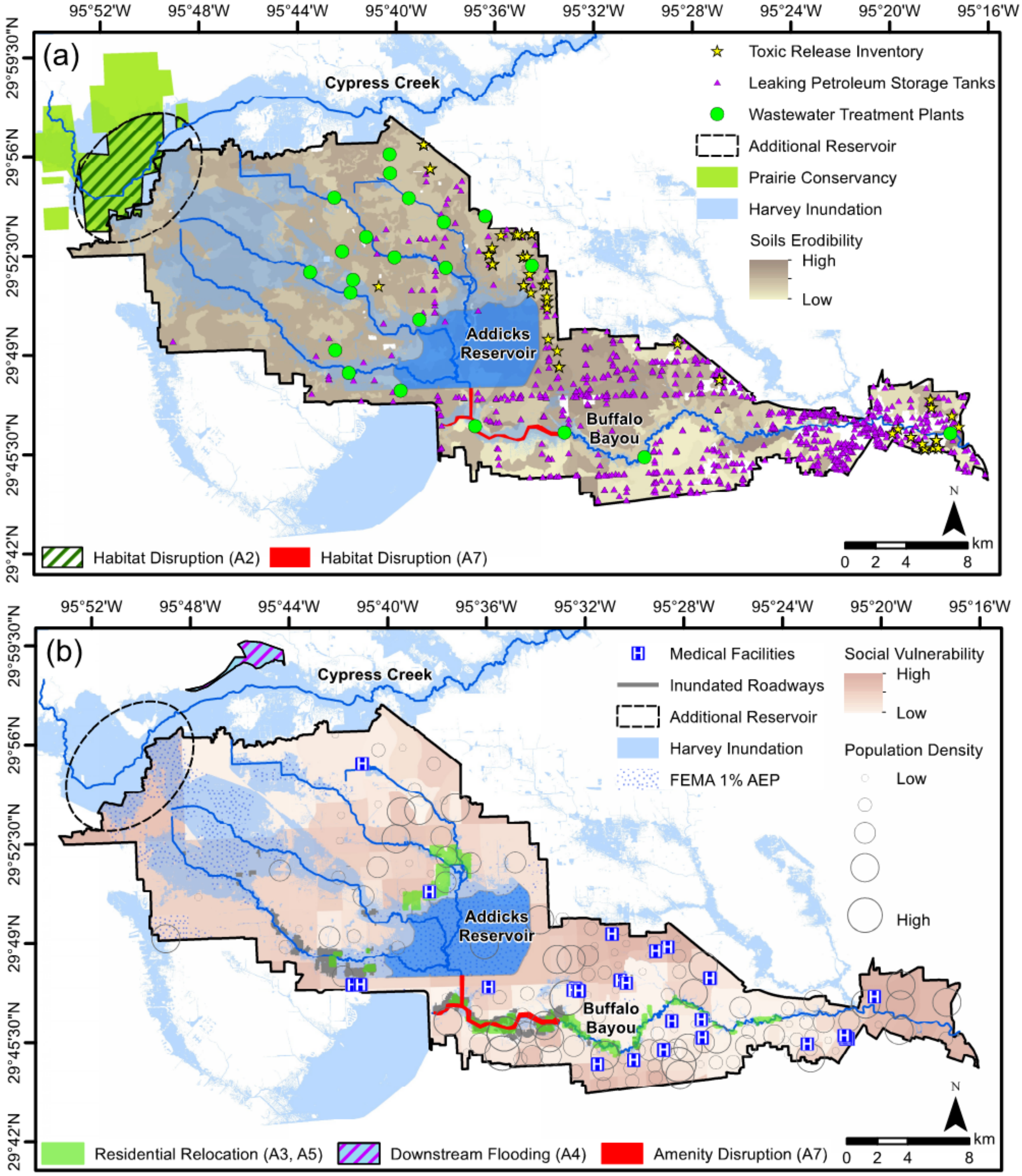

285 **Figure 4:** Composite impact factors for the ABRS watershed system in Houston, Texas, USA, depicted for mitigation alternatives $A_{1\text{-}8}$, for **(a)** environmental hazards and **(b)** social vulnerabilities.

2.2 AHP Preference Weighting

In following (Reddy et al., 2019), an online survey was sent to various stakeholders familiar with the ABRS system (including neighbourhood advocates, environmental leaders, engineers, and policy-makers) to identify the relative importance of social and environmental criteria according to local values. The questionnaire was structured using a standard Likert-scale (i.e., a qualitative continuum from least to most important) and converted into AHP format using **Table 3**. The respondents were asked to consider various environmental and social factors associated with local reservoir mitigation and to select the level of importance for each criterion when viewed holistically.

Table 3: Conversion of Likert-scale questionnaire responses (qualitative) to Saaty's 9-point scale (quantitative).

Likert-scale Rating	Saaty's 9-Point Scale
Least Important	1
Significantly Less Important	2
Moderately Less Important	3
Slightly Less Important	4
Neutral	5
Slightly More Important	6
Moderately More Important	7
Significantly More Important	8
Most Important	9

Individual AHP matrices were created from the survey responses using pairwise comparisons between all possible criteria factors for each stakeholder and mitigation alternative. The individual matrices were normalized to tabulate relative criteria weights and then averaged to obtain an aggregate decision matrix, according to

$$W_{jk} = \frac{\sum_{r=1}^{n} w_{jk}^{r}}{n}, \quad (3)$$

where W_{jk} is the aggregate weighting for criteria (j) in mitigation alternative (k), and w_{jk} is the individual decision matrix (j x j) for respondent r with n total respondents.

The reliability of the stakeholder judgments was then validated using the AHP consistency ratio (CR), where $CR < 0.10$ suggests the matrices comprise consistent weighting valuations, calculated by

$$CR = \frac{CI}{RI};\ CI = \frac{(\lambda_{max} - j)}{(j-1)}, \quad (4)$$

where CI is a consistency index, λ_{max} is the largest eigenvalue in the matrix (j x j), and RI is a random index representing the average CI from many matrices of order j, tabulated by Saaty (1980).

