Human-water-environment Feedbacks in Flood-control Reservoir Management

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Key Points:

- Aging flood-control reservoirs impact millions of people and face significant challenges with rising urbanization and climate change
- An adaptive framework may be used to integrate spatial risk with standard hydrologic and hydraulic modeling of reservoirs
- Feedbacks between reservoir management and society are complex but must be understood holistically for long-term sustainability

Abstract

Urbanization and climate change increase water pressure in dams and stress the stability of flood-control structures. Many of the existing dams are aging and have been classified as deficient or having potential for life-threatening hazards in the event of failure. Common mitigation measures include optimizing reservoir release rates and/or implementing additional large—scale infrastructure. Such decisions are typically investigated with drainage models that do not consider co-evolving variables, such as environmental effects or socio-economic impacts. Flood-control reservoirs form complex hydrologic systems that contain numerous interdependencies and intricate feedbacks that must be balanced to achieve optimal resiliency. A spatial multicriteria analysis (SMCA) framework is presented that integrates a suite of social and environmental vulnerabilities with reservoir modeling and decision-making weights. An implementation of adaptive flood control case study of the Addicks and Barker Reservoirs in Houston, Texas, USA during Hurricane Harvey is used to illustrate the proposed technique and to highlight the complexities involved in reservoir decision-making. Hydrologic synergies that would be realized from maintaining status quo operations, optimizing reservoir releases, or increasing storage capacity through engineered solutions are explored. The SMCA methodology is used to visualize how such relationships alter environmental and social vulnerabilities for improved decision-making. In this way, the decision-making process becomes an endogenous component of the integrated human-water-environment feedbacks, thus enabling adaptive management of flood-control reservoirs with comprehensive risk.

Plain Language Summary

Flood mitigation strategies need to consider environmental and societal vulnerabilities. Adaptive strategies that incorporate reservoir release management and non-structural water storage options should be part of a holistic framework to ensure resiliency under climate change.

1 Introduction

Managing flood risks typically involves estimating the probability of flooding at a given location without explicitly considering additional cascading effects, such as social vulnerabilities and environmental consequences. Interactions between flood management and co-evolving dynamics have been largely lacking in reservoir research, where human-environment phenomena are treated as exogenous to hydrological decision-making (Wallington and Cai, 2020). A comprehensive understanding of the overall risk and broader impacts of flood infrastructure requires inter-disciplinary research and reliable datasets for integrating such concepts into standard practice (Schanze, 2006, Ebert et al., 2009). In the United States, over 90,000 reservoirs (i.e. dams) have been constructed since the Flood Control Act of 1936. Many of these reservoirs were constructed of earthen material where increases in water pressure from urbanization and climate change have threatened their structural stability. Over one-third of the nation's dams have been classified as 'significant-hazard potential', 'high-hazard potential', or 'deficient', according to the severity of anticipated consequences in the event of a dam break or emergency releases (ASCE, 2017); thus, the water levels in these aging reservoirs must be strategically managed to reduce the risk of catastrophic flooding. Common measures for addressing reservoir-induced flooding include a combination of structural (i.e. channel improvements, increased storage, additional infrastructure) and non-structural (i.e. optimizing downstream releases, flood warning systems, property buyouts) approaches (Weber, 2019). Such solutions are typically analyzed with complex hydrologic and hydraulic models that do not account for environmental or social impacts, despite growing evidence of the interdependencies between flooding and overall community resiliency (Bodenreider, 2019; Cutter et al., 2013).

The interplay between the perception of flood risk and societal patterns is complicated, and numerous attempts have been made to increase our understanding of such feedbacks (Blair and Buytaert, 2016; Di Baldassarre et al., 2013a,b; Di Baldassarre et al., 2015; Elshafei et al., 2014; Gober and Wheater, 2015; Jongman et al., 2015; Konar et al., 2019; Lu et al., 2018; Sivapalan et al., 2012; Troy et al., 2015; Viglione et al., 2014; Winsemius et al., 2016; Yu et al., 2017). At present, the prominent methods for studying the dynamics of social systems with hydrological processes include mathematical descriptors, statistical analyses, surveys, and agent-based modeling (Haer et al., 2019; Di Baldassarre et al., 2015; Loucks, 2015). While the aforementioned methods have shed light on relationships between flood risk and societal patterns, they remain in the research domain and not oft used in practice due to their complexity. Moreover, interactions between flooding and environmental contamination are often studied with models that couple hydrology and nonpoint-source pollution (Abbaspour et al., 2007; Borah and Bera, 2004; Gao and Li, 2014; Tsakiris and Alexakis, 2012; Wang et al., 2013); however, these approaches are rarely then integrated with socio-hydrological modeling (Chaves and Alipaz, 2007). For this reason, reservoir operations continue to prioritize economic assets without explicit consideration of the interconnected dynamics in the region (Cutter et al., 2013). A balanced approach to aging-dam management should resolve the economic, social, and environmental factors associated with robust community sustainability for multifaceted decision-making (de Brito and Evers, 2016).

Reservoir management may benefit from the use of a multicriterion decision analysis (MCDA) approach for evaluating flood scenarios with co-evolving dynamics (Yazdandoost and Bozorgy, 2008), such as social risk and environmental consequences. Such enhanced decision support tools allow consideration of the tradeoffs involved in different scenarios and visualization of how flood conditions impact the community at-large. Spatial multicriteria analyses (SMCAs), which integrate spatial data with stakeholder criteria, have gained popularity due to the increasing availability of geographic datasets (Afshari and Yusuff, 2012; Malczewski and Jankowski, 2020). In the context of flood management, MCDAs are often used to evaluate the overall net impact of mitigation measures with slightly less attention to vulnerability and risk assessment (de Brito and Evers, 2016; Fernandez et al., 2016; Malczewski, 2006; Meyer et al., 2009). Reservoir MCDA research has traditionally relied on analytic hierarchy processes or fuzzy-logic approaches for optimizing reservoir operations (de Brito and Evers, 2016; Fu, 2008; Fu et al., 2013; Labadie, 2004; Teegavarapu et al., 2013; Tilmant et al., 2002; Zamarrón-Mieza et al., 2017; Zhong et al., 2008). Such methods have been constrained to academic exercises and lack real-world application due to the perceived difficulties with complex analytical approaches and the highly regulatory nature of reservoir management (Labadie, 2004; Labadie, 2005). Previous studies also do not typically address real-time emergency reservoir management, such as dam failure or emergency-induced releases, due to the complexities associated with emergency conditions that differ from long-term mitigation planning (de Brito and Evers, 2016). As we experience a regime shift in extreme storm events from climate change, emergency-induced reservoir conditions are expected to increase (Emanuel, 2017; Sörensen et al., 2016). A clear example of this is Hurricane Harvey in Houston, Texas as described further below.

During Hurricane Harvey, large volumes of water spilled over an upstream watershed divide and entered the local reservoirs (HCFCD, 2015; Sebastian et al., 2019). Such interbasin transfers introduced significant variability and uncertainty regarding reservoir capacity and operational procedures during emergency conditions (Li et al., 2016). To accommodate these increased inflows and to reduce the risk of catastrophic dam failure during Hurricane Harvey, the reservoir waters were released according to emergency-surcharge procedures, causing widespread flooding in the receiving channel (HCFCD, 2020; USACE, 2017). Simultaneously, overland flow conditions in the receiving and adjacent watersheds interacted with the reservoir releases and compounded hydrological conditions. Such co-evolving occurrences are not well represented in the literature, as many drainage analyses assume static conditions (Li et al., 2016). As observed during Hurricane Harvey, our aging reservoir infrastructure is not equipped to handle such intense increases in rainfall, and as a result, emergency conditions may quickly arise. For this reason, flood risk management is trending toward a synergistic approach that combines mitigation measures with adaptation (Lennon et al, 2014). Instead of relying mainly on expensive structural solutions that attempt to hold back water at all costs, we are starting to embrace the uncertainty of intense rainfall events and aging infrastructure by living strategically with floods (Sung et al., 2018). The implementation of softer adaptation measures, such as optimized timing of releases or community buyouts, impacts the public in a unique manner compared with retaining the water completely. We must, therefore, be able to better understand the synergies between complex hydrologic phenomena and the scale of underlying vulnerability for a resilient approach to flood management (Lennon et al, 2014).

