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Peak flow trends highlight emerging urban flooding hotspots in Texas

Matthew D. Berg[1*]

Abstract: In the aftermath of flooding disasters, a temptation is to pursue recovery while also dismissing the event as unlikely to recur. Is it possible that underlying streamflow trends, which often avoid detection, help explain individual flooding episodes and should influence future expectations? How do impoundments (dams) affect these trends? Our study provides a comparative analysis to answer these key questions that help determine whether flood planning will be successful. Examining the 25 largest Texas metropolitan areas, we assessed peak flow trends for stream gages having at least 25 years of data. Of 181 total gages, 34 (18.8%) exhibited significant upward trends. Over 85% of those with upward trends are located in the Dallas-Fort Worth-Arlington (17.6%) and Houston-The Woodlands-Sugar Land (67.6%) areas. Approximately 62% of gages with upward trends are in Harris County. Among 84 sites impacted by impoundment, 11 (13.1%) still exhibited upward trends. These findings show that increasing peak flows underlie recent flooding in some areas, spotlighting streams in greatest need of examination. Increasing peak flows in some locations even after impoundment suggest dams might not be a complete solution. Finally, maintaining a robust monitoring network is critical to flood planning, and analysis is hampered when data are lacking.

Keywords: Flooding, peak flow, streamflow, impoundment, planning

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Terms used in this paper

Acronym	Descriptive name
USGS	U.S. Geological Survey

INTRODUCTION

When not bearing the load of extreme weather events, the rivers, creeks, bayous, and lakes in many portions of Texas are often viewed as valuable community amenities—and rightly so (Kulshreshtha and Gillies 1993; Wilson and Carpenter 1999; McKean et al. 2005). But these peaceful periods conditions belie a lengthy historical dark side. Texas has gained its reputation for flooding the hard way. The particular geographic and climatic setting of the state makes it vulnerable to some of the most intense precipitation events in the world, resulting in exceptional stream discharges and extensive landscape inundation (Slade, Jr. and Patton 2003; O'Connor and Costa 2004; Winters 2012; Breaker et al. 2016; Schumann et al. 2016). As a result, Texas leads the nation in flood damages and averages more flood-related deaths than any other state (Brody et al. 2008; Costa and Jarrett 2008; Sharif et al. 2015).

When the state's waters invade homes, schools, businesses, roads, and other critical infrastructure, a frequent quick response is a loud call to action to prevent similar impacts in the future. Even before the landfall of Hurricane Harvey in 2017, the Texas Legislature announced its interest in flood planning by releasing funds to the Texas Water Development Board in support of initial steps toward statewide coordination. Such flood planning, while requiring thoughtful interregional cooperation for any real chance at success, is inherently and operationally a local endeavor (Brody et al. 2008). Measures to moderate floods may have widespread benefits, but the most pronounced impacts, both positive and negative, typically are site-specific.

Similarly, the causes of flooding are location-specific, dependent upon a suite of local characteristics (Changnon et al. 2001; Douben 2006). By analyzing historical streamflow data, it may be possible to highlight emerging hotspots in greatest need of preventative action—but only after a thorough investigation of specific local causes. Streamflow trend analyses are common in Texas and neighboring states for a variety of water resources needs, often including questions of water supply and water quality (Esralew and Lewis 2010; Esralew et al. 2011). Such studies frequently focus on mean values or minimums to meet critical resource needs, but there is also tremendous value in examining maximums for the purpose of flood planning. Utilizing this approach allows us to compare different locations and supports resource prioritization for where the need is greatest.

In some Texas basins, particularly on major rivers, the construction of dams for various purposes has dramatically affected streamflows, from the creation and prolonging of flood-like hydrographs in areas upstream from such impoundments to large reductions in peak flows in others (Asquith 2001; Heitmuller and Greene 2009; Barbie et al. 2012; Lucena and Lee 2017). And while these impoundments can dramatically decrease peak flood magnitude downstream from their sites, dikes and levees often actually increase flood stage by reducing overall channel capacity (Pinter et al. 2001; Alexander et al. 2012). To develop a fuller understanding of statewide peak flow trends, it is important to account for the impact of impoundments on trends in peak flow.

As efforts proceed to analyze flooding impacts and make specific recommendations, two critical questions emerge: 1) to what degree should we consider flood events as chance occurrences as opposed to part of deeper, developing trends; and 2) given the perceived popularity of dams as a flood mitigation solution, what has been the impact on peak flows of such structures already in place?

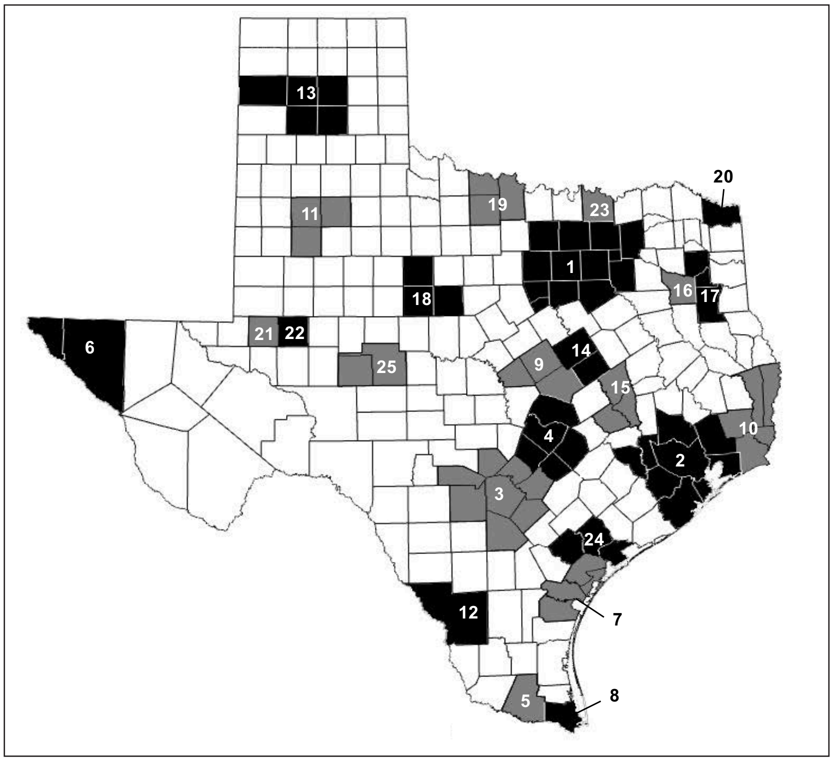

Figure 1. The 25 most-populated Texas metropolitan areas. Differences in color are simply used to distinguish the boundaries of adjacent metropolitan areas.

