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LETTER

How much water can be captured from flood flows to store in depleted aquifers for mitigating floods and droughts? A case study from Texas, US

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Abstract

Extreme flooding from Hurricane Harvey (∼100 km³, ∼80 million acre feet, maf of rainfall) in Houston, Texas, US co-located with depleted aquifers raises the question of whether we can capture floodwater to reduce flooding impacts and replenish aquifers for droughts. Here we quantified how much water could be captured from high magnitude flows (HMFs) in 10 major rivers discharging to the Gulf of Mexico for potential storage in depleted aquifers along the Texas Gulf Coast. Results show that HMFs (≥95th percentile) from rivers discharging to the Gulf of Mexico total 37 km³ (30 maf) in 2015–2017, similar in capacity to US Lake Mead (32 km³, 26 maf). These flows are less than modeled unappropriated flows that consider appropriated water rights and limited analysis suggests moderate reduction from environmental flows. Similarity in high flow volumes and modeled groundwater depletion in the Gulf Coast Aquifer system (∼25 km³, 20 maf) underscores the potential to partially mitigate flooding using aquifer storage. Interim storage would be required to resolve disconnects between high flood intensities and low aquifer injection rates. Engineering approaches will become increasingly important to manage climate extremes.

1. Introduction

Climate extremes, including floods and droughts, are among the most common natural hazards, causing devastating impacts globally. These climate extremes are challenging for water resource managers, resulting in too much water during floods and insufficient water during droughts. The frequency and/or severity of floods and droughts are projected to increase with climate change in many regions globally according to the 2012 Intergovernmental Panel on Climate Change (IPCC) special report on extreme events (Murray and Ebi 2012). The US has been subjected to many extreme floods and droughts within the past decade. US coastal regions along the Gulf of Mexico are highly vulnerable to flooding due to extreme rainfall and storm surges caused by tropical storms and hurricanes and sea level rise (Woodruff et al 2013, Little et al 2015, Wahl et al 2015). Hurricane Harvey in 2017 resulted in ∼100 km³ (80 maf) of rainfall over southeastern Texas and southern Louisiana over about six days with more than 150 cm (59 inches, in) of rainfall over southeastern Texas, causing extensive flooding in the city of Houston and surrounding region, resulting in at least 68 direct fatalities and total economic loss of over 100 billion US dollars (USD) (Blake and Zelinsky 2018, Milliner et al 2018). Hurricane Harvey contrasts with the previous Hurricane Katrina in 2005 in neighboring Louisiana which was related primarily to storm surge, cresting at ~8 m (26 ft) and resulting in 25 km³ (20 maf) of water in the region. However, Hurricane Katrina was much more catastrophic than Hurricane Harvey, resulting in ~1000 fatalities (Brunkard et al 2008). Flooding is particularly prevalent in these Gulf Coastal regions with South Central Texas considered the most flood-prone region in the US, known as ‘Flash Flood Alley’ (Sharif et al 2015). This region experienced several devastating floods, including the
Wimberley floods (May, 2015) with the Blanco River rising 9 m (30 ft) in less than 3 h. However, these regions also experience long-term droughts with drought in Texas extending from 2011 through early 2015 and the 2011 drought considered the most extreme one year drought on record for many parts of the state, resulting in agricultural economic losses totaling 8 billion USD (Fernando et al. 2016) (figures S1 and S2 are available online at stacks.iop.org/ERL/14/054011/mmedia). The southwestern US, particularly California, is also subjected to long term droughts (recent 2012–2016 drought) interspersed with extreme floods related to atmospheric rivers (Young et al. 2017).