To address this gap, we propose a framework that synthesizes unique hydrologic and hydraulic modeling with the tripartite coupling of human-water-environment interactions. 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 interbasin transfer and emergency-induced discharges, are investigated and compared to hypothetical reservoir management strategies. The outputs from these modeled scenarios are integrated into a GIS-based decision-making framework to amalgamate environmental and social risk with hydrological conditions. In this paper, we recommend adoption of the Weighted Overlay method, which is a simplified Spatial Multicriteria Analysis or SMCA, for flood reservoir management to model suitability by normalizing criteria according to relative influence. The Weighted Overlay method is advantageous due to the relative ease with which geospatial data may be combined with stakeholder criteria to derive intuitive maps (Fernandez et al., 2016; Malczewski, 2006). This simplified method has been applied to investigate risks associated with management strategies of aging dams in China (Yang et al., 2011). We extend the SMCA Weighted Overlay framework to not only visualize reservoir flood risk holistically, but also to elucidate how complex engineered solutions affect human-water-environment systems. In light of the nascent research focus into socio-hydrological feedbacks, we posit that a weighted SMCA framework will allow improved investigation into observed trends and predictions associated with reservoir resiliency.

2 Motivating Background and Need for Integrative Framework

2.1 Co-evolving feedbacks in reservoir-induced flooding

The impacts of flooding on environmental and social systems have been widely observed in the literature. After major flood events, numerous papers are published that investigate environmental consequences and social vulnerabilities. Following Hurricane Harvey, research revealed an exacerbation of environmental inequalities from disparate exposure to toxins. Superfund sites, industrial facilities, and wastewater plants were impacted, releasing various pollutants into the air and waterways (Bodenreider, 2019; Christine and Yue Xie, 2018; Du et al., 2017; Folabi, 2018; Horney et al., 2018; Kapoor et al., 2018; Kiaghadi and Rifai, 2019; Miller and Craft, 2018; Schwartz et al., 2018; Stone et al., 2019). Several studies pointed to acute and chronic environmental impacts that were specifically triggered by the emergency reservoir releases (Folabi, 2018, Kiaghadi and Rifai, 2019). Research also revealed that unique social factors caused people to experience the effects of flooding and long-term recovery differently, despite being impacted by the same storm. Issues such as endemic poverty, housing, long-term health, mobility, resiliency, and post traumatic stress disorder were analyzed (Bodenreider et al, 2019; Chakraborty et al., 2019; Christine and Yue Xie, 2018; Dickerson, 2017; Grineski et al., 2020; Hallisey, 2018; Jonkman et al., 2018; Klotzbach et al., 2018; Koks et al, 2014; Shultz and Galea, 2017). 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 physical and social systems into flood risk management has not reached its full potential (Girons Lopez et al, 2017).

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). For example, the armoring of urban districts with large-scale flood control reservoirs has long been associated with a phenomenon called the 'levee effect'. After a reservoir is constructed, smaller, more frequent flooding is reduced; however, development then expands to the protected areas, which increases vulnerability to infrequent but potentially catastrophic flooding (Di Baldassarre et al., 2015; Montz and Tobin, 2008; White, 1945). Another observed dynamic between hydrology and social systems is the 'adaptation effect', where the overall impact of a flood decreases as the frequency of flooding increases. This phenomenon is attributed to the way communities adapt and revitalize after repetitive flooding through changes to land use planning, coping strategies, and regulations (Di Baldassarre et al., 2015; Melcher and Bouwer, 2014). Hydrological and social systems are also linked to the concept of environmental justice, which describes inequalities in the distribution of environmental hazards (Walker and Burningham, 2011). Decisions regarding the human-environment framework, such as expanding greenspaces or altering waste and industrial sites, impact the environment according to unique spatial patterns, thus imposing a distinct risk of flood contamination according to location (Walker, 2009). Inequalities regarding demographics and socioeconomics have been widely linked to variable environmental hazards related to flooding (Cutter et al., 2013; Walker and Burningham, 2011). Each of these relationships are impacted by long-term societal trends but also short-term decision-making regarding the design and operation of flood-control infrastructure.

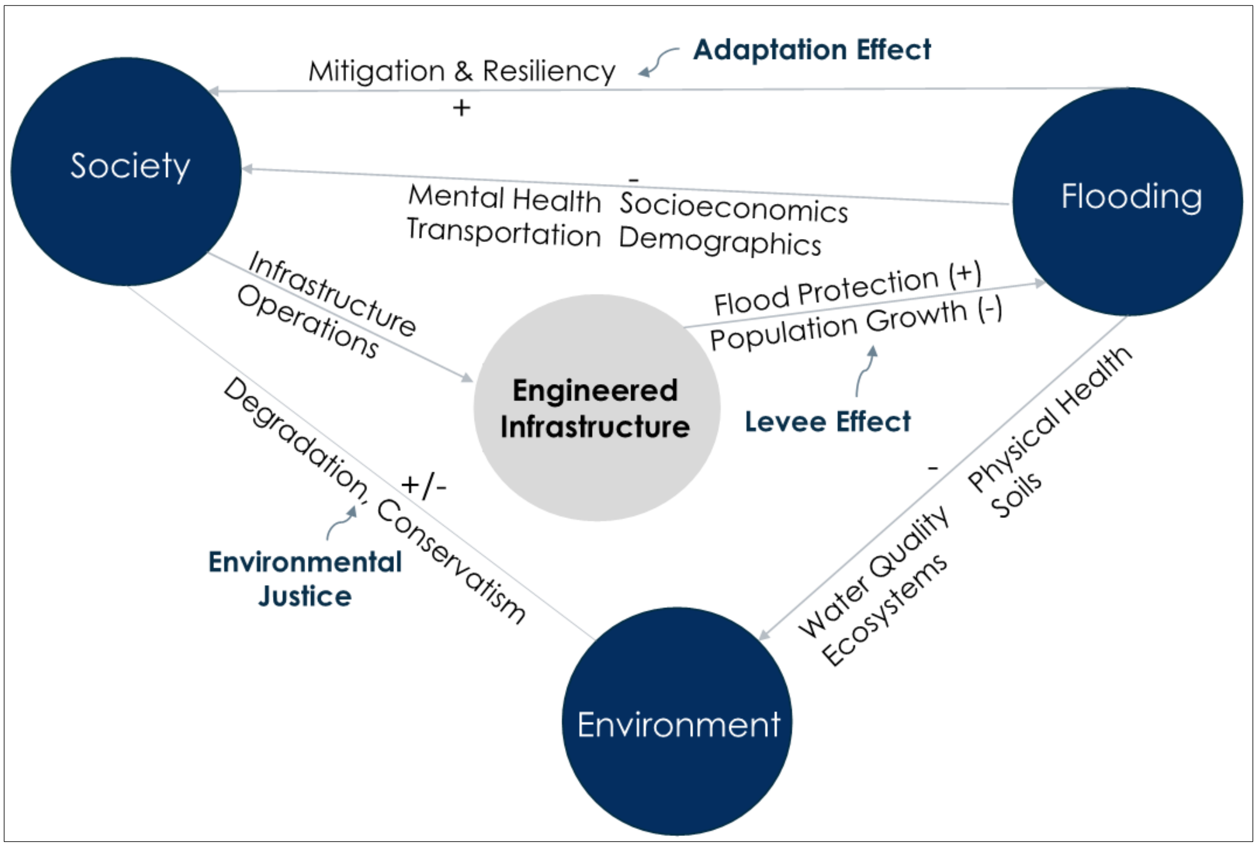


Figure 1: Positive and negative feedbacks associated with the human-water-environment system as related to decision-making for flood-control reservoirs (installing new infrastructure for long-term mitigation or optimizing the operational releases of existing infrastructure for an adaptive approach)

Figure 1 highlights the conceptual feedbacks between human-water-environmental systems and decision-making for flood-control reservoirs. The flood control strategy applied by a society over the long-term (i.e. adaptation versus mitigation) impacts each of these interactions uniquely. Despite a burgeoning interest in studying socio-hydrological feedbacks, there exists a limited understanding of how specific engineering decisions will impact the system holistically and alter both acute and long-term vulnerabilities (Sung et al., 2018). For this reason, we recommend integrating standard hydrologic and hydraulic models with a spatial representation of risk to allow visualization of flood phenomena for real-time and long-term reservoir management. This methodology would provide both a practical approach to reservoir decision-making and also serve to capture the dynamics that emerge from the three-way synergies depicted in *Figure 1*.