2.3 Hydraulic & Hydrologic Modelling

Hydraulic geometries for each of the mitigation alternatives (**A1-A8**) were modelled using the HEC-HMS/HEC-RAS hydrologic and hydraulic software to replicate the assumed flood extents used in the USACE (2020) study. Baseline watershed

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models for the ABRS system were downloaded from HCFCD (2019) and calibrated to local stream gauge flows, high water marks, and high-resolution imagery obtained during Hurricane Harvey (HCFCD, 2017, 2018; NOAA, 2017b). Detailed model assumptions, parameter values, and hydrological outputs are described in the Supplementary Information and introduced here (see *Text S1-S2*). Parameterization for the HEC-HMS models was conducted with the HMS-PrePro Toolbox (Castro and Maidment, 2020) using the Curve Number method for the Addicks Watershed (*Table S1*) and the Green and Ampt method for the Buffalo Bayou watershed (*Table S2*). Multi-sensor, quality-controlled radar and rain gauge data was obtained from the National Oceanic and Atmospheric Administration (NOAA) for hourly time-series estimates encompassing Hurricane Harvey rainfall (August 24, 2017 21:00 to August 29, 2017 23:00, NOAA, 2017a), averaged over each sub-catchment, and interposed as rain gauges in the hydrological basin models for each alternative (*Fig. S1*).

The hydrological models for the ABRS system were linked by simulating diversion nodes in HEC-HMS for cross-basin overflow (*Fig. S2*), which were used as source gauges in the adjacent watersheds (*Fig. S3-S4*). Reservoir releases into the receiving channel were calibrated according to observations during Hurricane Harvey (*Table S3*) and optimized to simulate releases for Alternative A_6 (see **Appendix B** for further information about the complex timing of reservoir releases under emergency conditions). Flows from the HEC-HMS output hydrographs were used as inputs to the HEC-RAS models (*Table S4*) to derive a graphical depiction of flood inundation in each of the modeled alternatives (e.g., *Fig. S5*). The inundation boundaries were created as a conceptual estimate of spatial variation to investigate how flood mitigation strategies impact the region holistically and should not be used as a detailed representation of flooding related to the ABRS.

2.4 Spatial Weighted Overlay

2.4.1 Criteria Normalization

An inventory of criteria associated with negative impacts from reservoir-induced flooding was determined from a literature search of local factors exacerbated by Hurricane Harvey flooding within the ABRS watersheds (**Sect. 2.1.3**). A geospatial database was compiled using *ArcGIS Desktop* by digitizing all data layers into raster format and aggregating the indicators to produce a composite impact map within the study area, classified into levels from low to high impact. For each pixel in the database, all indicators were quantified such that high values represent an adverse social or environmental impact, and low values represent ideal conditions.

Since the criteria factors were measured using unique scales, the factor values must be standardized before aggregation. Each dataset was normalized using the minimum-maximum approach (Voogd, 1982) on a scale from 0 to 100, where 0 represents the total absence of potential socio-environmental impact, and 100 corresponds to the total presence of potential impact. Thus, impact varies linearly between the minimum and maximum values of each criteria factor, according to

$$e_j' = \frac{e_j - \min(e_j)}{\max(e_j) - \min(e_j)} * 100 , \quad (5)$$

where e_j' represents the normalized evaluation score, and e_j represents the grid value of each criterion (j).

2.4.2 Impact Mapping

Regional impact maps were generated by multiplying the AHP weights by the normalized evaluation score for each criteria factor and mitigation alternative. The geospatial impact layers were aggregated using the additive utility approach, such that

$$I_{k(E|S)} = \sum_{j=1}^{n} w_{jk} e_j' \,, \tag{6}$$

where $I_{k(E|S)}$ refers to the impact value of the gridded cells for each spatial map within the domain (E: environmental, S: social), n represents the total number of criteria in the domain, w_{jk} refers to the relative AHP-based weight of each criterion (j) within the mitigation alternative (k), and e_j' represents the normalized evaluation score (0 to 100).

Spatial overlay maps were created to denote potential socio-environmental impacts associated with flood inundation, which indicate the intensity of adverse effects within each pixel of land (i.e., the inverse of flood suitability maps). Each ABRS criteria factor was converted into a raster dataset and normalized on a scale from 0 to 100 (**Eq. 5**) using various spatial analysis functions, which are summarized in **Table 4** according to source, type, and scale.

Table 4. Geospatial database compiled of environmental and social impact factors associated with reservoir-induced flooding in the ABRS watersheds.

	Criteria	Data Type	ArcGIS Spatial Analysis Function	Low Value	High Value	Primary Data Source
Envr.	Toxic Release Inventory	Point	*Euclidean Distance*	18	100	EPA, 2016
	Leaking Petroleum Tanks	Point	*Euclidean Distance*	0	100	TCEQ, 2019
	Wastewater Treatment	Point	*Euclidean Distance*	53.6	100	COH, 2019
	Soil Erodibility	Raster	*Raster Calculator*	18	52	USDA, 2019
	Habitat Disruption	Polygon	*Polygon to Raster*	No=0	Yes=100	TPL, 2018
Social	Medical Facilities	Point	*Euclidean Distance*	0	49.2	COH, 2019
	Population Density	Raster	*Raster Calculator*	0	97.5	USCB, 2020
	Inundated Roadway	Polyline	*Buffer*	No=0	Yes=100	USCB, 2019
	Flood Insurance	Polygon	*Polygon to Raster*	No=100	Yes=0	FEMA, 2019
	Residential Relocation	Polygon	*Polygon to Raster*	No=0	Yes=100	USACE, 2020
	Downstream Flooding	Polygon	*Polygon to Raster*	No=0	Yes=100	Dunbar et al., 2019
	Amenity Disruption	Polygon	*Polygon to Raster*	No=0	Yes=100	USGS, 2016
	Social Vulnerability (SVI)*	Raster	*Raster Calculator*	4.1	96.3	CDC, 2016

Note: All data layers were projected to the NAD 1983 2011, State Plane South Central coordinate system.
*The SVI contains an aggregated indicator that measures a community's resilience to natural disasters according to census data across four themes (i.e., socio-economic status, household composition, race/ethnicity/language, housing/transportation).

The raster datasets used in this case study (i.e., soil erodibility, population density, and social vulnerability) were already normalized on a scale of 0-100 by their respective sources and were thus simply clipped to the extents of the ABRS study area. Point-layers were converted to rasters using the *ArcGIS Euclidean Distance* function to define human proximity to social and environmental point layers. Euclidean distances convert feature layers into gridded datasets by assigning a value to each cell that indicates the distance of that cell to the nearest criterion, thus standardizing space and creating hotspots of adverse socio-environmental consequences (Chainey and Ratcliffe, 2013; Dutta et al., 2021). Since distance to a point layer is not constrained

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to the watershed extents where a person may be located, the Euclidean distance function was applied using geospatial points within all watersheds adjacent to the ABRS system, normalized per **Eq. 5**, and then clipped to the case study area. An example of hotspot maps created using the Euclidean distance function is shown in *Fig. S6*.