Floods and droughts are also widespread in many regions globally. India, Bangladesh, and China are the most flood-prone countries in Asia. Floods in the Ganges Basin, encompassing northern India and Bangladesh, are often triggered by heavy precipitation during monsoon months. For example, severe floods from ~950 mm (37 inches, in) of rain on 26 July 2005, in Mumbai, India resulted in 1094 deaths (Kumar et al. 2008). In 1988, 1998, and 2004, nearly two thirds of Bangladesh was inundated. These regions also experience severe droughts, such as the 2009 drought in the Ganges Basin related to declines in monsoonal precipitation (Hazra et al. 2013). In China, heavy rainfalls are often associated with strong El Ninos (Zhang et al. 2016), such as the 1998 great flood inundating 12% of the Yangtze River Basin (21 million hectares, Mha of land) and causing economic losses exceeding 20 billion USD (Zong and Chen 2000). South and East Africa commonly show opposing responses to El Nino Southern Oscillation (ENSO) events (Nicholson and Kim 1997), with El Nino resulting in drought in South Africa (e.g. 2015–2017 Cape Town drought associated with 75% reduction in residential water consumption (Muller 2018)) and flooding in East Africa (e.g. 1998 flood in Kenya, East Africa (Conway 2002)). Many droughts end with extreme floods, such as the termination of the millennium drought in southeastern Australia (1997–2010) by extreme flooding in 2010 related to ENSO (van Dijk et al. 2013).

The challenges to water resources management posed by these climate extremes can be managed in different ways, such as storing more water from wet periods for use during droughts. While surface reservoirs have provided the dominant storage mechanism historically, natural and depleted aquifers can enhance drought resilience by providing much greater storage capacity than some surface reservoirs and by reducing evaporative losses. The concept of the ‘Ganges Water Machine’ brought up by Revelle and Lakshminarayana (1975) provides an integrated approach to tackle water resource management in regions that suffer from floods, droughts, and groundwater depletion by storing floodwater in depleted aquifers. More recently, pilot projects have been developed in the Ganges to store flood water in depleted aquifers under the program termed ‘underground taming of floods for irrigation’ (Reddy et al. 2018). Groundwater depletion occurs in many areas of the US. The regions in Texas impacted by Hurricane Harvey overlie depleted aquifers that could store some of these high flows using Managed Aquifer Recharge (MAR) or Aquifer Storage and Recovery (ASR) (Dillon et al. 2018). Groundwater modeling reveals that aquifer storage near the Houston region declined by ~31 km³ (~25 maf) (1900–2008), resulting in land subsidence (Konikow 2015). To manage subsidence, districts were created (e.g. Harris Galveston Subsidence District) and water use shifted from groundwater to surface water. Studies in California and Arizona indicate that reservoir capacity in aquifers related to deep water tables is naturally high with additional capacity provided by historical groundwater depletion, similar to or exceeding current surface reservoir capacity by up to three times (Scanlon et al. 2016). Besides the vast potential for storage in aquifers, studies in California indicate that MAR and groundwater storage are much more cost-effective than surface reservoir storage (e.g. groundwater storage could provide six times more storage capacity than surface reservoirs for the same cost) (Perrone and Rohde 2014, 2016). Similar approaches could be applied globally where hotspots of groundwater depletion are collocated with areas that experience periodic flooding. Global hydrologic models and remote sensing using GRACE satellites have been used to delineate groundwater depletion, such as depletion in the Ganges Basin, North China Plain, Mexico, the Middle East, and North Africa (Wada et al. 2010).

A number of factors need to be considered to capture high flows from floods to store them underground. One of the major issues is the high intensity of floods relative to low rates that water can be injected into aquifers. Therefore, interim storage is generally required to facilitate this process. Potential impacts of capturing high flows on human water right appropriations and environmental flow requirements for ecosystems need to be considered (Dillon et al. 2009, Page et al. 2018).

Although there is currently substantial discussion on global water issues, ultimately water issues need to be addressed at regional scales; therefore, we evaluated the feasibility of storing flood flows in depleted aquifers for use during droughts using the Gulf Coast region in Texas as a case study. We evaluated how much water could potentially be stored from high flows in depleted aquifers considering water rights and environmental flow requirements. We quantified the volume, duration, and frequency of high magnitude flows (HMFs) (>95th percentile) in major rivers that discharge to Gulf of Mexico from Texas.

2. Methods

2.1. Study area
There are 15 river basins and eight coastal basins in Texas. In this study, we focused on the Texas Gulf
region (Hydrologic Unit Code 12, 474 000 km²; 183 000 mi² area), including drainages that discharge into the Gulf of Mexico (figure 1). The Texas Gulf region includes 10 river basins and eight coastal basins (figure 1). Among the 10 river basins, only the Brazos River discharges directly into the Gulf of Mexico via the Brazos River estuary; all of the remaining rivers discharge into a system of bays and estuaries along the coast. River flows vary from ephemeral flows in more semiarid southwestern basins to perennial flows in the humid eastern basins. Small coastal basins are bounded by large river basins and are generally named after the bounding river basins. The coastal basins have stream gages installed to monitor discharge into the system of bays and estuaries.