METHODS

To improve our understanding of the growing challenges posed by urban flooding in Texas, we conducted a detailed analysis of streamflow trends in major cities across the state (Figure 1 and Table 1). For each of the 25 most populous metropolitan areas in Texas (as designated by the 2010 United States Census), we identified the U.S. Geological Survey (USGS) stream gages located in the counties comprising these areas (https://nwis.waterdata.usgs.gov/nwis/peak?state_cd=tx). Within the designated metropolitan counties, we obtained streamflow data for each stream gage meeting the following

Table 1. The 25 largest Texas metropolitan areas (as designated by 2010 United States Census) used in this study. Metropolitan areas marked with an asterisk (*) did not include any qualifying stream gages.

1) Dallas-Fort Worth-Arlington
2) Houston-The Woodlands-Sugar Land
3) San Antonio-New Braunfels
4) Austin-Round Rock-San Marcos
5) McAllen-Edinburg-Mission*
6) El Paso*
7) Corpus Christi
8) Brownsville-Harlingen*
9) Killeen-Temple-Fort Hood
10) Beaumont-Port Arthur
11) Lubbock*
12) Laredo
13) Amarillo
14) Waco
15) College Station-Bryan
16) Tyler*
17) Longview
18) Abilene
19) Wichita Falls
20) Texarkana*
21) Odessa*
22) Midland*
23) Sherman-Denison
24) Victoria
25) San Angelo

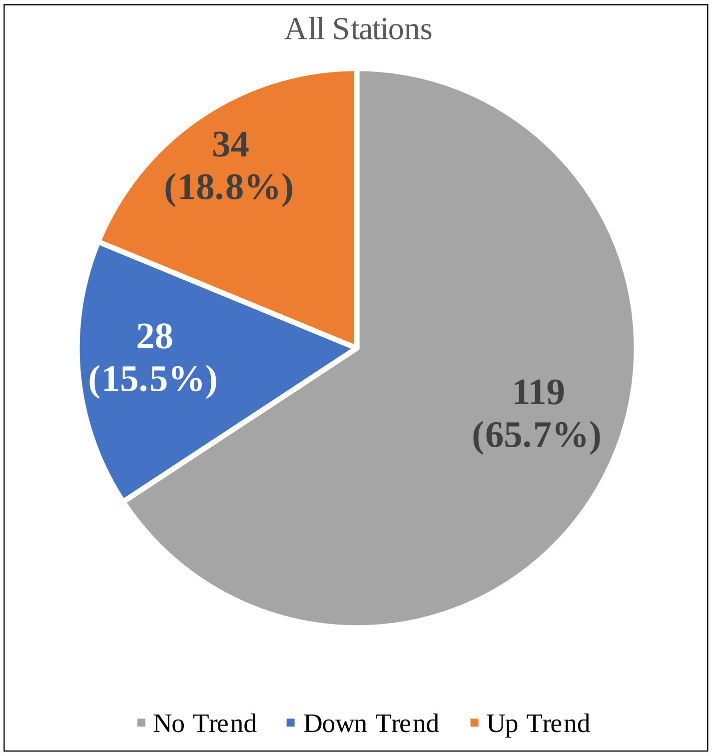

Figure 2. Proportion of examined stream gages from all metropolitan areas exhibiting no statistically significant trends, downward trends, and upward trends in peak flow.

criteria: 1) period of record at least 25 years; 2) period of record extends until at least 2010; and 3) most recent 10 years of data represent 10 consecutive years. We then performed non-parametric Mann-Kendall trend analyses using the annual peak streamflow measurements for each qualifying stream gage. Two-tailed statistical tests were assessed for significance at $\alpha = 0.1$ (Lettenmaier et al. 1994; Berg et al. 2016). Streamflow data were used in favor of gage heights because these volume measures are considered to be absolute, more robust to changes in channel morphology and gage placement, and comparable between locations. We excluded historical data points outside the instrumental record due to the imprecise nature of their measurement and the problematic nature of including historical outliers in trend analysis.

For those stream gages that yielded a significant trend in Mann-Kendall analysis, we computed the best-fit regression equation for the period of record. Resulting regression equations were used to calculate relative changes in peak flows at each stream gage over the period of record.

A number of stream gages across the state, particularly those on large rivers, are impacted by impoundment. To account for these effects on historical streamflow trends, we conducted a parallel analysis of these gages, truncating datasets to the period during which each site has been considered to be affected by regulation or diversion (USGS Qualification Code 6 in stream gage metadata). We then proceeded with the same Mann-Kendall and regression analyses. At certain sites, the entire period of record is impacted by impoundment. In these cases, the entire period of record is included in both the overall analysis and the impoundment analysis.

In all analyses, we limited the data examined to the water year ending in 2016. This allowed us to both consider the most recent available full year of data and also exclude data associated with Hurricane Harvey. This decision was made to prevent the objection that upward trends are unduly influenced by catastrophic outlier events.

RESULTS

Of the 181 stream gages we identified, a majority (65.7%) displayed no trend in peak flows over the period of record. A total of 28 (15.5%) actually exhibited significant downward trends, while 34 (18.8%) exhibited significant upward trends (Figure 2). While all stations showed variability between years, many displayed clearly discernible patterns over time even before quantitative analysis (Figure 3). When considering the geographic distribution of stream gages, a few observations are immediately apparent (Figure 4). First, nearly all metropolitan areas are predominately characterized by stream gages exhibiting no trend in peak flows. In addition, nearly all areas host one