2.2 Implementation case study: Addicks & Barker Reservoir System in Houston, TX

The framework implementation case study described in this paper investigates a hydrologically complex watershed network, as shown in *Figure 2*, that encountered extreme flooding during Hurricane Harvey. 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 (HSC). The original 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 to Galveston Bay. The Addicks and Barker reservoirs were constructed from 1942-1948, which, at the time, were approximately 15 miles west of the Houston city limits in largely unpopulated prairie lands (Wurbs, 2000). Land development quickly spread to the protected areas throughout the 1950s, and the remaining items from the original plan were eliminated, due in part to rising land costs and availability of space (Rivera Ramirez, 2004).

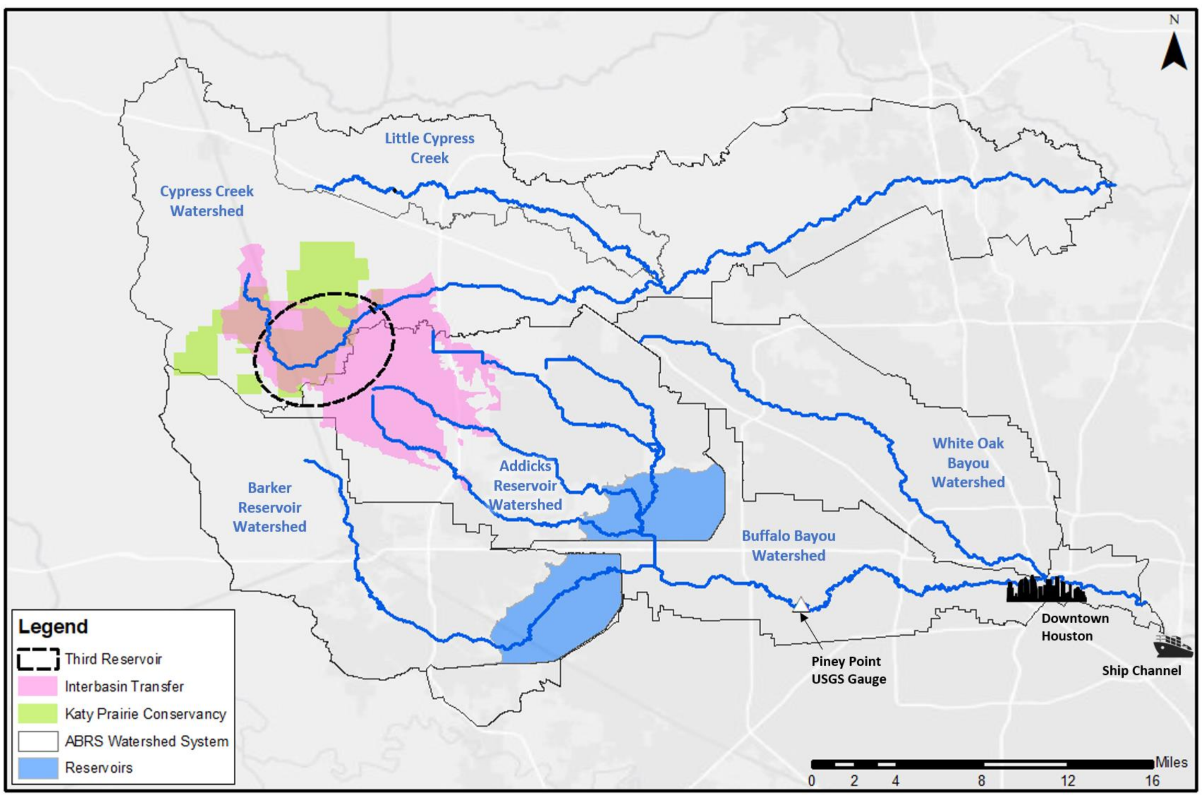


Figure 2: Addicks and Barker Reservoir System (ABRS) in Houston, Texas, USA

As demonstrated on the timeline in *Figure 3*, several major rain events occurred throughout the decades following construction of the reservoirs. Prior to Hurricane Harvey, these rain events had not directly stressed the ABRS watersheds to the point of triggering emergency-induced levels. As explained by the so-called 'levee effect' (White, 1945), urbanization continued to intensify in the inter-connected watersheds as flood risks from smaller-intensity storms were reduced by the reservoirs, and the 'adaptation effect' did not have an opportunity to unfold.

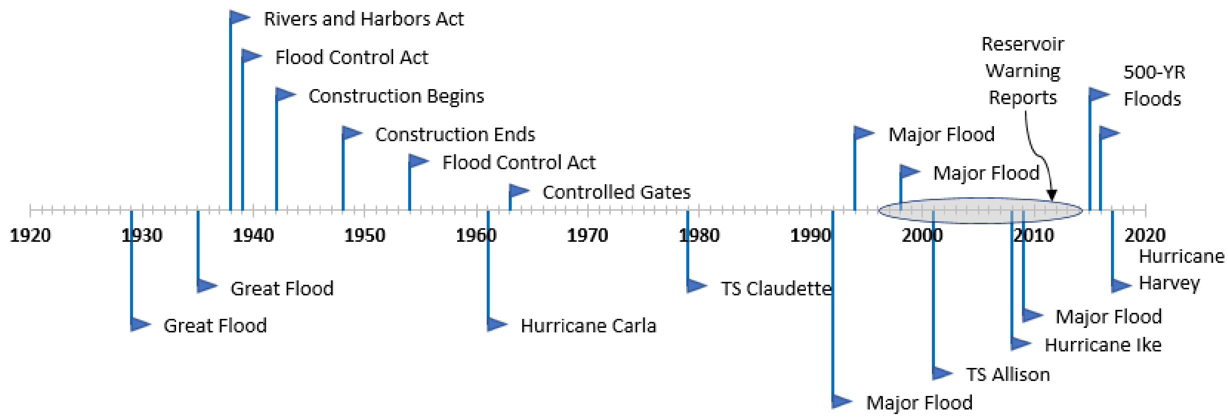


Figure 3: Addicks and Barker Reservoir System (ABRS) timeline of major events

Various social dynamics shaped the history of the ABRS development and therefore influenced how mitigation decisions were conducted over time. For example, major subdivisions were built within the actual limits of the reservoir pool levels; however, these limits of potential flooding were largely unknown by the general public (Satija et al., 2017). Community coping and adaptation strategies related to reservoir flooding was lacking at the time of Hurricane Harvey, despite several reports being released that demonstrated significant impacts if the dams overtopped or were released under emergency operations (HCFCD, 1994; HCFCD, 2015; USACE, 2008). Fewer than 20% of the homes that flooded in the Houston-area possessed active flood insurance at the time of Hurricane Harvey because they were located largely outside of the floodplain and had not experienced widespread flooding from previous storms (Klotzbach et al., 2018). Ongoing changes in dam operations and local environmental conditions led to failure zones in the earthen reservoir outlets (Chow et al., 2013). The reservoirs were consequently designated with a Dam Safety Action Classification I Urgent and Compelling, which donates an 'extremely high risk' for catastrophic structural failure (Battelle, 2013; USACE, 2010). Shortly after the dams were re-classified, studies warned 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, triggering record interbasin transfer conditions and maximum pool levels (HCFCD, 2018). Plans were proposed for structural mitigation of the aging reservoirs (USACE, 2012a; USACE, 2013); however, many of the proposed modifications were large-scale in nature and had not been completed at the time of Hurricane Harvey (2017). This progression of compounding factors and long-term decisions contributed to the risks encountered during Hurricane Harvey. The emergency-induced releases that ensued were unprecedented but were necessary to reduce the risk of more severe flooding in the surrounding communities (Sebastian et al., 2017). Such complex feedbacks and interactions between society, environment, and hydrology are explored in this paper through the ABRS case study. A detailed explanation of the differences between normal reservoir operating procedures and the emergency-induced releases observed during Hurricane Harvey are included as *Supporting Information*.