Polygon-layers were converted to rasters using the ArcGIS *Polygon to Raster* function. For most of these layers (i.e., habitat/amenity disruption, residential relocation, downstream flooding), the cells that represented the data source boundary were valued at 100, while all other data cells within the study area were defined as 0. The flood insurance layer was quantified such that areas of voluntary insurance were defined as high impact (100), since most of the flooded homes during Hurricane Harvey lacked mandatory FEMA insurance (Dickerson, 2017), and the remaining cells were valued at 0. The polyline-layer (i.e., inundated roadways) was converted into a raster by buffering each road within the Hurricane Harvey inundation boundary by 10 feet, corresponding to an average roadway width of 20 feet (COH, 2021), such that areas of roadway inundation were valued as high-impact. A pixel resolution of 30-meters was applied to all data layers, corresponding to the finest spatial unit of the composite geodatabase.

2.4.3 Risk Mapping

Flood risk functions were obtained for each alternative using aggregate zonal statistics (ArcGIS *Zonal Statistics as table* tool), indicating the intensity of adverse impacts that would be triggered by flood inundation within a spatial parcel. Flood inundation masks were applied to the composite indices, resulting in an overlay of various social and environmental thematic layers and flood exposure according to the drainage characteristics of each mitigation alternative. Thus, the total risk included a hybrid combination of environmental, hydrological, and societal factors using spatially distributed data, local values, and robust flood modelling. The spatial intersection of flood inundation area (i.e., exposure) and the adverse socio-environmental impact function (i.e., hazard and vulnerability) was represented by

$$R_{k(E|S)} = \left[\left(A_1 \cap I_{k(E|S)} \right) - \left(A_k \cap I_{k(E|S)} \right) \right] , \tag{7}$$

where $R_{k(E|S)}$ is the spatial risk function associated with each alternative (k) and spatial domain (E: environmental, S: social), A_1 is the flood inundation boundary for the baseline condition, A_k is the food inundation boundary for the mitigation alternative, and $I_{k(E|S)}$ is the composite impact function [adapted from Rincón et al. (2018)].

In order to analyze the influence of socio-environmental factors on flood risk (R_k), the weighted overlay maps (I_k) were intersected with flood exposure bounds (A_k), as conceptualized by **Eq. 1**, where each A_k cell was assigned a binary value of 0 (no inundation) or 1 (inundation). Hence, the percentage of risk change for each mitigation strategy was obtained as a function of total raster area, where higher values of R_k indicate greater risk deviance from the baseline strategy. Values of R_k near 0 indicate a similar socio-environmental risk to the baseline scenario. Conversely, positive R_k values suggest greater risk than the baseline strategy, while negative R_k values represent less risk. The outcome of this approach is a spatial representation of flood risk, describing the intensity of socio-environmental impacts (i.e., hazards and vulnerabilities) exposed to flooding, per high-resolution mapping and robust hydro-dynamic modelling.

3 Results and Discussion

3.1 Stakeholder Valuation

Weighting values were derived from an online survey sent to 34 regional stakeholders affiliated with the ABRS system, of which 13 participants responded. A Likert-scale questionnaire was distributed to identify stakeholder values for each social and environmental criteria factor relative to all other factors using a qualitative scale from least to most important. The questionnaire results were converted to Saaty's 9-point quantitative scale for AHP modelling, as summarized in *Tables S5-S6*. Ancillary factors were incorporated into the hierarchy of responses by deriving individual AHP matrices for each mitigation alternative (A_1-A_8), according to their respective socio-environmental impacts (*Tables S7a-h*).

The individual AHP matrices were then aggregated into a composite matrix, as summarized in **Table 5**, for each mitigation alternative and socio-environmental domain. The weightings represent tradeoffs between multiple indicators according to stakeholder preference and pairwise comparison, which were used to estimate the magnitude of socio-environmental impacts associated with ABRS flooding. To assess the predictability of influence weightings from individual stakeholders, CR ratios were calculated for each AHP matrix (*Table S8*). All CR values were less than 0.1, denoting acceptable consistency of stakeholder judgements during the survey (Saaty, 1980). The ranking of stakeholders' preference for each criteria factor is shown in *Fig. S9*, demonstrating high variation in preference for some criteria (e.g., toxic releases, soil erosion) with lower variation (i.e., better agreement) amongst other factors (e.g., roadway inundation, residential relocation, amenity disruption). These results highlight the importance of including a variety of stakeholder inputs across a large sample size, which we note was a limitation of this study.

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Table 5. AHP-based weightings (in percent, %) for n=13 Likert-scale survey responses for environmental and social impact factors related to ABRS case study mitigation alternatives A_1-A_8.

	Criteria (j)	Aggregate Weight (w_j) for Each Alternative (k) A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
Envr.	Toxic Release Inventory	34.5	30.9	34.5	34.5	34.5	34.5	30.9	34.5
	Leaking Petroleum Tanks	17.0	15.0	17.0	17.0	17.0	17.0	15.0	17.0
	Wastewater Treatment	23.1	20.5	23.1	23.1	23.1	23.1	20.5	23.1
	Soil Erodibility	25.5	17.5	25.5	25.5	25.5	25.5	17.5	25.5
	Habitat Disruption	-	16.1	-	-	-	-	16.1	-
Social	Medical Facilities	29.3	29.3	26.8	24.4	26.8	29.3	26.5	29.3
	Population Density	27.3	27.3	25.2	22.5	25.2	27.3	24.9	27.3
	Inundated Roadway	6.6	6.6	6.2	5.2	6.2	6.6	6.2	6.6
	Flood Insurance	14.9	14.9	13.7	11.5	13.7	14.9	14.0	14.9
	Residential Relocation	-	-	7.7	-	7.7	-	-	-
	Downstream Flooding	-	-	-	17.7	-	-	-	-
	Amenity Disruption	-	-	-	-	-	-	8.2	-
	Social Vulnerability	21.9	21.9	20.4	18.7	20.4	21.9	20.2	21.9