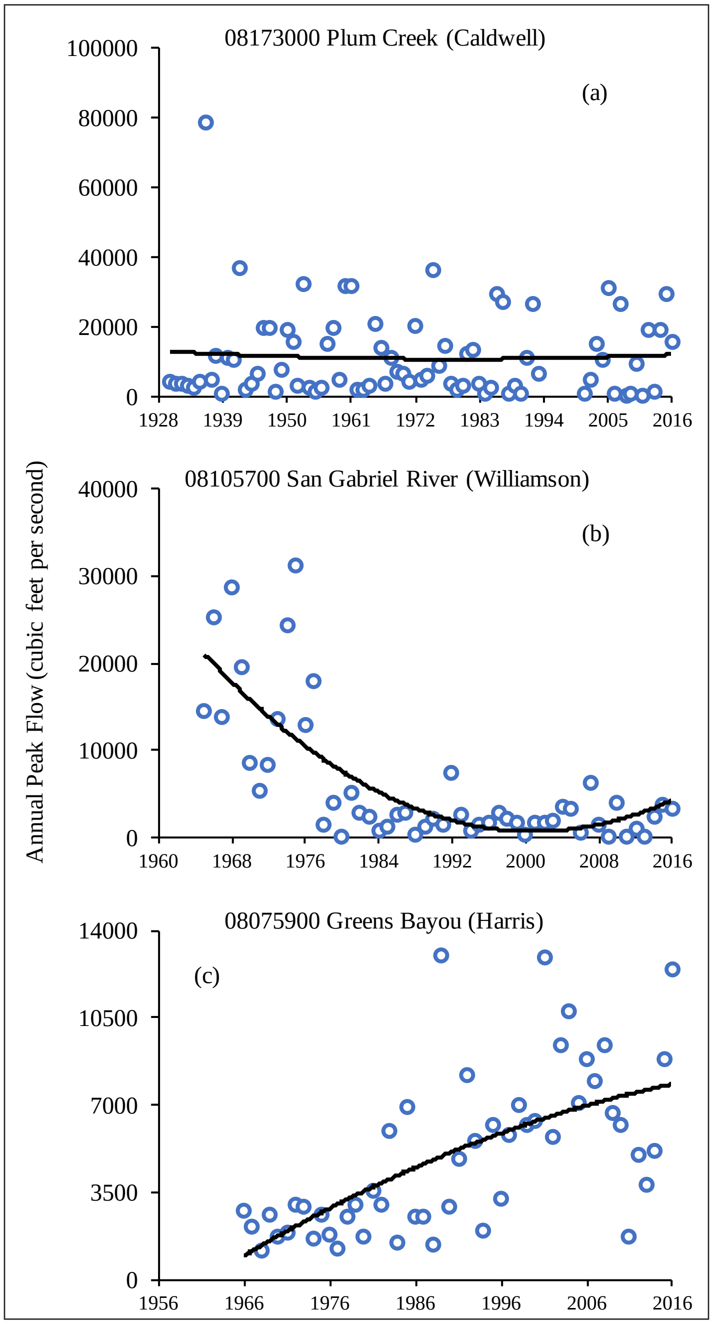

Figure 3. Examples of different peak flow patterns over time. No trend (a), downward trend (b), and upward trend (c).

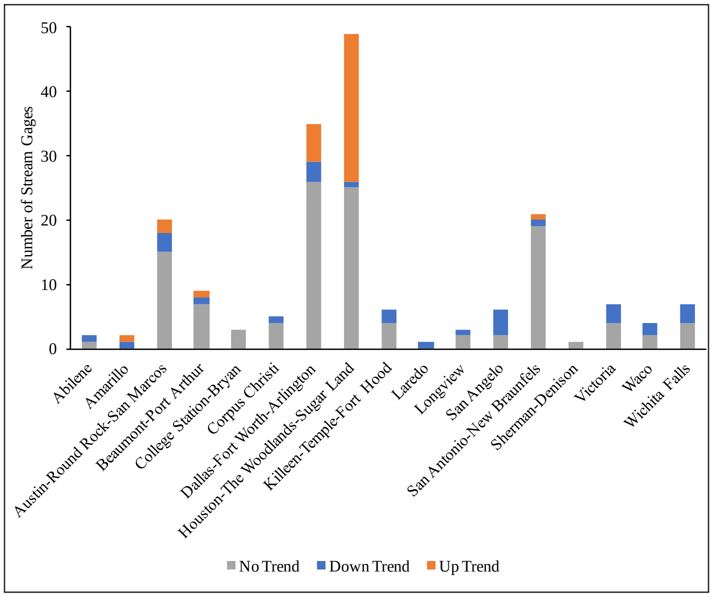

Figure 4. Number of examined stream gages exhibiting no statistically significant trends, downward trends, and upward trends in peak flow, separated by metropolitan area.

or two stream gages with streamflows that exhibit a downward trend. Finally, the geographic distribution of upward trends is illuminating, with such stream gages in a small number of metropolitan areas and nearly entirely concentrated in Dallas-Fort Worth-Arlington (6 gages) and Houston-The Woodlands-Sugar Land (23 gages). Approximately 85% of all stream gages with increasing peak flows are located in these two areas.

Examining the data at an additional level of geographic detail, the distribution of stream gages and those exhibiting trends is roughly equivalent across the counties of the Dallas-Fort Worth-Arlington area (Figure 5a). However, the number of stream gages in the Houston-The Woodlands-Sugar Land metropolitan area is dominated by Harris County, home to the City of Houston. In Harris County, an incredible 70% of stream gages exhibited upward trends (Figure 5b). Considering the data another way, Harris County represents 16.6% of urban stream gages across the entirety of Texas but a full 61.2% of gages with significantly increasing peak flows.

When including the length of the instrumental record and examining the relative change in peak flows over time, it is clear that tremendous variation exists between stream gage sites (Figure 6). Among gage locations with significantly increasing peak flows, current peak flows ranged from 102.3% of those at the beginning of the historical record to nearly 6400%—a whopping 64-fold increase. Taking into account the timing and magnitude of peak flow trends, the longest-running stream gages tend to be those with decreasing trends. These are sites on major rivers (e.g., Colorado, Brazos, Concho, and Neches rivers), and some of these today are characterized by peak flows that are essentially 0% of early historical peak flows. At the other end of the spectrum, those with the most rapidly rising peak flows tend to be found where stream gages have been installed more recently, in many cases within the last 50 years. Of note, it is interesting that 12 of 13 of the fastest rising peak flow trends are found in Harris County.

For those stream gages impacted by impoundment, the proportion of upward and downward trends is somewhat similar to that in the overall analysis. Of 84 affected locations, 22 (26.2%) exhibited significant trends, distributed equally between increasing and decreasing peak flow trends (Figure 7a).