2.2. Streamflow data
We used daily mean streamflow data from 152 US Geological Survey (USGS) stream gages with at least 50 years of record ending in 2018 within the Texas Gulf region (figure 1, table S1). In addition, stream gages with more than five continuous years of missing data (a year with less than 310 records is considered as a year of missing data) within the past five decades were omitted from the dataset. The selected gages cover all 10 river basins and three of the eight coastal basins within the Texas Gulf region. In each river basin, we selected the most downstream gage on the river as the outlet gage (table S2). Among the 152 selected gages, the Hydro-Climatic Data Network classified 58 gages as unimpaired (unaffected by anthropogenic effects, e.g. reservoirs) (table S1).

2.3. HMFs metrics
The 95th percentile of each gage was selected as the threshold for HMFs. Previous studies in California used the 90th percentile as a threshold (Kocis and Dahlke 2017); however, the 95th percentile was selected to be more conservative and was also suggested by results of environmental flow studies in the San Antonio and Brazos basins (TIFP 2017, 2018). Four metrics were used to quantitatively describe the HMFs at each gage, similar to the metrics applied in California (Kocis and Dahlke 2017). Volume is the total volume of flow above the 95th percentile; intra-annual frequency is the annual number of HMF events (HMFs occurring over consecutive days are considered one HMF event); duration is number of days of
over the past 50 years. Each HMF metric is reported as the mean value of the total HMF for that gage over the past 50 years were then selected as wet years.

2.4. Water availability models (WAMs)

In Texas, surface water is owned by the state and regulated according to prior appropriation, which translates to ‘first in time, first in right’, i.e. senior water rights must be satisfied prior to junior water rights. The Texas Commission on Environmental Quality (TCEQ) regulates surface water and runs the WAM to determine if there is any available water for newly requested water rights. The WAM simulates the amount of surface water in a river or stream considering existing water rights under a sequence of hydrologic conditions and a specific set of management conditions (Wurbs 2005).

Here, we used two WAM runs from the TCEQ: namely full authorization simulation model (WAM3) and current conditions simulation model (WAM8). The full authorization model (WAM3) is used to evaluate applications for perpetual water right permits and amendments assuming that all currently permitted perpetual water right holders utilize their maximum authorized amount of water. In contrast, the current authorization model (WAM8) assumes the current water use of water rights holders which is often less than their permitted water right and considers return flows.

We ran both simulation models, and the simulated unappropriated streamflow at the outlet gages was then compared with the HMF volumes to assess availability of HMFs after considering water rights. More details about the WAM are provided in SI.

3. Results

Each HMF metric is reported as the mean value of streamflow exceeding the 95th percentile threshold over the past 50 years (1968–2017) and also over the recent 3 years wet period (2015–2017). Streamflow measured at river basin outlet gages was used to represent the integrated flow over basins.

3.1. Volume of HMFs

HMFs in the Texas Gulf Coast total ~197 km³ (160 maf) over the past 50 years and ~37 km³ (30 maf; 20% of the total) within the past three wet years (2015–2017) (figure 2(a)). For context, water use in Texas totaled 17.5 km³ (14.2 maf) in 2016, ~four times the mean annual HMF over the 50 year period (4.5 km³, 3.6 maf) (TWDB 2019). The HMF volume over the past three years generally corresponds to the capacity of Lake Mead in Nevada (32 km³; 26 maf), the largest reservoir in the US. The temporal distribution of HMFs is highly variable, with ~55% (108 km³, 88 maf) of the total HMF occurring in 20% of the years (10 out of 50 years) ranked from highest as follows: 1992, 2016, 2015, 2007, 1998, 2004, 2002, 2017, 1973 and 2001. About 10% (20 km³, 16 maf) of the total HMF occurred in 1992 which was a strong El Niño year (http://ggweather.com/enso/oni.htm). Although the intensity of El Niño in 1983, 1998, and 2016 was stronger than that in 1992, HMFs in those years were less than that in 1992. HMFs are distributed across the entire region with the three largest river basins (Brazos, Trinity, and Colorado, ~70% of river basin area) accounting for about half of the total HMF (table S2).