3 Datasets

The datasets used for the SMCA analysis were from publicly available geographic repositories and have been shown to impact flood susceptibility. *Table 1* lists the data types and their sources, and *Figure 4* shows a compilation of the unique databases for analyzing flood risk.

Table 1. Data sources and applied weighting for environmental and social causative factors

Data	Source		Weight
Toxic Releases	Environmental Protection Agency	EPA, 2016	25%
Leaking Storage Tanks	Texas Commission on Environmental Quality	TCEQ, 2019	25%
Wastewater Plants	City of Houston	COH, 2019	25%
Soil Erosion Potential	U.S. Department of Agriculture	Voogd, 2019	25%
Water Quality	TCEQ (2020) & Kiaghadi and Rifai (2019)		N/A
Medical Facilities	City of Houston	COH, 2019	5%
Population Density	Census Bureau	USCB, 2019	20%
Inundated Roadway	TIGER and Modeling	USCB, 2019	5%
Flood Insurance	FEMA National Flood Hazard Layer	FEMA, 2019	5%
Social Vulnerability	Centers for Disease Control	CDC, 2016	65%

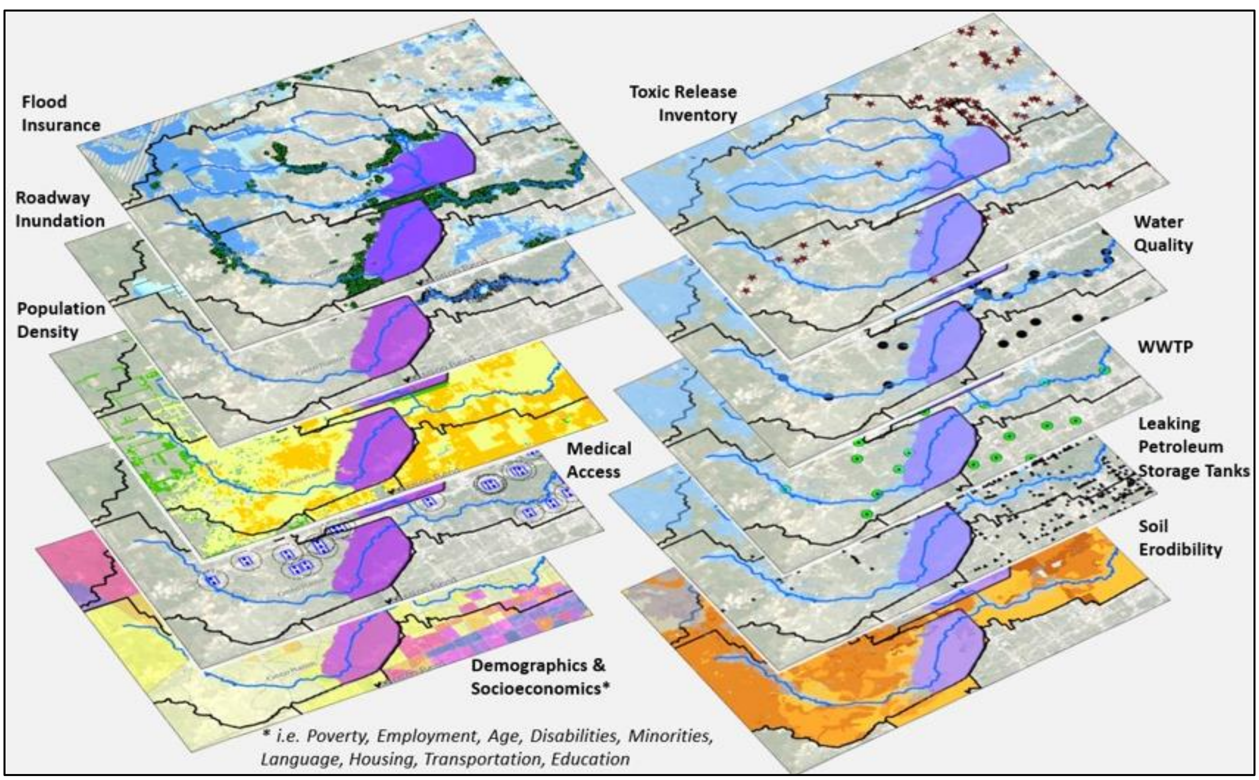


Figure 4: Geospatial layers used in SMCA analysis of impacts associated with reservoir flooding

Each of the 4 environmental factors (the first 4 factors in *Table 1*) were given an equal weighting of 25%, which describes the importance or impact of the individual criterion in comparison to the comprehensive database, according to a review of pertinent literature sources and local knowledge (Folabi, 2018; Kiaghadi and Rifai, 2019). Environmental hotspots resulting from the composite weighted overlay were compared to local surface water quality samples obtained after Hurricane Harvey. Predictors of water quality, such as total suspended solids, hardness, and metals, correlated well with the weighted analysis, providing ground-truth validation to the SMCA methodology.

The 2016 Center for Disease Control (CDC) Social Vulnerability Index (SoVI) was used to provide an aggregated risk for socioeconomic status, household composition, disabilities, minority status, languages spoken, and types of housing. Additional social factors used in this study include population, flood insurance, roadway inundation, and proximity to medical facilities, which were chosen based on availability of data and findings from relevant studies (Bodenreider et al., 2019, Christine and Yue Xie, 2018, Koks et al., 2015, Casteles, 2018, Grineski, 2020). Population density is used for social vulnerability due to increased flood impacts in urban areas and the risk of increasing population in the studied watersheds. The spatial risk associated with flood insurance was based on FEMA flood zones and a repository of repetitive loss structures in the community. It was assumed that residents within the FEMA 1% and 0.1% flood zones carried flood insurance, while 20% of all other residents had purchased voluntary insurance (Klotzbach et al., 2018). The depth of roadway inundation was chosen as a limiting mobility factor for access to and from emergency services. Water inundation was exported from pre-defined hydraulic modeling ensembles and used to select roadways that would be inaccessible with at least six inches of water depth. Finally, the proximity to hospitals and urgent care establishments was included in the composite social risk. Weights were assigned based on best judgment by the authors and discussion with local authorities; these weights were used to illustrate general impacts from various reservoir flooding scenarios. Individual risk factors and weighting values will differ according to the location, storm event, and objective (i.e. emergency conditions, mitigation planning, long-term adaptation). The datasets and weightings used in this framework would typically be gathered in advance and applied or adjusted according to local conditions.

4 Methodology

A GIS-based weighted overlay analysis was conducted to evaluate potential flood impacts on the overall system and to better understand the tradeoff of risk and resilience in reservoir flood mitigation decisions. Typical weighted overlay steps are shown in *Table 2*.