3.2 Flood Exposure Mapping

3.2.1 Hydraulic & Hydrologic Calibration

The flood exposure boundaries for each mitigation alternative were modelled in HEC-HMS/HEC-RAS due to limited inundation data within the USACE (2020) report and to better understand the unique hydrological interactions within the ABRS watershed system. To validate the models, the simulated flood elevations were compared to local stream flow gauges (USGS, 2017) for the Hurricane Harvey flood event, as summarized in **Table 6**. Several evaluation statistics were calculated to assess model performance for the Addicks and Buffalo Bayou watersheds (i.e., Nash-Sutcliffe efficiency (NSE), RMSE-observed standard deviation ratio (RSR), and index of agreement (*d*)). Agreement between the benchmark elevations and the modelled outputs were deemed satisfactory, per well-established efficiency thresholds denoting 'very good' watershed model performance (i.e., NSE ≥ 0.75, RSR ≤ 0.50, *d* ≥ 0.90) (Kouchi et al., 2017; Moriasi et al., 2007, 2015).

Table 6: Observed and modelled water surface elevations in the Addicks watershed (top) and Buffalo Bayou watershed (bottom) for the Hurricane Harvey storm event.

Creek Name	USGS Gauge	HEC-RAS XS Name	Peak Observed Elevation (ft)	Peak Modelled Elevation (ft)	Efficiency Criteria
Mayde Creek	HCFCD Site 2190	67829.7	144.61	145.29	
	HCFCD Site 2150	33134.2	114.95	115.58	
	USGS Site 08072680	28295.0	114.72	114.97	
Bear Creek	HCFCD Site 2180	63028.6	149.54	149.63	NSE = 0.999
	USGS Site 08072730	27754.8	114.71	115.05	RSR = 0.037
Langham Creek	HCFCD Site 2140	57359.7	134.5	135.64	*d* = 0.999
	HCFCD Site 2120	33728.9	111.4	111.07	
	USGS Site 08072760	33859.9	111.85	111.78	
Horsepen Creek	HCFCD Site 2130	14080.0	115.9	115.92	

Creek Name	USGS Gauge	HEC-RAS XS Name	Peak Observed Elevation (ft)	Peak Modelled Elevation (ft)	Efficiency Criteria
Buffalo Bayou	USGS Site 08073500	232632.3	77.45	77.01	NSE = 0.955
	USGS Site 08073600	214953.1	71.23	71.53	RSR = 0.211
	USGS Site 08073700	196463.1	63.94	62.40	*d* = 0.990
	HCFCD Site 2260	184862.8	60.30	58.03	

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3.2.2 Complex Hydro-dynamics

Flood modelling outputs between the baseline scenarios ($A_{1(A|B)}$) and the mitigation alternatives (A_{2-8}) were compared to better understand the drainage characteristics of the ABRS watershed (detailed in the Supplementary Information, *Text S2*). As described in TWDB (2015), overland flow from Cypress Creek enters the Addicks and Barker watersheds during extreme storm events. This cross-basin overflow presents complexities with managing the timing of releases from the reservoirs, which were originally designed for intra-basin flows within a largely undeveloped region of the Houston metroplex (**Appendix A**). As such, reservoir releases into Buffalo Bayou are dependent on how much water enters the Addicks and Barker watersheds as a function of Cypress Creek hydraulics and land use changes. These synergies are further compounded by the spatial representation of social vulnerabilities and environmental hazards within the ABRS. For example, simulated flood modelling for the Buffalo Bayou watershed suggested a strong correlation between inundated area and reservoir release operations. To optimize the timing of releases, the reservoirs must contain adequate storage capacity and structural integrity. If water would have breached the reservoir spillways, for example, widespread flooding would have triggered further compound impacts throughout the ABRS. While reduced overtopping may have limited downstream flooding, the reservoirs may have filled to capacity, worsening upstream flooding in neighbourhoods with greater socio-environmental risk. In the event of major dam breach, the entire Downtown district could have flooded, impacting the robust industrial facilities along the Houston Ship Channel and affecting regional economic trade.

In reviewing the flood modelling outputs (*SI Text S2*), we note that the addition of a third reservoir here does not fully mitigate the flood issues with the Addicks watershed, which is driven largely by overland flow. The spatial configuration of flooded areas is improved with an additional upstream reservoir; however, the attenuated peak flow entering the downstream reservoir is not shown to be reduced enough to eliminate surcharges into Buffalo Bayou, which is hydrologically driven by the timing of reservoir releases. Instead of dispersing the flow over time, the peaks of the hydrographs before and after the releases combined, causing widespread flooding along Buffalo Bayou. Nonetheless, overland flow in this basin must be carefully considered when deciding the quantity and timing of releases because the flow impacts compound in this area. As such, a linked timing mechanism of ABRS releases (through robust hydro-dynamic modelling) is needed to fully understand how cross-basin transfer affects overland flow, reservoir storage, and the potential for emergency releases into Buffalo Bayou. The feasibility of altering the reservoir releases during a major storm such as Hurricane Harvey is contingent not only on the rainfall and runoff conditions within the inter-linked watersheds but also on the storage capacity and release schedule of the reservoirs, which is influenced by upstream conditions from cross-basin overflow.

Such dynamic factors must be considered during hydrological decision-making regarding large-scale reservoir infrastructure. These results highlight how the overall flood exposure within dam-influenced watersheds is compounded by hydrologic complexities, which should be explicitly incorporated within the modelling paradigm to capture overall risk. Moreover, these findings suggest that additional engineered infrastructure should not be the only solution to complex hydrological systems. Soft solutions that should be considered include a robust analysis of the reservoir release operations

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coupled with overland flow predictions and retaining water on-site through natural systems to reduce the amount of flow reaching the streams. As described in **Sect. 1**, existing MCDA-based approaches for flood risk management rely primarily on simplified drainage characteristics due to the complexities associated with robust hydrological modelling. As such, the dynamics of compound hydrological interactions must be considered explicitly when attempting to combine socio-environmental impacts with flood exposure, which is further demonstrated in the following section.