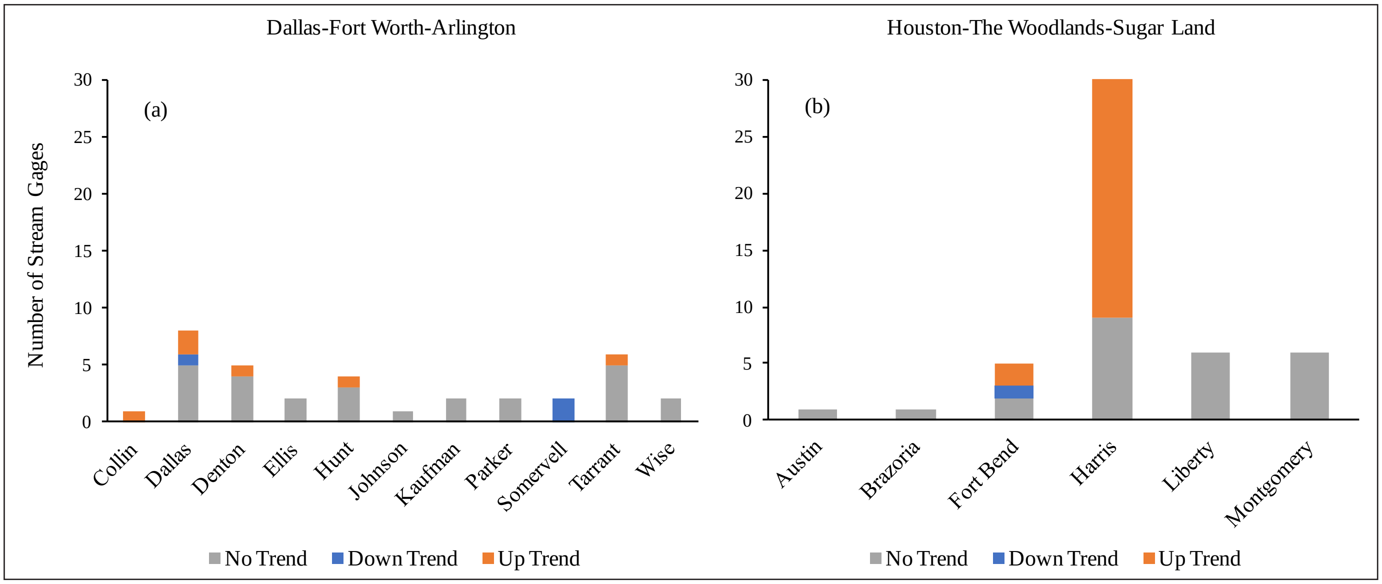

Figure 5. Number of examined stream gages in (a) Dallas-Fort Worth-Arlington and (b) Houston-The Woodlands-Sugar Land metropolitan areas exhibiting no statistically significant trends, downward trends, and upward trends in peak flow, separated by county.

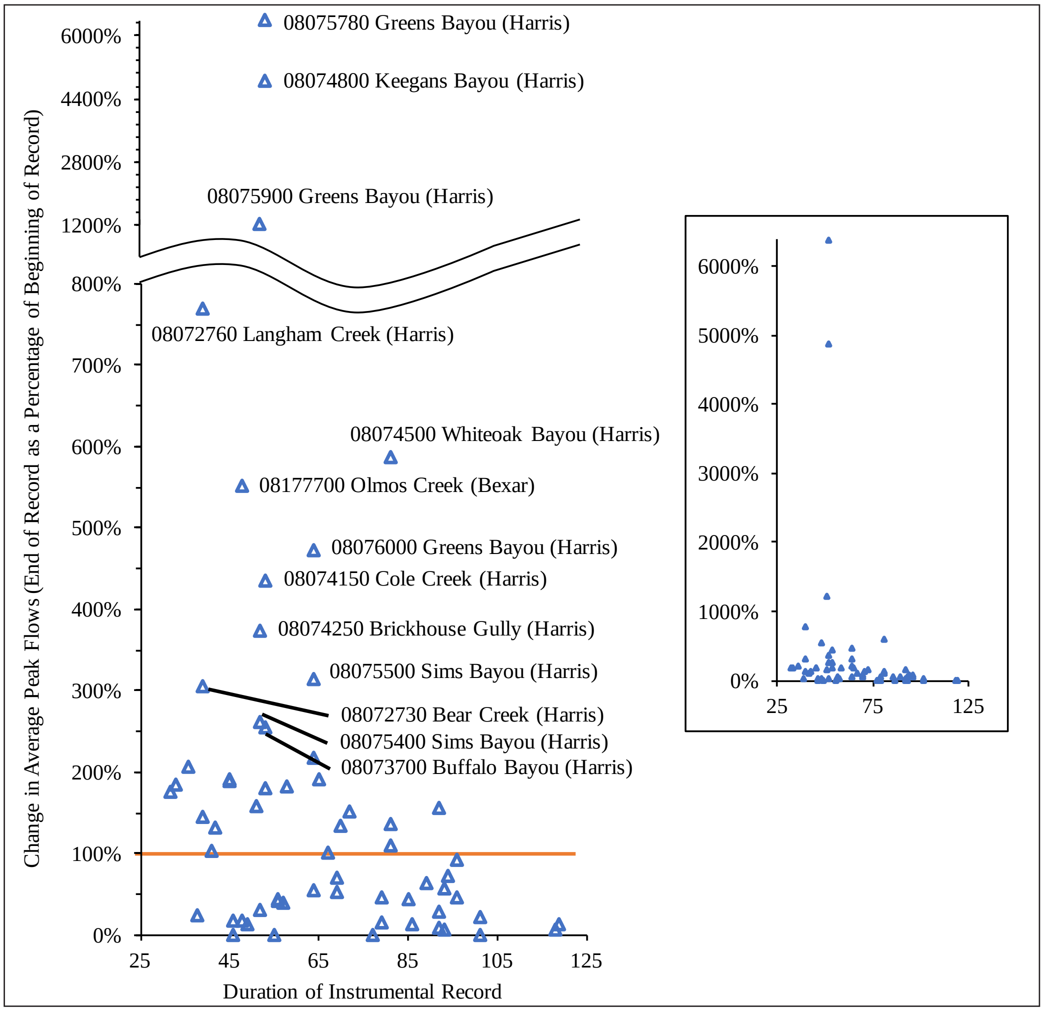

Figure 6. Relative change in peak flows (as a percentage of initial values) for those stream gages exhibiting significant trends over the period of record. The horizontal line at 100% separates increasing trends above and decreasing trends below. Inset at right displays the same data with an unbroken vertical axis and unmodified scale to visualize very high values.