Table 2: Standard Weighted Overlay Steps (Ryan and Nimick, 2019)

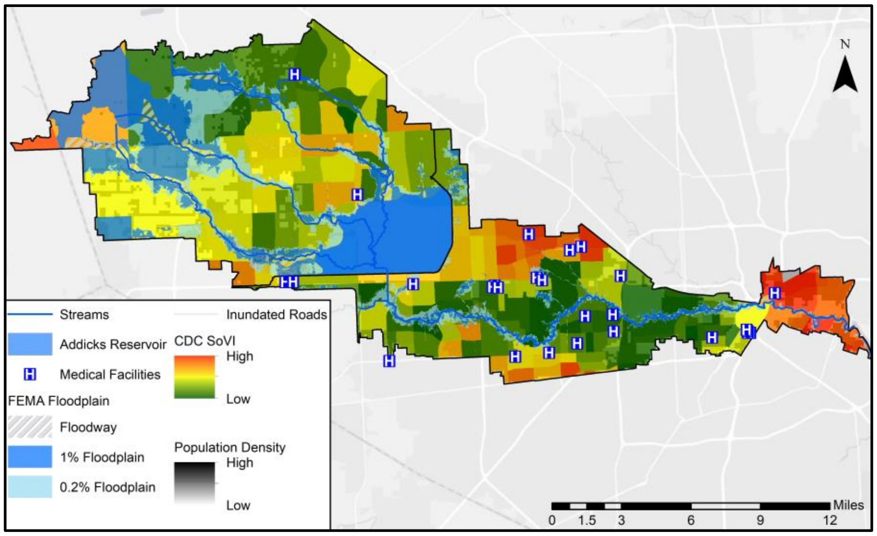
No.	Description
1.	Define the problem, goal, or objective holistically
2.	Determine criteria and constraints from local sources and expert opinion
3.	Standardize factors into a common scale through reclassification
4.	Rate and weight the importance of each factor according to percentiles
5.	Aggregate layers and criteria into an overall suitability map
6.	Apply constraints

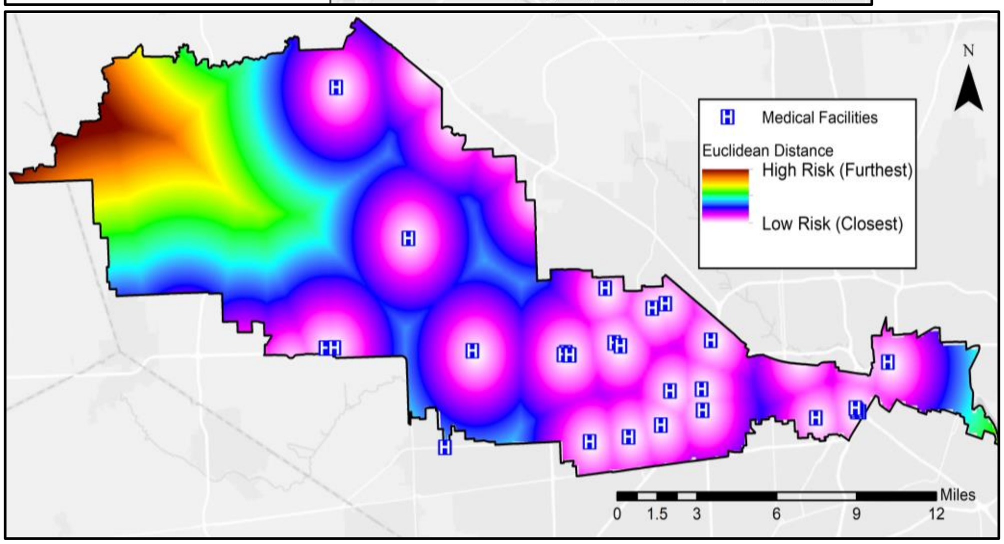
The external decision-makers to guide the approach and outcomes will typically define the SMCA goal. The causative factors described in *Section 3* were derived from local knowledge, discussion with local authorities, literature review, and availability of public datasets. Each of the environmental and social factors were converted to standardized raster datasets with a uniform scale from 0 to 100 (higher values represent greater risk). To standardize the point and polyline feature classes into spatially varied datasets, the *Euclidean Distance* tool in ArcGIS was applied. 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 causative factor, thus standardizing space and creating hotspots in multi-criteria decision making. The influence of each causative factor was incorporated into the analysis by multiplying the standardized datasets by the user-defined percentiles from *Table 1*. The weighted layers were aggregated to produce overall vulnerability maps within the ABRS system in terms of environmental and societal causative factors and classified into levels from low to high risk, as shown in *Figure 5*. A mask of inundated areas was then applied as the model constraint to classify flood risk for differing reservoir scenarios.

The Addicks and Barker Reservoirs and their watersheds were modeled for storm conditions during Hurricane Harvey using the HEC-HMS/HEC-RAS models. Several hypothetical scenarios were created to capture cross-basin overflow from Cypress Creek and to estimate the impact of engineered solutions, such as additional flood storage infrastructure or optimizing the timing of releases. The Buffalo Bayou watershed was modeled with unique release scenarios to simulate how various downstream populations and environmental consequences may be impacted in a high-intensity rainfall event and reservoir operations. Reservoir releases based on various operating procedures and observed flows were coupled with overland rainfall-runoff simulations in HEC-HMS to capture the hydrological response of Buffalo Bayou to the reservoir dynamics. The reservoirs were linked with the upstream Cypress Creek watershed by simulating diversion nodes to capture interbasin transfer. A hypothetical 'Third Reservoir' was added to the models as a mitigation option with either full capacity for the Hurricane Harvey overflow or partial capacity. The rainfall-runoff hydrographs from HEC-HMS were used as input to HEC-RAS models for a graphical depiction of flood inundation for each scenario. 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. The weighted overlay analysis of influencing factors and variables was coupled with the HEC-HMS/HEC-RAS hydrological and hydraulic models for various flood storage and release conditions. Different reservoir configurations were analyzed to explore the cascading regional impacts of this mitigation strategy. The various reservoir-modeling scenarios are listed in *Table 3*; detailed assumptions and analysis for the runs are included in *Supplementary Information*.

Table 3. Reservoir hydrologic and hydraulic modeling scenarios

Cypress, Addicks, Barker Basin Models	Buffalo Bayou Basin Models
1. Emergency-induced overflow conditions	1. Emergency-induced releases
2. Additional third reservoir with full capacity	2. Standard operating releases
3. Additional third reservoir with partial capacity	3. Optimized releases


N
Streams
Inundated Roads
Addicks Reservoir
CDC SoVI
High
Low
Medical Facilities
FEMA Floodplain
Floodway
1% Floodplain
0.2% Floodplain
Population Density
High
Low
Miles
0 1.5 3 6 9 12


N
Medical Facilities
Euclidean Distance
High Risk (Furthest)
Low Risk (Closest)
Miles
0 1.5 3 6 9 12