3.3 Socio-environmental Risk Change

The resulting composite risk maps from the MCDA approach are shown in **Fig. 6(a-n)**. Environmental risks are more uniformly spread throughout the watershed system, whereas the social risks are isolated in specific pockets above and below the reservoirs. This points to the disproportionate impacts and benefits that may result from unique operational procedures and long-term planning scenarios. In reviewing the composite risk map results for the Addicks watershed, we noted the flood risk was diverted largely to unpopulated, low-vulnerability areas with higher likelihood for soil erosion potential, thus lowering the choice suitability. A review of flood risk maps in the Buffalo Bayou watershed shows disproportionate exposure to flooding in the areas downstream of the reservoirs, particularly if interim operating procedures had been followed during Hurricane Harvey (e.g., all alternatives except A_6).

The flood exposures were extracted from the overlay maps to identify changes to socio-environmental risk as a function of total area (**Fig. 5**). Negative values along the x-axes represent a lower scale of absolute risk in comparison to baseline conditions, thus indicating ideal mitigation options (shaded in grey). Positive values indicate a higher scale of absolute risk, suggesting that the do-nothing strategy produces less socio-environmental impacts, per spatial unit, in comparison to the mitigation alternative. In following the USACE (2020) approach for narrowing the preliminary array into a focused array of ideal mitigation alternatives, we were able to use the general characteristics of overall risk and flood exposure to better understand the overall picture. When viewed through the lens of spatial risk factors, Alternatives A_4 (diversion levee) and A_5 (Buffalo Bayou buyouts) represent ideal solutions for reducing adverse impacts to society and the environment, as noted by the negative shift in spatial risk (**Fig. 5**). In the Buffalo Bayou watershed, the preferred mitigation option using CBA (A_7 – channel improvements) transitioned to the least desirable alternative when considering socio-environmental risk. Similarly, alternative (A_2 – additional reservoir), which was included in the USACE (2020)'s optimal focused array, shifted toward the middle of **Fig. 5**, suggesting worsened socio-environmental risk for this mitigation strategy when compared to the do-nothing (i.e., baseline) scenario. Alternative A_3 (Addicks buyouts) demonstrated a neutral environmental risk impact but worsened societal risk, relative to the baseline. While Alternative A_6 (increased storage) displayed a modest improvement for environmental risk, we noted a significant shift toward adverse social outcomes (i.e., positive risk change in **Fig. 5**) as a function of flood area.

It should be noted that Alternative A_8 (underground tunnels) displayed adverse risk changes, both in terms of societal and environmental factors, likely due to the areal approach used to quantify risk change from the baseline scenario. Naturally, the baseline scenario will result in greater areal extents of flooding, and thus may impact a larger percentage of social or

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environmental factors. As such, any large-scale mitigation strategy must also be assessed on the basis of total costs and overall flood benefits, which may become obscured through the MCDA aggregation. In the following section, we loosely combine the results of the MCDA case study with the CBA-based analysis used in the USACE (2020) to better understand the synergies and trade-offs amongst a multitude of complex factors associated with complex flood management.

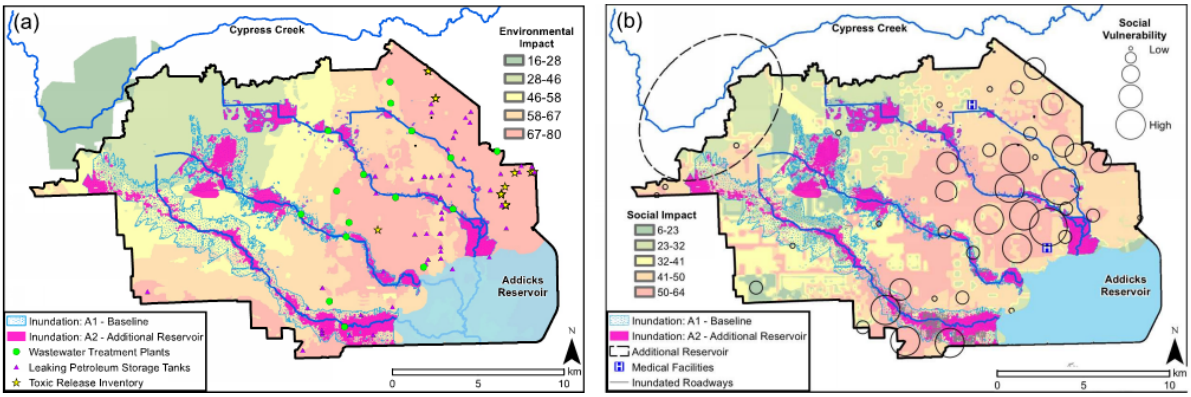

Figure 5: Composite risk maps for the ABRS watershed for each mitigation alternative ($\boldsymbol{A_k}$), for $\boldsymbol{k = 2 - 8}$, and study domain ($\boldsymbol{S}$: social, $\boldsymbol{E}$: environmental): **(a)** $\boldsymbol{A_2}$-*E*; **(b)** $\boldsymbol{A_2}$-*S*. [Note: Risk maps for scenarios A_3-A_8 are shown in supplementary materials, Fig. S10.]

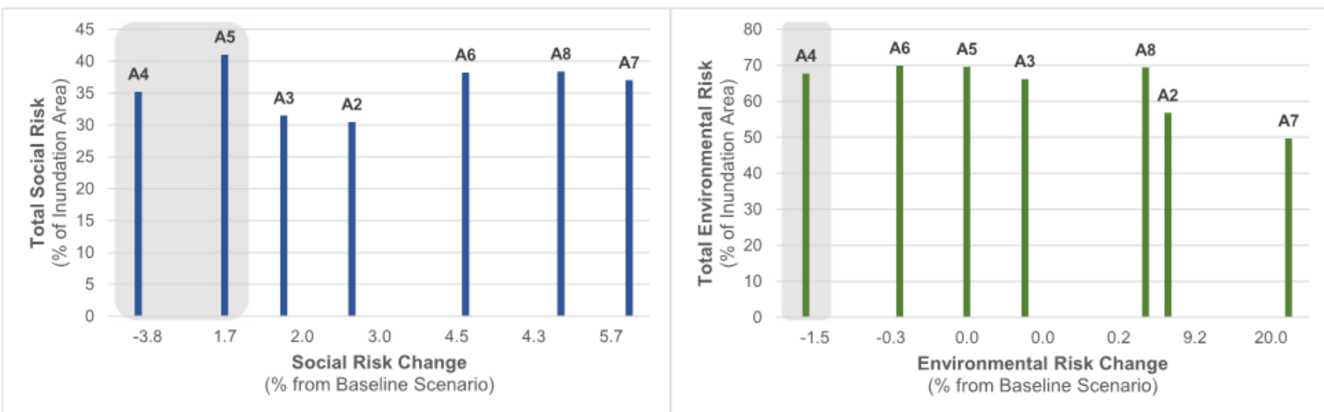

Figure 6: Magnitude of risk change between baseline scenario and each mitigation alternative as a function of total area for (left) social vulnerabilities and (b) environmental hazards within the ABRS watersheds.