Although one might think that the hurricane season would correlate with a higher volume of HMFs, results show that the 6 month hurricane season (June through November) contributes proportionately similar volumes of HMFs as other periods, resulting in ~46% (90 km³, 73 maf) of the total HMF. We calculated annual volumes of HMFs at basin gages during wet years. Although wet years differ among the river basins, 13 wet years are shared by at least six basins (figure 2(b)). The annual volume of HMFs at basin gages during these common wet years are generally higher than the annual magnitude during other years (figure 3). During wet years, mean HMFs at basin gages range from 0.002–2.5 km³ yr⁻¹ (~0.002–2.0 maf yr⁻¹), and abnormally large HMFs (~0.6 km³ yr⁻¹, ≥0.6 maf yr⁻¹) occurred in downstream regions of the Nueces, Guadalupe, Colorado, and Sabine basins, and in the midstream and downstream regions of the Brazos and the Trinity basins (figure 1). During wet years, outlet gages for river basins contribute a mean annual HMF of ~12 km³ (~8 maf) to the Gulf of Mexico (table S3).

3.2. Intra-annual frequency and duration of HMFs

At all basin gages, the average number of HMF events ranges from 2–15 yr⁻¹, and the average length of each HMF event ranges from 1–35 d. On average, gages in the Nueces and Guadalupe basins have the lowest frequency of HMF events (3–4 yr⁻¹) with the longest mean duration (8 d) per event, while gages in the Lavaca and San Jacinto basins have the highest frequency of HMF events (8–9 yr⁻¹) with the shortest duration (3 d) per event. At the outlet gages, HMF events occurred almost 1800 times over the past 50 years (150 times in 2015–2017). The frequency of events decreases exponentially with the duration of events, with long duration, low frequency events contributing much more to the HMF volumes (figure 4). For example, 1–3 d HMF events represent ~50% of HMF events by number (~900 times) but
only contributed 5% of the HMF volume (∼9.6 km³, ∼7.8 maf), 7–20 d events represent ∼20% of events (360 times) but contributed ∼50% (90 km³, 73 maf) of the HMF volume, and ≥20 d events represent only 4% by number (64 times) but contribute 35% (68 km³, 55 maf) of the HMF volume. In summary, about half of the HMF events occurring over a week (7 d) or longer account for ∼80% of the total HMF volume (160 km³ 197 km³, 130 maf/160 maf HMFs). Similarly, ≥7 d events contribute to ∼90% of the HMF volume in 2015–2017 (34 km³/37 km³, 28 maf/30 maf HMFs). The significant contribution of ≥7 d events occurs not only at the outlet gages, but also in other upper stream gages. At 54 of 152 gages (36%), the ≥7 d events contribute at least 80% of the total volume over the past five decades (figure S7). This linkage between duration and HMF volumes has important implications for aquifer storage because long-duration low-intensity events are more readily captured for storage in aquifers.

Figure 2. (a) Annual HMFs (grey bar) and cumulative HMFs (dark blue line) at the outlets of 10 river basins from 1968–2017 (see the equivalent figure in units of maf in the SI, figure S5(a)). (b) Annual HMFs at the outlet of each river basin from 1968–2017. Blue dots indicate wet years and red dots indicate years with no HMF at the outlet of a basin. There are 13 common wet years shared by at least six basins: 1968, 1973, 1987, 1991, 1992, 1998, 2001, 2002, 2004, 2007, 2015, 2016, and 2017. Basins are ordered from SW to NE. Note that the scales of y axes for basins are different. See the equivalent figure with a unique scale in the SI (figure S5(b)).
3.3. Inter-annual frequency of HMFs
During the past five decades, the recurrence of HMF events exceeded 50% at most (97%) of the gages, indicating that HMFs occur at least 25 out of 50 years or HMFs have at least a 50% probability of occurring in any year for most gages (figure S9). The average recurrence rate is 45 out of 50 years in the three largest basins (Brazos, Colorado, Trinity), Lavaca, and San Antonio basins. At the basin outlets, the recurrence rate ranges from 31 to 48 out of 50 years. The high inter-annual frequencies reveal the high reliability of HMFs, which is important for replenishing depleted aquifers. In addition, similar to flood recurrence intervals (Dalrymple 1960), we determined the HMF volumes of different recurrence intervals (50, 25, 10, 5, and 2 year) by ranking the HMF events occurring between 1968 and 2017 by volume at the outlet of each basin (figure S10, table S4). For example, the 2 year recurrence interval corresponds to HMF events with $\sim$0.4 km$^3$ ($\sim$0.3 maf) at the outlet of the Brazos Basin, meaning that there is 50% probability that an HMF with $\sim$0.4 km$^3$ ($\sim$0.3 maf) will occur in any year.