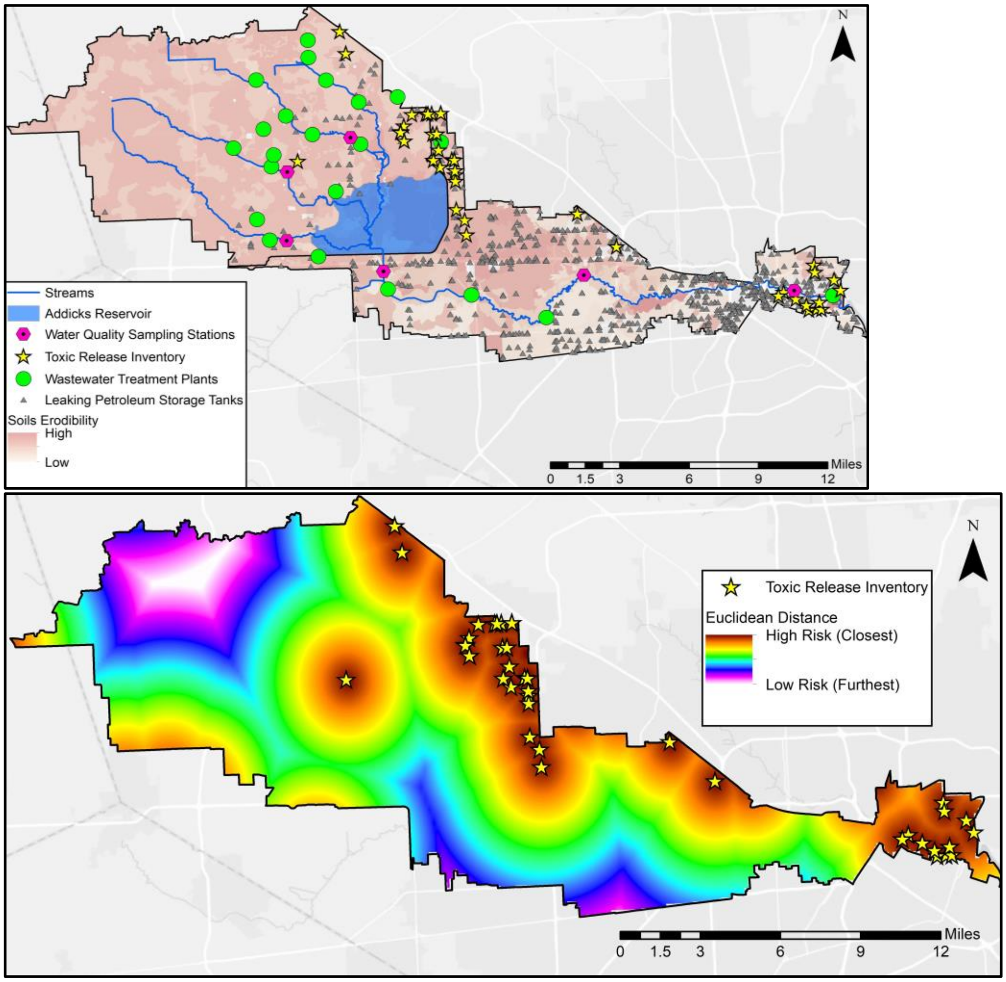


Figure 5: (top) Social datasets used in ABRS watershed system; (second from the top) Sampling of social dataset hotspots using Euclidean Distancing and standardized weights; (third from the top) Environmental datasets used in ABRS watershed system; (bottom) Sampling of environmental hotspots using Euclidean Distancing and standardized weights

5 Results & Discussion

5.1 Social and environmental risks associated with flooding

The resulting composite risk maps from the weighted overlay methodology are shown in *Figure 6*. Environmental risks are more uniformly spread throughout the system, whereas the social risks are isolated in specific zones above and below the reservoirs. This points to the disproportionate risks and benefits that may result from real-time reservoir operations and long-term planning scenarios. *Figure 7* demonstrates the magnitude of difference in flood inundation for each distinct model simulation. In the base model with no mitigation/adaptation measures, approximately 16,000 acres of land was inundated in the upstream reservoir watersheds. With the addition of large-scale infrastructure, the modeled inundation was reduced to approximately 8,000 acres for full storage conditions and 12,000 acres for partial storage conditions, with coverage variability according to the interbasin transfer and controlled release mechanisms. In upper Buffalo Bayou, between the reservoir outlets and the Piney Point stream gauge (see Figure 2 for gauge location),, approximately 4,000 acres of land was inundated with the base model and the emergency-induced releases observed during Hurricane Harvey. When the releases were optimized, only 2,000 acres were inundated in the downstream watershed model.

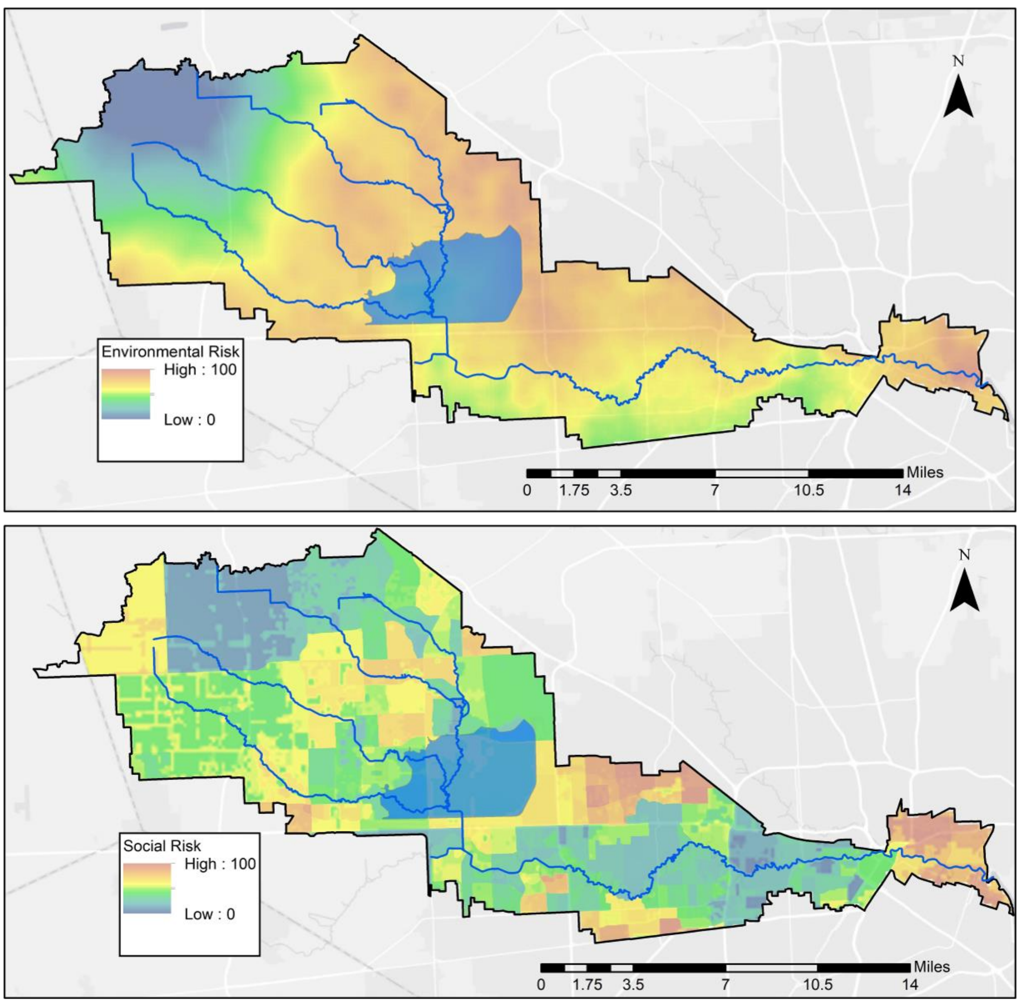


Figure 6: Composite risk maps of the Addicks & Barker Reservoir watershed system for select environmental factors (top) and social risk factors (bottom) with user-defined weightings