3.4 Holistic Flood Management

The magnitude of risk change between the alternatives may be assessed to better understand how socio-environmental impacts may interact with hydrological conditions across varying flood management approaches, including how such alternatives compare with the status quo. In this section, we explore the decision-making properties of ABRS flood management through the dual lens of CBA and MCDA. In **Fig. 7**, we plotted the magnitude of flood benefit as a function of adverse trade-offs (e.g.,

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net costs, socio-environmental risks) to better understand how preferred mitigation alternatives may shift when viewed collectively. A direct comparison of numerical indices between CBA and MCDA was not possible due to the limited cost-efficiency data presented in the USACE (2020) report. As such, the socio-environmental impacts, total costs, and flood inundation benefits for the CBA-based approach were extracted from the screening report and plotted as a relative function of magnitude (per *Table 2*).

In comparing the cost benefit indices results for each alternative (**Fig. 7**), we noted that Alternatives A_2 (additional reservoir) and A_7 (channel improvements) resulted in the highest cost-efficiencies when considering flood inundation as the sole risk factor. As such, the USACE interim report prioritized these strategies within their final array of optimized mitigation strategies (USACE, 2020, pg. 17 of 210). The USACE report also recommended Alternative A_5 (Buffalo Bayou buy-outs), but this strategy was only included in their focused array as a means to construct the widened receiving channel for Alternative A_7 (USACE, 2020, pg. 22 of 210). Shortly after publication of the interim dam study, a report was compiled by a local coalition of resiliency stakeholders highlighting the need for further consideration of ecological and social factors associated with the composite mitigation alternatives (Campbell et al., 2020). These constituents urged improved transparency of the decision-making framework and further exploration of the soft mitigation alternatives (e.g., A_3, A_6) in light of holistic environmental and social considerations.

In echoing these concerns, our case study was conducted to demonstrate how quantitative inclusion of social and environmental criteria within the decision-making process can alter the ranking of preferred mitigation strategies. **Figure 7** demonstrates changes to the rankings between the CBA and the MCDA frameworks as integrated measures across economic, social, and environmental domains. When we performed a risk-based assessment of socio-environmental impacts, we noted a trade-off between preferred alternatives on the basis of CBA versus MCDA. In the Addicks watershed, we demonstrate how Alternative A_7 produces high flood benefits for a relatively low cost (upper-left quadrant of **Fig. 7**) but also shifts toward worsened adverse impacts on the basis of socio-environmental concerns (upper-right quadrant of **Fig. 7**). Similarly, Alternative A_2 appears to be an ideal mitigation option when viewed solely as a function of cost-efficiency, but these benefits are offset by the high socio-environmental impacts associated with the strategy. A composite assessment of costs, benefits, and non-tangible risks maintained a disinclination toward residential relocation (A_3, A_5) by incorporating high costs of buyouts with a minimal improvement in social or environmental conditions. We noted a reduction in the relative preference of A_2 when compared with A_4 for mitigating cross-basin overflow, with the latter being excluded from the USACE (2020) focused array of alternatives.

The composite factors that represent ideal cost-efficiency (i.e., the large, shaded circles in the upper-right quadrant of **Fig. 7**) shift when we consider location-specific impacts and stakeholder valuation metrics in the MCDA approach. As such, we note how reliance upon a narrative-based approach for understanding socio-environmental impacts limits the decision-making capability of amalgamating many complex factors in flood management. Given such findings, we are encouraged to consider a robust coupling of hydro-dynamic properties with varied socio-environmental factors when deciding which alternatives should transition to a focused array and which strategies may be eliminated. In viewing these results collectively, we suggest a transition from the USACE (2020)'s focused array (A_2 and A_7) toward a risk-based array (A_4 and A_5), which demonstrate ideal risk reduction from the baseline scenario in terms of social and environmental factors while maintaining reasonable flood benefits according to overall cost. By collectively viewing the synergies between the economic, hydrologic, social, and environmental domains, we identified a need to further investigate several alternative mitigation strategies prior to discounting their efficacy within the screening phase. Specifically, the summary statistics along the axes in **Fig. 7** capture spatial reality and are a meaningful way to quickly summarize the complex, multi-dimensional, and sometimes elusive nature of socio-environmental considerations in flood risk management. By evaluating the total socio-environmental risk versus high-risk locations that are flooded under unique management strategies, we elucidate how the added consideration of risk alters which policies are deemed more or less effective. This, in turn, encourages additional stakeholder reflection and discussion of the overall social, hydrological, and environmental considerations at the early stages of reservoir planning. By combining high-resolution modelling with well-established AHP and MCDA techniques, we can better understand the tripartite components involved in flood risk management and transition toward a structured, transparent, and holistic means of early screening for large-scale flood management.