3.4. Relationship between HMFs and depleted aquifers
HMFs total 37 km$^3$ (30 maf) in the recent wet years (2015–2017) with 29 km$^3$ (24 maf) occurring in the basin outlets overlying the northern Texas Gulf Coast Aquifer, including the city of Houston area, and 8 km$^3$ (6 maf) over the central portion of the aquifer (figure 1). The dominant aquifers in the region include the Chicot (youngest), Evangeline, and Jasper (oldest)
and consist of interlayered clays, sands, and gravels that were deposited in glaciofluvial and marine environments (Kasmarek 2012). Groundwater storage in the northern portion of Texas Gulf Coast Aquifer declined by ∼31 km³ (∼25 maf) (1990–2008), with ∼35% from inelastic storage losses from clays (∼11 km³, ∼9 maf) resulting in subsidence (Konikow 2015). Compared to the northern portion of Texas Gulf Coast Aquifer, much less depletion (∼5 km³, ∼4 maf) was modelled in the central portion, resulting in no detectable subsidence (Konikow 2015). Therefore, the depleted Texas Gulf Coast Aquifer provides ∼25 km³ (∼20 maf) storage capacity, which is sufficient to store ∼70% of the HMFs in 2015–2017, underscoring the potential to partially mitigate flooding using aquifer storage.

3.5. Will capturing HMFs impact water right appropriations?

Unappropriated flows simulated by WAM8 assuming water rights are partially appropriated under current conditions generally exceed flows simulated by WAM3 assuming water rights are fully appropriated, as expected. However, simulated unappropriated flows based on WAM3 still exceed HMF flows at all outlet gages except the Nueces Basin (figure S8), indicating that capturing the HMF flows at these outlet gages will not impact water availability of existing water right holders, even under the fully appropriated condition. There is a significantly positive correlation \( (R \geq 0.7, P < 0.05) \) between HMFs and unappropriated flows simulated by WAMs at all outlet gages (table S5), further highlighting that HMFs are mostly not appropriated for water rights. The unappropriated water volumes at outlets of the Guadalupe, Brazos, Trinity, Neches, and Sabine basins are much higher than at the outlet of the other basins and the HMF volumes at these outlet gages are less than 30% of the total unappropriated water simulated by WAM3 (table S5).

3.6. Environmental flows

In Texas, environmental flow/instream flow is defined as a flow regime that can adequately support a sound ecological environment in streams and rivers, including riparian zones and floodplains (NRC 2005). The Texas Legislature passed Senate Bill 2 in 2001 to establish the Texas Instream Flow Program (TIFP) with the goal of determining instream flow recommendations by performing comprehensive scientific studies, with completed studies for the San Antonio and Brazos basins (TIFP 2017, 2018).

To assess potential impacts of diverting HMFs on environmental flows, we compared results of our HMF analysis with environmental flow recommendations for the San Antonio and Brazos basins. The instream flow studies for these basins were estimated using a hydrology-based environmental flow regime approach which considers four key flow components: subsistence flow, base flow, high pulse flow, and overbank flow, defined by the TIFP and multiple ecological processes.