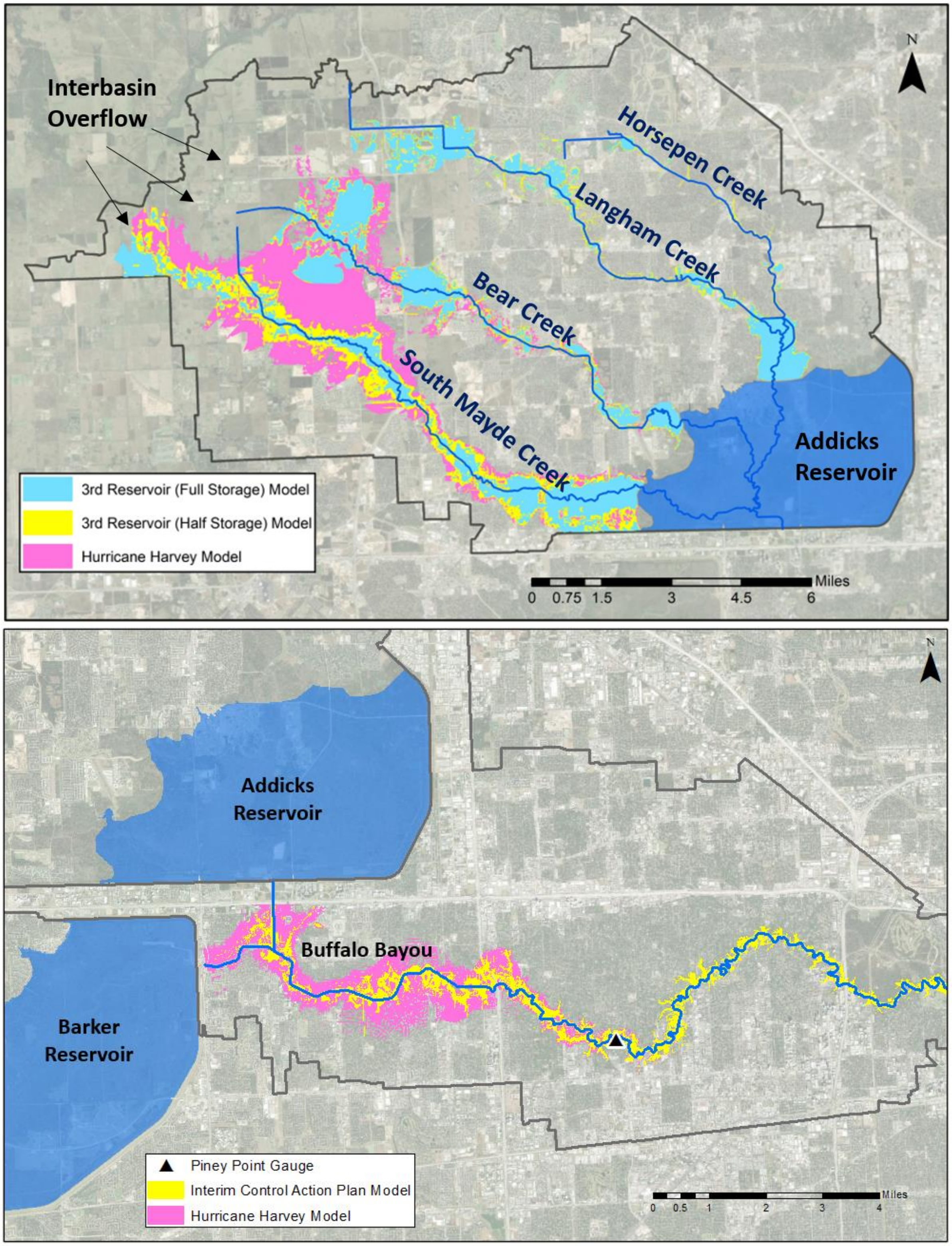


Figure 7: Modeled flood inundation simulations for Addicks & Barker Reservoirs upstream watersheds (top) and downstream watersheds (bottom)

If water were to have spilled over the top of Addicks reservoir, the overflow could have released several environmental contaminants adjacent to the reservoir, as shown in *Figure 8*, thereby causing a worsening of pollutant conditions throughout the area. The extent of reservoir releases into Buffalo Bayou determines the resulting flood inundation levels, which impacts specific wastewater treatment plants uniquely. In the event of full dam failure, the entire Downtown district would have flooded, impacting the robust industrial facilities along the Houston Ship Channel and affecting economic trade. Each decision to be made for large-scale hydrological infrastructure during a major flood event has cascading, and in some cases, compounding impacts on the surrounding community and must be explicitly incorporated into modeling frameworks to adequately capture overall risk. While reducing downstream flooding may have limited contaminant transport in that area, the reservoirs may have subsequently filled to capacity and caused a worsening of upstream flooding in the neighborhoods developed within the pool levels. Thus, the altered socio-economics along the affected region must then be considered. The neighborhoods downstream of the reservoir, for example, are more affluent, while the upstream communities consist of more economically diverse populations. As shown in *Figure 8*, the presence of additional engineered infrastructure and the extent of capacity for storing interbasin overflow affects the surrounding populations in unique and different ways that should be considered in decision-making.

5.2 Inherent complexities with adaptive flood management

In addition to impacting the surrounding communities uniquely, reservoir decisions contain inherently complex hydrological phenomena that are not well understood. A number of the hydrologic complexities associated with reservoir management, as revealed through this study, are summarized below with a discussion of findings and insights. Additional details are included in the *Supporting Documentation*.

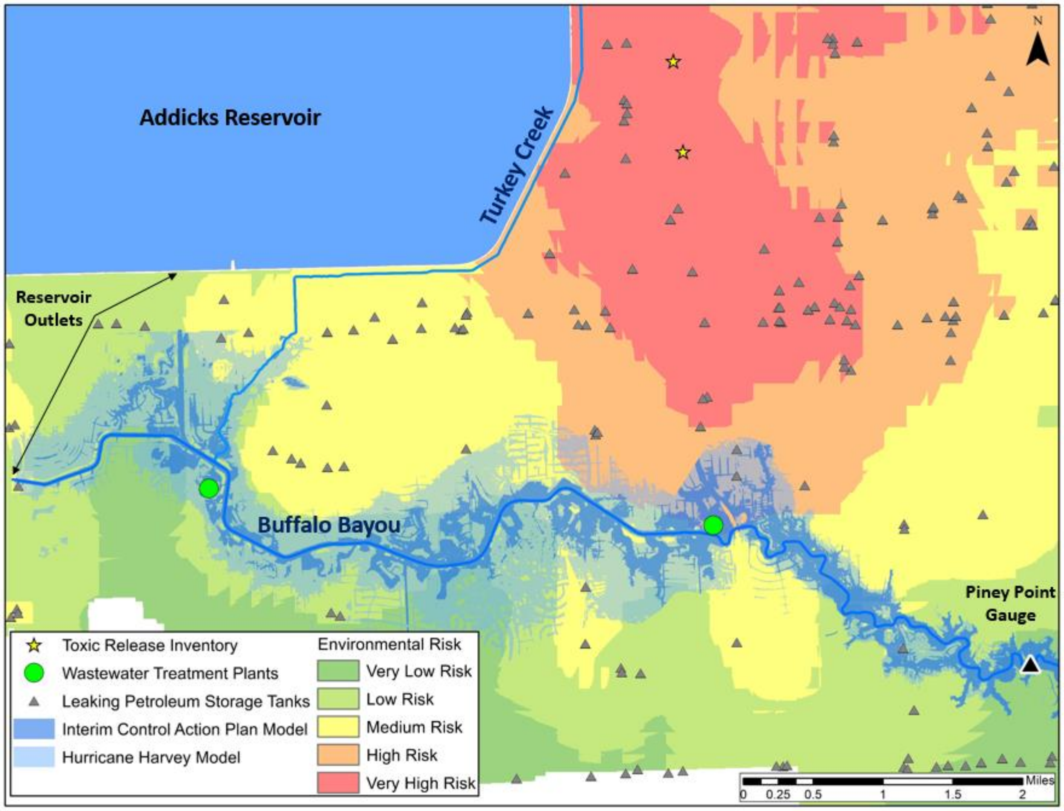
- *What is the impact of reservoirs compared with overland flow as a driving factor?*
    - Results from this study suggest that the Addicks Watershed, upstream of the reservoirs, is driven primarily by overland flow. The addition of a Third Reservoir would capture some of the interbasin transfer from Cypress Creek but would not provide a complete solution to the complex hydrological system. The Buffalo Bayou watershed, directly downstream of the reservoirs, is driven primarily by the timing of reservoir releases; nonetheless, overland flow in this basin must be carefully considered when deciding the quantity and timing of releases, because the potential for compound flow impacts in this area.
- *How does additional engineered infrastructure impact the reservoir watersheds?*
    - In this case study, an additional reservoir would be needed to store all of the estimated overflow from Cypress Creek to remain below the Emergency Release threshold. Previous studies suggest a Third Reservoir could store approximately one-half the flows noted in Hurricane Harvey; a comprehensive analysis is necessary to understand the detailed impact of an additional reservoir on the system. Nevertheless, findings from this study suggest that additional engineered infrastructure should not be the only solution to complex hydrological systems. Soft and adaptive solutions should be considered that include a robust analysis of the reservoir release operations coupled with overland flow predictions and retaining water on-site through natural systems to reduce the amount of flow

reaching the conveyance streams. This enables adaptive strategies towards reducing the societal and environmental risks presented above.