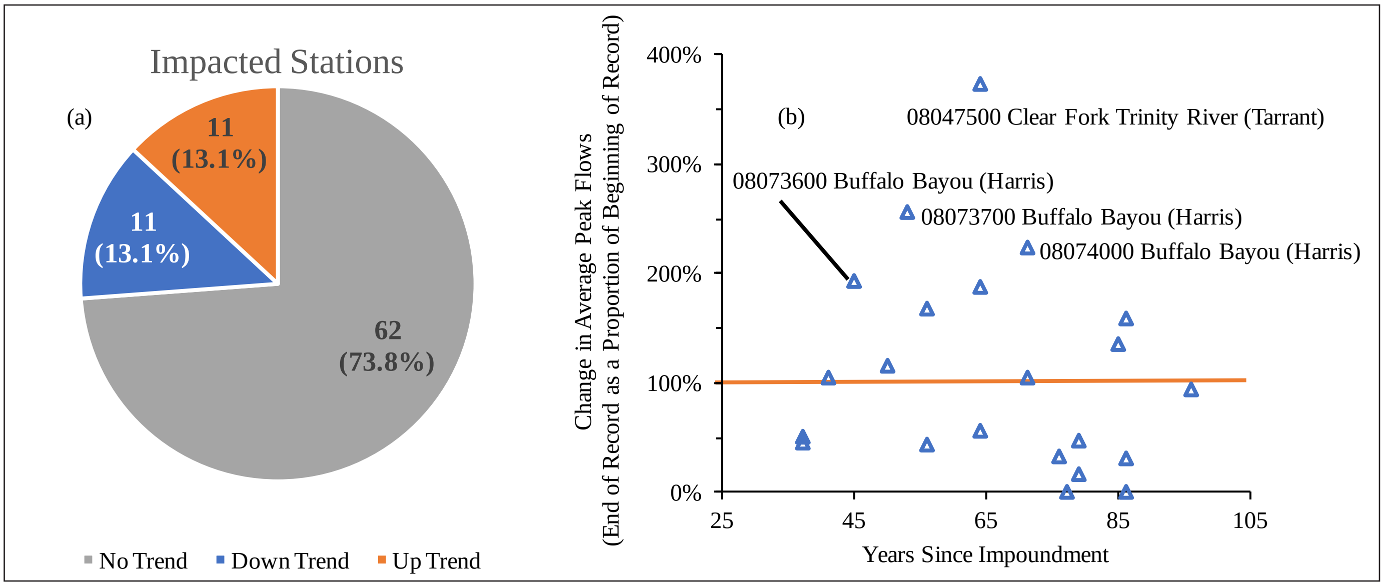

Figure 7. Summary data for stream gages impacted by impoundment in all metropolitan areas. Proportion of stream gages exhibiting no statistically significant trends, downward trends, and upward trends in peak flow (a). Relative change in peak flows (as a percentage of initial values) for those stream gages exhibiting significant trends over the period since impoundment (b). The horizontal line at 100% separates increasing trends above and decreasing trends below.

In contrast with trend magnitudes over time among all gages (Figure 6), the range of increases among this subset is much smaller, reaching a maximum of 372% (current peak flows compared with peak flows immediately following impoundment). Again, Harris County features prominently, with three different Buffalo Bayou stream gages experiencing some of the greatest increases in peak flows since upstream impoundment (Figure 7b).

DISCUSSION

Increasing peak flows

We found that, in most of the largest metropolitan areas across Texas, increasing trends in annual peak flows are rare and are actually outnumbered by decreasing trends. However, some trouble spots become clear. Nearly all of those urban streams with increasing peak flows are located in only two metropolitan areas, with the vast majority located within a single county (Harris) of one single region (Houston-The Woodlands-Sugar Land). All of these stations are within the Buffalo Bayou Basin. Identifying and comparing such emerging flooding hotspots must be a part of any statewide efforts to mitigate flooding impacts.

Of greatest importance, what do these results mean? Principally, we must understand that an upward trend in peak flows does not necessarily equate to flood frequency or severity. If a stream regularly fills only a small portion of its channel, then even a sizable increase may be manageable, with flood damage remaining minimal. However, if such increases are sustained over years (or decades) the margin between peak flows and flood impacts narrows—or worse. In many places, stream channel capacity changes over time, whether through natural processes or planned efforts to increase stormwater conveyance. However, unless such capacity increases occur along the entire length of a stream, increasing flows will eventually cause problems downstream where channel enlargement has not occurred.

Likewise, a lack of increasing trends does not indicate that floods do not occur nor even that they are not increasing. Increasing flood frequency or severity may still be possible even when mean peak flows themselves are not significantly increasing. Take, for example, the case of USGS gage 08158700 (Onion Creek at Driftwood in Hays County, Figure 8). At this location, the highest of peak flows do appear to exhibit an upward trend, while an increasing number of very low peak flows balances the highest peak flows, resulting in no overall increasing trend. Such apparent increasing variability poses significant challenges to development, management, and the environment (Ahn and Merwade 2014; Kelly et al. 2016).

With that established, identifying trends helps us see past individual flood events for a more comprehensive, deeper story. Only then can we begin to understand and ask bigger questions of the mechanisms behind stream dynamics in and near urban areas. This is an important component of successful planning and focuses on addressing root causes, not being lured into addressing symptoms. Just as steadily rising temperatures send us to a doctor to accurately diagnose the cause before prescribing a solution to the symptoms, steadily rising

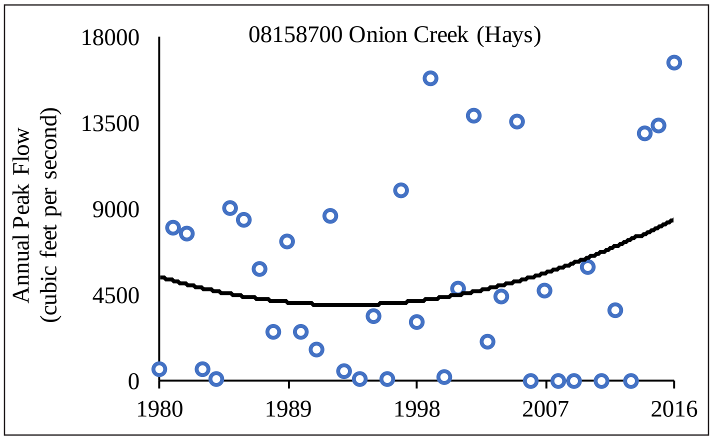

Figure 8. Peak flow history for stream gage 08158700 Onion Creek in Hays County (Austin-Round Rock-San Marcos metropolitan area). Though not exhibiting a statistically significant trend in peak flows overall, this site does reveal some interesting dynamics among very high and very low values.

peak flows should lead us to dedicate time, care, and detail in assessing flooding causes to ensure we pursue the right remedy. Anything short of this would miss an opportunity to provide adequate change, potentially with damaging consequences.