To support the ecological environment, these four key flow components need to be maintained. The HMF thresholds at the outlets of the San Antonio River (∼70 m³ s⁻¹; ∼2500 cubic feet per second, cf²) and Brazos River (890 m³ s⁻¹; ∼31 400 cf²) exceed subsistence flows and base flows; therefore, capturing the HMFs should not impact these two key flow components (table S6). However, the thresholds for HMFs at the outlets do not exceed some of the high pulse flows and overbank flows (e.g. a 3 d event of at least 1980 m³ s⁻¹ (70 000 cf²) flow between June and October for the Brazos River). We adjusted the HMF estimates between 2015 and 2017 at the outlets of those two rivers by considering the high pulse flow and overbank flow recommendations. Before adjustment, between 2015 and 2017, the HMFs totaled ∼0.9 km³ (∼0.7 maf) at the San Antonio outlet and ∼0.6 km³ (∼0.5 maf) at the Brazos outlet. After adjustment, the HMF was reduced by ∼35% at both outlets, resulting in ∼0.6 km³ (∼0.5 maf) and ∼0.2 km³ (∼0.5 maf) at the basin outlets, suggesting that capturing ∼65% of the HMF should maintain the high pulse flows and overbank flows and hence should not negatively impact the ecological environment.

Instream flow studies show that up to 0.3 km³ (0.2 maf) can be removed annually from the San Antonio (30% of total annual flow) and 0.7 km³ (0.6 maf) from the Brazos (10% of total annual flow) without negatively impacting the ecological environment as well as maintaining a stable channel geometry. According to our HMF analysis, the average HMF over the past 50 years is 0.2 km³ (∼0.2 maf) at the San Antonio and 0.8 km³ (0.6 maf) at the Brazos outlets, which is similar to the recommended average removable water (0.3 km³, 0.2 maf and 0.7 km³, 0.6 maf) given by

![Figure 4. Duration, frequency, and volume (color) of HMF events at outlet gages. Log scale is used for x and y axes. An equivalent plot is in a linear scale in the SI (figure S8). The black arrow marks events with 7 d duration. A, B and C mark the longest three HMF events. (A) HMF event at Guadalupe River Basin outlet, 12/22/1991 to 04/07/1993 (72 d); (B) HMF event at Colorado River Basin outlet, 12/22/1991 to 03/18/1992 (88 d); (C) HMF event at Brazos River Basin outlet, 12/22/1991 to 04/07/1992 (108 d). Note that 1992 was the wettest year over the past five decades, contributing ∼20 km³ (16 maf) to the total HMF volume (197 km³, 160 maf) (figure S8(a)).](image-url)
the instream flow study (TIFP 2017, 2018). During the wet period 2015–2017, the adjusted annual HMF at the outlets is 0.2 km$^3$ for the San Antonio and 2 km$^3$ for the Brazos outlets. At the outlet of the Brazos the adjusted annual HMF (2 km$^3$) accounts for ~14% of the total annual flow, which is slightly higher than the averaged proportion recommended by the instream flow study (10%) (TIFP 2018). Therefore, the removable annual volumes from the instream flow recommendation generally agree with our HMF analysis. During 2015–2017, about 65% (6.6 km$^3$, 5.4 maf) of the HMF at the San Antonio and Brazos outlets could be removed without negatively impacting the ecological environment. In addition to the four flow components considered for instream flows, sediment transport should also be included. To address sediment transport issues, the instream flow recommendation studies suggest capturing a much smaller percentage (5%) of lower flows (57 m$^3$ s$^{-1}$, 2000 cfs, San Antonio; 142 m$^3$ s$^{-1}$, 5000 cfs, Brazos); however, our annual HMF estimate is ~65% of much higher flows (70 m$^3$ s$^{-1}$, ~2500 cfs, San Antonio; 890 m$^3$ s$^{-1}$, 31 400 cfs, Brazos). Capturing such low flows is infeasible with Texas water right appropriations. Thus, the sediment transport aspect of the instream flow recommendations would further limit the potential to capture HMFs. However, detailed modeling would be required to evaluate whether or not removing large portions (e.g. 65%) of HMFs can maintain sediment transport and channel geometry for these basins.

Environmental flows are also critical for the ecological health of the bay and estuary system by transporting nutrients, sediment, and freshwater to the receiving bay and estuary system (Sklar and Browder 1998). There is no doubt that too little freshwater flow harms the bay and estuary ecosystem because of lack of nutrients and sediment and elevated salinity. However, too much freshwater flow can also harm the ecosystem primarily because of reduced salinity and its effects on species, e.g. oysters (Turner 2006). Storing some of the HMFs could reduce the negative impacts on ecosystems, such as oysters in Galveston bay.

3.7. Interim storage capacity
High intensity HMFs cannot be injected directly into depleted subsurface aquifers because aquifer injectivity is generally much less than HMF intensity.