- *What factors should be considered when designing and operating flood control systems?*
    - Traditionally, engineered flood controls systems focus on reducing inundation impacts to structures and economic interests. The long-term effects on society are not a primary consideration in models and engineering decisions. This research illustrates how environmental and social risk vary throughout a watershed network and how underlying causes might be included in overall vulnerability analyses. As urbanization and climate change continue to intensify, we will encounter long-withstanding impacts from the effects of flooding. Communities should include a variety of factors when deciding the placement, scale, and operation of engineered systems. In this study, social and environmental factors were shown to be strongly correlated risks to flooding and inundation. Individual social and environmental factors will differ according to geography; however, inclusive considerations must become commonplace in hydrological analysis and decision-making for optimal resiliency.
- *How does the timing of reservoir releases impact the overall system?*
    - The inundated area for each of the modeled scenarios varies according to changes in the hypothetical reservoir releases. Given similar land and climate conditions, the overall risk is influenced by the operations of large-scale flood control reservoirs during an extreme event. While the structural stability of the reservoirs is of paramount importance, this study suggests that a change in the timing of releases could have significantly altered the severity of flooding in the receiving watersheds. Any decision-making regarding the methodology of releases should consider simultaneous overland flow patterns, climate predictions, environmental risk, and societal vulnerability based on current data and simulation models.

5.3 Adaptive reservoir releases strategies

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 Buffalo Bayou watershed but also on the storage capacity of the Addicks and Barker reservoirs, which is influenced by the upstream reservoir watershed conditions and thus the Cypress Creek overflow. Flooding and storage in the upstream watershed is contingent on the magnitude of mitigation options applied for the interbasin transfer, the physical conditions of the watershed, and the rainfall forecast. The study results illustrate the interconnected nature of these watersheds that must be considered holistically when making mitigation and management decisions for optimal risk reduction. Intricate connections exist between the hard and soft approaches to flood reservoir management. The complex dynamics associated with such decisions should be incorporated holistically into socio-hydrologic frameworks. For extreme storm events, holding back flood reservoir water compared with releasing stored water affects unique populations differently. The aging of our national reservoir structures adds an additional risk component to such scenarios. Moreover, the long-term decisions regarding reservoir management and spatial planning influence the local conditions in the interconnected watersheds. *How do we then strategically decide what regions will flood and how much water should be released for optimal reservoir management?* The dynamic impacts of these decisions are not often explicit in flood mitigation decisions. It is suggested that additional investigation be made regarding the unique timing of reservoir releases during extreme events by better understanding the populations affected in each scenario and optimizing how and when reservoirs are released in emergency situations. The significant pool levels and induced surcharges experienced in Hurricane Harvey were unprecedented, and future optimization opportunities exist to both protect reservoir systems while limiting societal impacts.



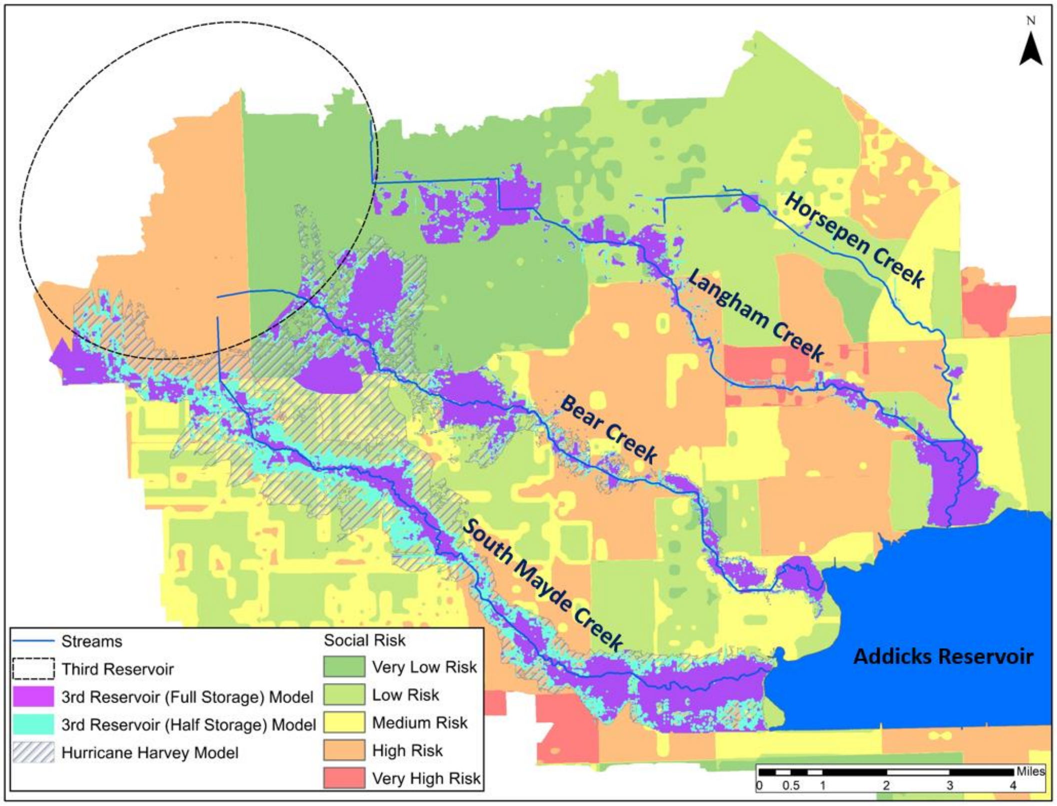


Figure 8: Modeled flood inundation overlaid onto the composite environmental and social risks for Addicks & Barker Reservoirs downstream watersheds (top) and upstream watersheds (bottom)

6 Conclusions

Large-scale flood control reservoirs impact the fate of millions of people and may be at risk in terms of their effectiveness when challenged by climate change and increased urbanization. The study findings suggest that additional engineered infrastructure alone will not address the issue of interbasin transfer within hydrologically complex interconnected systems such as the ABRS watershed network in Houston, Texas. The timing of reservoir releases, overland flow, basin characteristics, environmental consequences, and population dynamics must be considered for comprehensive risk assessment of adaptive flood mitigation decisions. The visualized maps of flooding, social and environmental risks that were simulated with the developed models showcase the distribution and severity of risk for differing scenarios while highlighting the complexity of implementing flood mitigation systems. This study showcases how despite the seemingly complex nature of inter-connected watersheds, a streamlined approach to integrating social and environmental risk into standard flood modeling is possible, due in large part to the increased availability of reliable geospatial datasets. Such spatial connections will help stakeholders visualize the feedbacks between hydrological decisions and overall risk for improved mitigation efforts and long-term resiliency strategies.

The nonoccurrence of catastrophic flooding in the studied watersheds after construction of the ABRS contributed to the local levee effect, where development continued to intensify despite repeated warnings of the potential for widespread flooding if the reservoirs were overtopped or needed to release under emergency-induced conditions.. We posit that increased urbanization and climate intensification will continue to impact engineered levee systems, thus necessitating an intuitive understanding of the interplay between reservoir operations and comprehensive risk. Findings from this paper suggest that dynamic adjustment of reservoir release strategies with explicit incorporation of societal and environmental risk may be used as an adaptive form of flood control, complementing physical solutions that may not provide a complete measure of protection. The research provides evidence of the feedbacks between society and flood mitigation measures while offering a framework for incorporating such interactions into common flood modeling workflows via geospatial data analysis.

Flood reservoirs can be perceived as a complex adaptive system with changes in behavior in response to differing inputs and settings. By incorporating the inter-disciplinary science of hydrological modeling with social vulnerability and environmental risk, it is possible to consider conflicting demands and tradeoffs across the flood control domain. The SMCA/MCDA methodology presented in this paper may be used to integrate robust stormwater modeling scenarios with multiple risk factors to better understand the correlation of hydrologic systems with overall vulnerabilities. Such comprehensive indicators of risk provide insight into the regional effects of large-scale mitigation decisions regarding extreme storm events. By linking traditional hydrological modeling with GIS-based vulnerability assessments, the differential impacts of flooding on a population can be analyzed over space for informed mitigation strategies. This approach to reservoir management and planning integrates the decision-maker as an explicit endogenous driver to the holistic human-water-environment system in response to increasingly complex storms, societies, and environments. When taken, such approaches will enhance our ability to form actionable insights regarding community resiliency.

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Datasets for this research are included in this paper (and its supplementary information files).

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