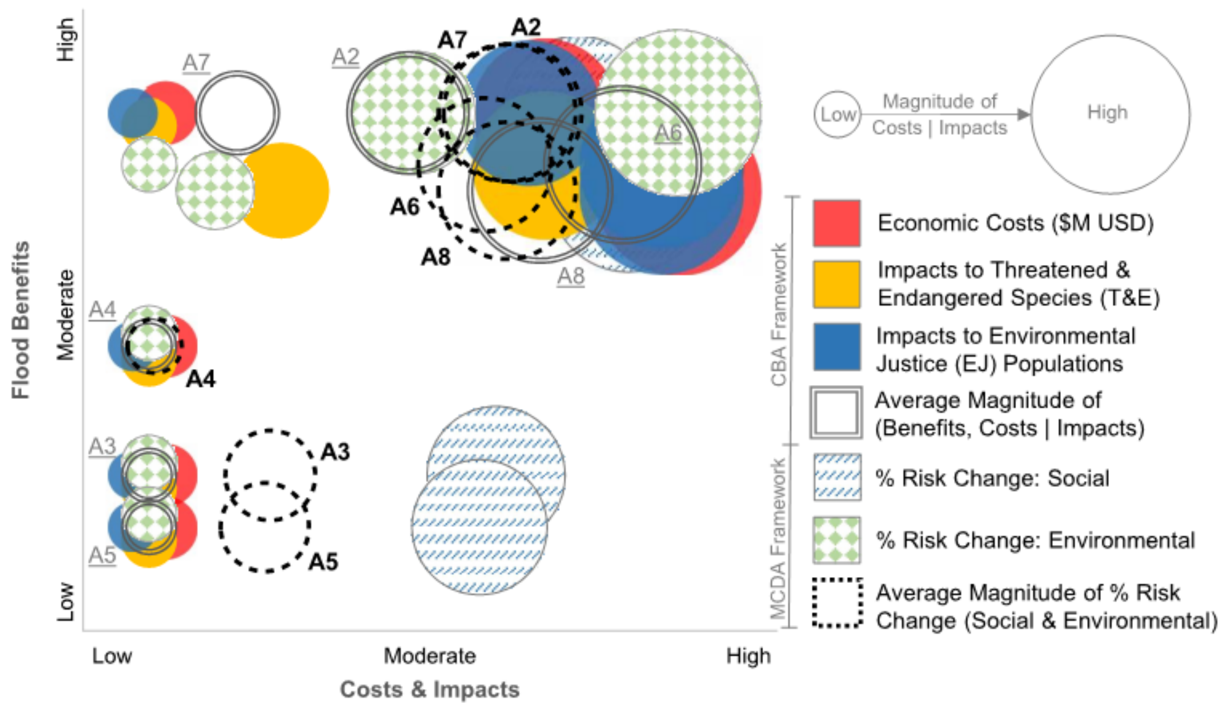

Figure 7: Heat-map of flood benefits and costs/impacts for each of the Addicks & Barker Reservoir System (ABRS) mitigation alternatives, according to the cost-benefit analysis (CBA) and the multi-criteria decision analysis (MCDA) frameworks.

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4 Conclusions

The 91,000 dams in the United States have an average age of 60+ years (ASCE, 2021). These aging structures, as well as the hundreds of thousands of dams throughout the world, risk structural failure and widespread flooding without near-term mitigation strategies, impacting the fate of millions of people in dam-influenced watersheds. The emergency-induced surcharge releases observed during Hurricane Harvey were unprecedented; however, we posit that without adequate mitigation of aging dam structures, such decisions will become more common-place. As climate change continues to stress aging dam structures, and as populations continue to densify around urban centers, traditional operating procedures for flood control dams will become increasingly challenged. While additional mitigation measures will aid in lowering the risks of such extreme, dam-induced flooding, we must understand the risks amongst and between each mitigation alternative for optimal decision-making and use of capital funds. In other words, we must consider both the soft approaches and innovative hard-scale engineering solutions for dam management, which will require evaluating both the humans being impacted by the proposed alternatives and also the environments in which the systems reside according to unique spatial properties (Pathak et al., 2020). The nuanced impacts of these decisions are not often explicit in flood mitigation frameworks. Thus, we necessitate an intuitive understanding of the interplay between reservoir mitigation and regional risk (e.g., environmental contamination, habitat disruption, social vulnerability, and other local factors), especially considering the substantial costs associated with new infrastructure. Interactions between society, water, and the environment abound in nature and are further compounded by human-induced decisions regarding large-scale drainage infrastructure, each of which is valued differently by the society within which they reside.

The results of the case study suggest that additional engineered infrastructure alone will not solve the varying impacts associated with extreme flooding within the ABRS watershed network. The timing of reservoir releases, overland flow patterns, basin characteristics, environmental triggers, and population dynamics must be considered holistically to understand the spatial distribution and severity of total risk within dam-influenced watersheds. By incorporating hydro-dynamic modeling with socio-environmental risk mapping, it is possible to consider conflicting demands and tradeoffs across the flood control domain. Standard CBA approaches for flood management screening provide a representative view of flood extents while lacking an account of socio-environmental vulnerabilities. In this sense, CBA frameworks provide an assessment of flood *exposure* rather than flood *risk*. In relying upon a narrative-based approach for socio-environmental impacts in flood risk management, the results may be skewed toward total costs and inundation bounds. To amalgamate socio-environmental factors within the flood risk paradigm, MCDA serves as a useful tool for evaluating non-monetary impacts of exposure across space. By integrating the variability of socio-environmental vulnerabilities and hazards with flood inundation, using standard flood modelling, this framework supports practicable decision-making and early-stage screening in a manner that considers local values through robust datasets and stakeholder weightings. Thus, we are bridging the gap between datasets and decision-makers to reduce risks in complex urban watersheds by better understanding the system behaviour as a whole and how such processes are impacted by unique management interventions.

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Appendix A: History of the Addicks & Barker Reservoir System

The ABRS has experienced a long history of flood management issues. After two devastating floods in 1929 and 1935, the Addicks and Barker Reservoirs were authorized under the Rivers and Harbors Act, later modified by the U.S. Congress Flood Control Act of 1939 (Cotter and Rael, 2015), to provide protection to Houston's Downtown district and the Houston Ship Channel. The original 1940 project plan included three reservoirs (Addicks, Barker, and White Oak) with diversion levees and canals to prevent overflow from Cypress Creek and to convey releases around Houston toward Galveston Bay (USACE, 1940). The Addicks and Barker reservoirs were constructed from 1942-1948, which, at the time, were approximately 25 kilometres west of the Houston city limits in largely unpopulated prairie lands (Wurbs, 2004). Land development quickly spread to the protected areas throughout the 1950s, and the remaining items from the original plan were eliminated (additional reservoir, diversion channels), due in part to rising land costs and availability of space (Rivera-Ramirez, 2004).

Various social dynamics shaped the history of the ABRS development and therefore influenced how mitigation decisions were conducted over time. As demonstrated by the timeline in **Fig. A1**, several major rain events occurred throughout the decades following construction of the reservoirs, prompting ongoing concerns regarding the ABRS system capacity. Throughout the 1970s-2000s, major subdivisions were constructed within the limits of the reservoir pool levels, raising the risks of flood damage if the reservoirs were to fill at maximum capacity; however, these limits of potential flooding were largely unknown by the general public (Satija, 2017). Community coping and adaptation strategies related to reservoir flooding was lacking at the time of Hurricane Harvey, and fewer than 20% of the homes that flooded in the Houston-area possessed active flood insurance (Klotzbach et al., 2018).