Figure 5. Annual HMF volumes (black line) and unappropriated flows simulated using WAM3 (water rights partially appropriated under current conditions, dashed blue line) and WAM8 (water rights fully appropriated, dashed red line) at the outlet of each basin. Capturing the HMFs should not impact water rights as the HMF volumes are less than the modeled unappropriated flows. Note that the scales of the y axes for the basins are different. See the equivalent figure with a unique scale for all basins in the SI (figure S11).
Therefore, interim storage is generally required to capture HMFs before slowly injecting them into the subsurface, either using surface infiltration basins in aquifer outcrop zones or ASR wells in confined portions of aquifers (i.e. where aquifers are overlain by low permeability materials). Surface reservoirs and off-channel reservoirs can store some of the HMFs temporarily. Currently, there are 188 major water supply reservoirs in Texas, defined as reservoirs exceeding 6.2 million m³ (0.005 maf) (TWDB 2018). Monitored major reservoirs (120) have a total storage capacity of ∼37 km³ (30 maf) (excluding flood pool) (table S7), ~2 times average annual water use (17.5 km³; 14.2 maf, 2016). The reservoirs were ~80% full on average over the past 50 years as well as over the past 3 years (2015–2017) (figure S4). Comparison between total surface reservoir storage in the basins with HMFs at the basin outlets shows that some basins (Nueces, Guadalupe, and San Jacinto) are often full, mostly ≥50% of the times when HMFs occur. In contrast, reservoirs in the Brazos and Colorado basins are never full when HMFs occur at basin outlets (figure 6). In addition, sometimes the HMFs exceed the available storage capacity of the reservoirs. Our analysis shows that when HMFs occur, nearly all of the HMFs could be stored in reservoirs in the Brazos and Colorado basins whereas the percentage of HMFs that could be stored in reservoirs is lower in other basins (e.g. 50% in the Trinity Basin reservoirs, only 4% in the San Jacinto Basin reservoirs) (table S7). This analysis refers to HMFs originating from storms at the upstream end of the basins with access to the entire reservoir storage in the basin. Existing surface reservoirs could have stored about half (107 km³, 87 maf) of the HMFs over the past five decades. All HMFs (67 km³, 54 maf) in the Brazos and Colorado basins could have been stored in surface reservoirs whereas only 30% of HMFs (40 km³, 32 maf) in other basins could have been stored. More storage space could be created by releasing some reservoir water ahead of HMF events. However, it is difficult to predict when HMFs occur and to modify reservoir operations accordingly.

4. Discussion

4.1. Aquifer storage, recovery wells, and storm water management wells

The aquifers throughout much of the Gulf Coast region are mostly confined, i.e. separated from the land surface by low permeability confining units; therefore, recharging such aquifers with HMFs or storm water will require ASR wells or storm water wells to inject water directly into the aquifer. The Environmental Protection Agency (EPA) and states regulate ASR wells and storm water management wells as class V injection wells. Texas now has three operational ASR projects in El Paso, Kerrville, and San Antonio, with the San Antonio project being the largest, consisting of 29 ASR project wells with injection capacity of 227 000 m³ d⁻¹ (60 million gallons/day, mgd) (TWDB 2011). Since 2004 the San Antonio Project has stored ~190 million m³ (~0.16 maf) water in the Carrizo-Wilcox Aquifer, which is ~75% of total storage volume planned by the San Antonio Water System (San Antonio Water System (SAWS) 2018). During the recent 2011 and 2014 droughts, about 60 million m³ (0.05 maf) of stored water was recovered from the Carrizo-Wilcox Aquifer via the ASR project (San Antonio Water System (SAWS) 2018). It would take ~44 d for this ASR project to inject the average daily HMF (~10 million m³, 0.01 maf) captured at the outlet of the San Antonio basin in the aquifer. Texas now has 66 storm water management wells which is negligible compared to the numbers in many other states, such as Washington (53 180), Arizona (29 981), and California (13 806) (figure S13). For a hurricane comparable to Hurricane Harvey, ~42 000 storm water wells would be required to inject 10% (10 km³ out of 100 km³, 8 maf out of 80 maf) of the storm water over a month assuming an injection rate of 8000 m³ d⁻¹ (2 mgd) similar to those reported in the San Antonio ASR project. Therefore, even though the depleted Texas Gulf Coast Aquifer provides substantial storage capacity for HMFs and storm water, more ASR wells and more storm water management wells would need to be developed to connect surface flows and depleted aquifers. In addition, water quality control is critical for groundwater recharge (Dillon 2005). Compared to MAR using surface spreading basins in unconfined aquifers, deep injection using ASR wells and storm water management wells requires more careful attention to the quality of the recharge water because the water is not filtered by soil or rock before reaching the aquifer (Casanova et al 2016).