If a stream exhibits consistent increases in peak flows year after year, that raises eyebrows. If such trends are seen at a number of different locations in the same part of a single region of the state—all within the same small river basin—this should raise a series of key questions.

If that particular part of Texas (Harris County) is home to most of the increasing peak flows in the state, what might be driving these changes not seen elsewhere? Among Texas counties, Harris County by far is home to the greatest number of long-running USGS stream gages, yielding a comparatively large dataset for this study. In addition, the Harris County Flood Control District itself has an extremely robust rainfall and streamflow monitoring program (https://www.harriscountyfws.org/). That there is such a dense data collection network speaks to the long-perceived need to understand flooding in the region. Indeed, the area boasts a very large urban population and associated infrastructure, exhibits very low slopes, is typified by a climate prone to intense tropical downpours, and features a concentration of low-permeability soils. As a result, this region has experienced some of the most devastating historical floods in the state. All of these local traits point to an inherent vulnerability to high streamflows. However, the proportion of local stream gages with upward peak flow trends, not just the total number, is much larger than in any other urban area, so we must consider other factors.

Some of the large number of increasing trends in and immediately surrounding Houston are due to multiple gaging stations on certain streams (e.g., Greens Bayou and Buffalo Bayou, Figure 6), where individual gages reflect systematic and correlated changes along entire water bodies. Not coincidentally, these streams also have reputations as recurring trouble spots. However, that many streams in this area prone to flooding—each of which is a tributary of Buffalo Bayou—also display increasing trends in peak flows should draw major attention. Systematic increases suggest an underlying regional mechanism driving these changes. What could that be? Soils themselves do not evolve on annual timescales. There is some evidence that the frequency and intensity of downpours is increasing locally (Berg, in preparation). While slope changes do not occur at the watershed scale in human timescales, they might occur within streams themselves, particularly along segments where channel straightening has taken place. This process can serve to accelerate the removal of water from some locations but to deliver larger, faster flows downstream to points where the capacity to receive higher streamflows does not exist. Of note, already by the early 1980s, studies indicated an increase in storm runoff in highly developed parts of the Houston area compared with prior decades (Liscum and Massey 1980; Liscum et al. 1987). The exact response of local hydrology to urbanization varies among metropolitan areas, but this is consistent with findings in watersheds near Austin (Veenhuis and Gannett 1986) and with principles of urban hydrology (Niemczynowicz 1999; Brown et al. 2009; Fletcher et al. 2013).

To guide regional drainage design, more recent studies of the Houston area indicated a need to account for significant increases in peak streamflow as the degree of watershed development increases (Asquith et al. 2011). However, our findings indicate that these increasing peak flow trends have continued and even accelerated. Identifying the drivers in play in multiple specific locations is beyond the scope of this study. To further untangle the specific place-based drivers of increasing peak flow trends where they exist, we recommend a thorough clarification of local rainfall-runoff relationships, maintaining a very high level of spatial resolution and documenting changes with as much temporal resolution as possible.

Impoundment impacts

In the aftermath of severe flooding, a common response is to call for new dams and associated reservoirs to store floodwaters and reduce downstream impacts. This was a favorite approach among most of the state's large rivers, many of which were dammed relatively early in the state's history to address flooding and meet other needs. Our findings indicate that in some cases, this has paid major dividends in reducing peak flows. Those stream gages with the longest period of record (major rivers) typically have decreasing peak flow trends compared with historical levels (Figure 6). In a small number of cases, impoundment occurred even before stream gages were installed, obscuring the true impact of such streamflow regulation. As a result, the proportion of impounded streams with either downward or upward trends may actually be slightly higher.

With these observations, it would seem that reservoirs have a key place as part of a comprehensive flood control strategy. However, great caution is urged here. Impoundment has major economic, political, agricultural, and ecological drawbacks, sometimes extreme. If the goal is merely to reduce peak flows, then this can be effective, but with the tradeoffs of displaced landowners and communities, reduced recreation, curtailed fisheries productivity, decreased soil fertility for agriculture, and increased evaporative losses (García et al. 2011; Maestre-Valero et al. 2013; Veilleux 2013; Auerbach et al. 2014; Null et al. 2014; Stafford et al. 2017;). The decision to rely upon flood control reservoirs as a primary strategy must be made only after considering a large suite of priorities; priorities that are often in competition with one another. In considering these costs, many jurisdictions increasingly have decided to forego such projects (Poff and Hart 2002; O'Connor et al. 2015).

Even when implemented, impoundment does not guarantee permanently suppressed peak flows (Figure 7). Additionally, gaging stations impacted by impoundment actually exhibited a slightly lower frequency of downward trends in peak flows (13.1%) than did stations not impacted by impoundment (17.5%, Figure 9). While modern peak flows may no longer match historical pre-impoundment extremes, many sites impacted by impoundment yet exhibit significant increases in peak flows, in one case increasing to almost 400% of post-impoundment peak flows. In fact, as many sites exhibit increasing peak flow trends as do those exhibiting decreasing trends. And, logically, if streams are already impacted by upstream impoundments, the potential for further benefits from additional impoundment is limited. Of the 181 stream gaging stations examined in this study, 84 (46.4%) currently are affected by impoundment. Constructing flood storage reservoirs in remaining locations may prove extremely difficult, given that many of these locations are in highly developed, urbanized watersheds with limited open space.

A further caution on the reliance on dams for flood mitigation is the so-called levee effect. In many cases where engineered structures are installed, earthen or otherwise, damages behind these structures can actually increase (Tobin 1995; Burton and Cutter 2008; Di Baldassarre et al. 2015). Shifting expectations, loss of institutional memory of past events, and a perceived elimination of risk can result in catastrophic losses when upstream dams fail or are forced into emergency operations. One can see similarities with the events along Buffalo Bayou, which experienced severe and sustained flooding during and after Hurricane Harvey. Clear and aggressive communication of not just current risk but also past events can help prevent widespread underestimation of vulnerability. An increasing number of economic analyses is recognizing the value (if not complex difficulty) of accepting and adapting to the reality of periodic flooding in improving long-term viability of community development (Eakin and Appendini 2008; Merz et al. 2009; Brody and Highfield 2013). In short, reservoirs by themselves are not a silver bullet when it comes to flood mitigation.