Prior to Hurricane Harvey, rain events had not directly stressed the ABRS watersheds to the point of triggering emergency-induced surcharge releases (see **Appendix B**), but ongoing reservoir warning reports had highlighted the significant impacts of such a risk occurring in the near future (HCFCD, 1994; TWDB, 2015; USACE, 2008). Several failure zones developed in the earthen reservoir outlets, prompting classification of the reservoirs' safety rating to Level I: Urgent and Compelling in 2010, which donates an 'extremely high risk' for catastrophic structural failure (BMI, 2013; USACE, 2010). The Level 1 risk classification suggests that without intervention, the dams were "almost certain to fail under normal operating conditions from immediately to within a few years" (USACE, 2014). Shortly after the dams were re-classified, studies emerged warning of the ability of the reservoirs to withstand further increases in climate change and land development (Sass, 2011). The reservoirs encountered several 500-year storm events in succession (2015-2016), triggering record cross-basin overflow conditions and maximum pool levels in Addicks and Barker (HCFCD, 2016, 2018). Plans were proposed for structural improvement of the aging reservoirs (USACE, 2012a, 2013b); however, many of the modifications were large-scale in nature and had not been completed at the time of Hurricane Harvey.

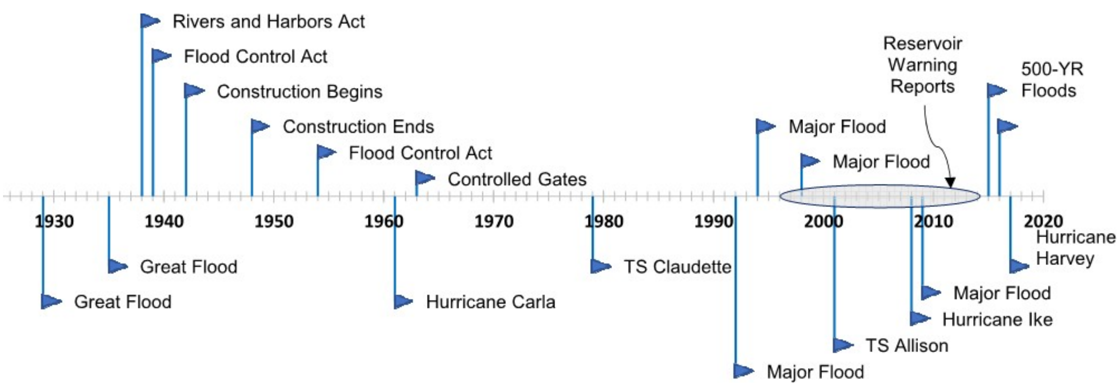

Figure A1: Timeline of Addicks and Barker Reservoir construction and major storm events, interspersed with warning reports highlighting the risks of the dams overtopping and/or necessitating emergency-induced surcharge conditions into the receiving channel (HCFCD, 1994; TWDB, 2015; USACE, 2008).

Appendix B: Emergency-induced Reservoir Release Operations

The optimal release of flood control reservoirs is a primary factor involved in mitigating flood risk, however, there remains significant uncertainty regarding how such release schedules should be crafted and executed (Rivera-Ramirez, 2004). Uncertainty in reservoir releases stems from the imprecise science of estimating available storage capacities, rainfall conditions, and inflow volumes through simulation models. A degree of uncertainty in large-scale reservoir releases is generally acceptable under average rainfall conditions, since "normal" operating conditions limit the amount of damage allowed in the downstream receiving channel while reducing overall flooding. Under extreme stormwater conditions, however, emergency-induced surcharge releases may be triggered that are intended to reduce the risk of complete dam failure and spillage by potentially and drastically exceeding downstream channel capacity (Rivera-Ramirez, 2004).

In the ABRS system, total combined releases are typically determined according to peak flows at the United States Geological Survey (USGS) Piney Point stream gauge along Buffalo Bayou. Normal operating procedures for the ABRS traditionally limited releases to 2,000 CFS at the Piney Point gauge to control downstream flooding (USACE, 2009, 2012b). After a national risk assessment was conducted for the ABRS in 2010, an Interim Reservoir Control Action Plan was developed that increased allowable standard releases from 2,000 CFS to 4,000 CFS at the Piney Point gauge to reduce pressure on the dams (USACE, 2010). Prior to Hurricane Harvey, the Interim Reservoir Control Action Plan releases had only been used once (Tax Day Flood of 2016), which successfully restored the reservoir holding capacities while minimizing risk to downstream property owners (HCFCD, 2016). During Hurricane Harvey, the pool levels in the reservoirs had surpassed critical levels (USACE, 2017), and floodwaters in the reservoirs were released according to an emergency-induced surcharge schedule (USACE, 2012b).

While the operational manuals for the studied reservoir system contained guidance for emergency-induced surcharge releases (USACE, 2012a), such drastic measures had never before been necessary prior to the unprecedented rainfall observed during Hurricane Harvey. As climate change continues to stress aging dam structures, and as populations continue to densify around urban centers, we anticipate that typical operating procedures for flood control dams will become increasingly challenged. We, therefore, must consider both the soft approaches and the traditional hard-scale engineering solutions for dam management, which will require an extension of the CBA paradigm to consider both the humans being impacted by the proposed alternatives and also the environments in which the systems reside.

Appendix C: Abbreviations

ABRS	Addicks and Barker Reservoir System
ASCE	American Society of Civil Engineers
CBA	Cost-benefit Analysis
EPA	Environmental Protection Agency
FEMA	Federal Emergency Management Association
FWS	U.S. Fish and Wildlife Service
GIS	Geospatial Information System
HCFCD	Harris County Flood Control District
MCDA	Multi-criteria Decision Analysis
NOAA	National Oceanic and Atmospheric Administration
SAW	Simple Additive Weighting
TWDB	Texas Water Development Board
USACE	United States Army Corps of Engineers

Data availability: Public data sources and numerical values used for modelling have been referenced within the manuscript and the Supplementary Information documentation.

Supplementary materials: The supplementary materials are available at: __________________.

Author contribution: Conceptualization, C.C. and H.R.; methodology, C.C.; software, C.C.; validation, C.C. and H.R.; formal analysis, C.C.; resources, C.C. and H.R.; data curation, C.C. and H.R.; writing—original draft preparation, C.C; writing—review and editing, C.C. and H.R.; visualization, C.C.; supervision, H.R.; project administration, H.R.; funding acquisition, H.R. All authors have read and agreed to the published version of the manuscript.

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