Groundwater in the Texas Gulf Coast Aquifer is an important drinking water source (TWDB 2018). Floodwater or stormwater runoff in urban areas contains dissolved and suspended solids, organic compounds, microbial contaminants, and other potential pollutants, such as heavy metal (Ellis 1986, Davis et al 2001). During floods, surface water quality will also be impacted because floodwater and storm water runoff can transport those pollutants into rivers and streams. Therefore, either the captured floodwater or diverted HMFs from rivers need to be treated to meet EPA drinking water standards (EPA 2018). However, HMFs diverted from rivers and streams would generally need less treatment than floodwater and storm water runoff (Kulabako et al 2007, Casanova et al 2016).

4.2. Cost-benefit of storing HMFs in depleted aquifers

The cost of storing HMFs in depleted aquifers and recovering this water during drought varies from
project to project depending on the project size, water source, water quality, and distance between water source and target aquifers etc. Analyses of data for California suggest that the cost of aquifer storage is generally low relative to surface reservoir storage (Perrone and Rohde 2016). Comparing unit capital costs of other water supply and treatment solutions, ASR can save from 50%–90% of the cost in different cases based on analysis of data throughout the US (Pyne 2017). With 227 000 m$^3$ (60 million gallons) daily injection/recovery capacity, the capital cost of the San Antonio ASR unit is $230 \text{ m}^{-3} \text{d}^{-1}$ ($0.87 \text{ per gallon per day}$) (TWDB 2011). Details of the capital costs and operating costs for the San Antonio ASR project are provided in SI. National ASR capital costs range from $130 to 530 \text{ m}^{-3} \text{d}^{-1}$ ($0.5–$2.0 per gallon per day) with an average of $\sim$300 \text{ m}^{-3} \text{d}^{-1}$ ($1.14 \text{ per gallon per day}$) (TWDB 2011). Detailed cost-benefit analysis will need to be conducted considering the costs of infrastructure to transport HMFs, temporary storage, treatment prior to injection, and ASR wellfield facilities etc relative to potential benefits, including flood mitigation, water supply during drought, and subsidence control.

5. Conclusions

The challenges of floods and droughts to water resource managers can be partially mitigated by storing HMFs in surface and subsurface reservoirs, as evaluated for the Texas Gulf Coast region. Estimated HMF volumes exceed modeled unappropriated water rights. Capturing an estimated 65% of HMF flows should not impact modeled environmental flow requirements, using the San Antonio and Brazos basins as case studies. The total HMF volume during the last three wet years (37 km$^3$; 30 maf, $\sim$2 times state water use, 2015–2017) is sufficient to replenish the depleted Texas Gulf Coast Aquifer system ($\sim$25 km$^3$, $\sim$20 maf). The inverse exponential relationship between number of HMF events and HMF duration and volume is favorable for aquifer storage as low numbers of long duration events (e.g. 1 week) contribute most (80%) to HMF volumes based on the past 50 years record. Capturing HMFs and storing them in these depleted aquifers will require additional wells for storm water management and aquifer storage and recovery in the Texas Gulf Coast region. In addition to quantifying the potential water volumes that can be captured from HMFs, this study highlights many of the additional factors that need to be

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![Figure 6](image-url). Daily HMF at the outlet of each basin versus reservoir residual storage capacity (maximum—actual storage capacity). The black line represents daily HMFs. Blue areas indicate the residual storage capacity of all monitored reservoirs in a basin. The gray vertical line represents the days when reservoirs are full (excluding flood pool). Note that daily storage data for reservoirs in the San Antonio basin have only been available since 1997. The scales of y axes for basins are different. See the equivalent figure with a unique scale for all basins in the SI (figure S12).
considered, such as water rights and environmental flows, to assess the feasibility of subsurface storage of flood waters.

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