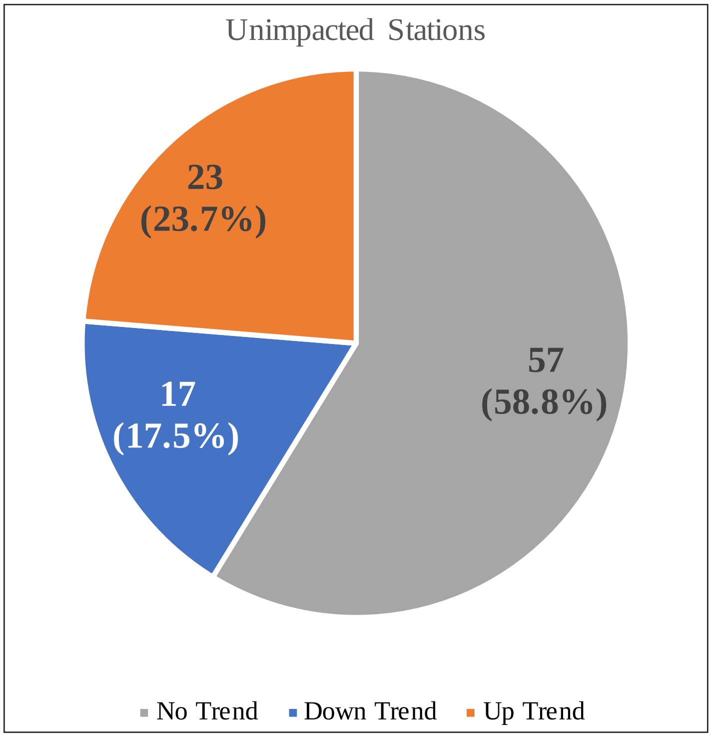

Figure 9. Proportion of examined stream gages not impacted by impoundment from all metropolitan areas exhibiting no statistically significant trends, downward trends, and upward trends in peak flow.

As an interesting last note on the impact of impoundment on peak flows, consider the difficulty of maintaining lower peak flows below a reservoir when the inflows to the reservoir exhibit extraordinary increases year over year. Of the largest upward trends in this study, two gages (on Langham Creek and on Bear Creek) are the major tributaries to Addicks Reservoir in Harris County. This flood control reservoir figured into severe flooding impacts both upstream and downstream of the critical U.S. Army Corps of Engineers dam adjacent to Buffalo Bayou. It is much easier for impoundments to store flood flows when these flows are not rapidly increasing on an annual basis. Thus, relying on large impoundment projects alone likely will not achieve success and again points back to our central emphasis of identifying causes, not just symptoms.

Challenges and needs

Peak flow frequency estimates can be computed with relative ease for natural, unregulated catchments in various areas of Texas, even those without stream gages (Heimann and Tortorelli 1988; Asquith and Slade, Jr. 1997; Asquith 1998; Asquith and Slade, Jr. 1999). At the same time, identifying baseline conditions for assessing streamflow trends can be a difficult task, especially when historical data are lacking (Tortorelli and McCabe 2001; Esralew 2010; Harwell and Asquith 2011). Furthermore, some such exercises yield single numbers that essentially assume a stationarity that, given our results, does not seem to be accurate (Sivapalan and Samuel 2009). In light of our findings, these challenges of uncertainty and watershed change generate complicated philosophical questions, such as: What does the concept of a 100-year floodplain even mean for a stream in which peak flows are 6400% of those just a couple decades ago? If peak flows in reservoir tributaries display strongly increasing trends, does it make sense to build a reservoir—within a reservoir?

Finally, we point to the eight of 25 largest metropolitan areas in Texas that have no long-term stream gaging stations, significantly hampering our ability to draw conclusions from these areas. We acknowledge that many complex variables go into decisions on stream gage placement (e.g., local population, exposure to economic impacts from floods, contributing drainage area, annual precipitation, precedent of historical events, funding availability), while also highlighting the irreplaceable value of long-term records. By focusing on urban areas in this study, we by no means intend to diminish the importance of flood damage of any degree to homes, schools, businesses, and the lives of individuals and families that do not happen to be located within metropolitan counties. Indeed, many of the costliest floods and many of the counties exposed to repeated floods are those outside designated metropolitan areas (Brody et al. 2008). In many instances, locations both within and outside of metropolitan areas are impacted by the same flood events and can provide advance notice of imminent threats to communities downstream. Metropolitan areas were simply chosen due to generally higher concentrations of population and property values in these areas, and, more importantly, the greater abundance of usable data. We applaud the recent steps by the USGS and Texas Water Development Board to expand the coverage of both stream and rain gages (AquaStrategies and Vieux 2016). As our analysis excluded a number of stations with long records that nevertheless ended years ago, we also emphasize the critical importance of not just adding new gages but maintaining existing gages in place for robust historical datasets. This will pay dividends for urban and rural communities alike.

That the trends described here are apparent even without the addition of data from Hurricane Harvey emphasizes our core message: that trends, not just events, matter. When data are incorporated from the water year that includes this tropical system, many of the increasing trends in this analysis become even more pronounced and some gages exhibiting no trends begin to exhibit significant upward trends as well.

CONCLUSIONS

A common response to severe flooding is to focus on individual events, isolated from temporal context and historical trends. Our findings suggest that this tendency is at best incomplete and a recipe for missed opportunities. We encourage decision makers to see past the events to the real trends and to resist the temptation to view floods—even the most catastrophic of disasters—as dismissible as one-off tragedies, unavoidable forces of nature, or acts of God, particularly when long-term trends paint a clear picture of increasing peak flows. Similarly, we further encourage flood planning efforts to look beyond the mere symptoms of flooding to consider and address the root causes of floods themselves. When significant increases in peak flows have been observed for many years, there is a deeper story that demands attention. Without this dedicated attention, flood mitigation planning efforts likely will not be successful. As solutions are developed, we also suggest against an overreliance on flood storage reservoirs. Finally, we urge the full maintaining of financial and technical support for streamgaging stations so that we can continue to build on the long-term records of historical sites, include additional sites as their periods of record increase, and position new sites where growing urban footprints may experience—or contribute to—flood impacts.

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REFERENCES

Ahn K-H, Merwade V. 2014. Quantifying the relative impact of climate and human activities on streamflow. Journal of Hydrology. 515(Supplement C):257-266.

Alexander JS, Wilson RC, Green WR. 2012. A brief history and summary of the effects of river engineering and dams on the Mississippi River system and delta. Reston (Virginia): U.S. Geological Survey. Report No. 1375.

AquaStrategies, Vieux. 2016. Recommendations for new stream and rain gages in Texas. Final Report. Grant No. 1600012027.

Asquith WH.1998. Peak-flow frequency for tributaries of the Colorado River downstream of Austin, Texas. Austin (Texas): U.S. Geological Survey. Report No. 98-4015.

Asquith WH. 2001. Effects of regulation on L-moments of annual peak streamflow in Texas. Austin (Texas): U.S. Geological Survey. Report No. 2001-4243.

Asquith WH, Cleveland TG, Roussel MC. 2011. A method for estimating peak and time of peak streamflow from excess rainfall for 10- to 640-acre watersheds in the Houston, Texas, metropolitan area. Reston (Virgina): U.S. Geological Survey. Report No. 2011-5104.

Asquith WH, Slade Jr RM. 1997. Regional equations for estimation of peak-streamflow frequency for natural basins in Texas. Austin (Texas): U.S. Geological Survey. Report No. 96-4307.

Asquith WH, Slade Jr RM. 1999. Site-specific estimation of peak-streamflow frequency using generalized least-squares regression for natural basins in Texas. Reston (Virginia): U.S. Geological Survey. Report No. 99-4172.

Auerbach DA, Deisenroth DB, McShane RR, McCluney KE, Poff NL. 2014. Beyond the concrete: accounting for ecosystem services from free-flowing rivers. Ecosystem Services. 10(Supplement C):1-5.

Barbie DL, Wehmeyer LL, May JE. 2012. Analysis of trends in selected streamflow statistics for the Concho River Basin, Texas, 1916-2009. Reston (Virginia): U.S. Geological Survey. Report No. 2012-5193.

Berg MD, Marcantonio F, Allison MA, McAlister J, Wilcox BP, Fox WE. 2016. Contrasting watershed-scale trends in runoff and sediment yield complicate rangeland water resources planning. Hydrology and Earth System Sciences. 20(6):2295-2307.

Breaker BK, Watson KM, Ensminger PA, Storm JB, Rose CE. 2016. Characterization of peak streamflows and flood inundation of selected areas in Louisiana, Texas, Arkansas, and Mississippi from flood of March 2016. Reston (Virginia): U.S. Geological Survey. Report No. 2016-5162.

Brody SD, Highfield WE. 2013. Open space protection and flood mitigation: a national study. Land Use Policy. 32(Supplement C):89-95.

Brody SD, Zahran S, Highfield WE, Grover H, Vedlitz A. 2008. Identifying the impact of the built environment on flood damage in Texas. Disasters 32(1):1-18.

Brown LR, Cuffney TF, Coles JF, Fitzpatrick F, McMahon G, Steuer J, Bell AH, May JT. 2009. Urban streams across the USA: lessons learned from studies in 9 metropolitan areas. Journal of the North American Benthological Society. 28(4):1051-1069.

Burton C, Cutter SL. 2008. Levee failures and social vulnerability in the Sacramento-San Joaquin Delta Area, California. Natural Hazards Review. 9(3):136-149.

Changnon SA, Kunkel KE, Andsager K. 2001. Causes for record high flood losses in the central United States. Water International. 26(2):223-230.

Costa JE, Jarrett RD. 2008. An evaluation of selected extraordinary floods in the United States reported by the U.S. Geological Survey and implications for future advancement of flood science. Reston (Virginia): U.S. Geological Survey. Report No. 2008-5164.

Di Baldassarre G, Viglione A, Carr G, Kuil L, Yan K, Brandimarte L, Blöschl G. 2015. Debates—Perspectives on socio-hydrology: capturing feedbacks between physical and social processes. Water Resources Research. 51(6):4770-4781.

Douben K-J. 2006. Characteristics of river floods and flooding: a global overview, 1985–2003. Irrigation and Drainage. 55(S1):S9-S21.

Eakin H, Appendini K. 2008. Livelihood change, farming, and managing flood risk in the Lerma Valley, Mexico. Agriculture and Human Values. 25(4):555.

Esralew RA. 2010. Determination of baseline periods of record for selected streamflow-gaging stations in and near Oklahoma for use in modeling applications. Reston (Virginia): U.S. Geological Survey. Report No. 2010-5106.

Esralew RA, Andrews WJ, Smith SJ. 2011. Evaluation and trends of land cover, streamflow, and water quality in the North Canadian River Basin near Oklahoma City, Oklahoma, 1968–2009. Reston (Virginia): U.S. Geological Survey. Report No. 2011-5117.

Esralew RA, Lewis JM. 2010. Trends in base flow, total flow, and base-flow index of selected streams in and near Oklahoma through 2008. Reston (Virginia): U.S. Geological Survey. Report No. 2010-5104.

Fletcher TD, Andrieu H, Hamel P. 2013. Understanding, management and modelling of urban hydrology and its consequences for receiving waters: a state of the art. Advances in Water Resources. 51(Supplement C):261-279.

García A, Jorde K, Habit E, Caamaño D, Parra O. 2011. Downstream environmental effects of dam operations: changes in habitat quality for native fish species. River Research and Applications. 27(3):312-327.

Harwell GR, Asquith WH. 2011. Annual peak streamflow and ancillary data for small watersheds in central and western Texas. Reston (Virginia): U.S. Geological Survey. Report No. 2011-3082.

Heimann DC, Tortorelli RL. 1988. Statistical summaries of streamflow records in Oklahoma and parts of Arkansas, Missouri, and Texas through 1984. Reston (Virginia): U.S. Geological Survey. Report No. 87-4205.

Heitmuller FT, Greene LE. 2009. Historical channel adjustment and estimates of selected hydraulic values in the Lower Sabine River and Lower Brazos River Basins, Texas and Louisiana. Reston (Virginia): U.S. Geological Survey. Report No. 2009-5174.

Kelly CN, McGuire KJ, Miniat CF, Vose JM. 2016. Streamflow response to increasing precipitation extremes altered by forest management. Geophysical Research Letters. 43(8):3727-3736.

Kulshreshtha SN, Gillies JA. 1993. Economic evaluation of aesthetic amenities: a case study of river view. Journal of the American Water Resources Association. 29(2):257-266.

Lettenmaier DP, Wood EF, Wallis JR. 1994. Hydro-climatological trends in the continental United States, 1948-88. Journal of Climate. 7(4):586-607.

Liscum F, Bruchmiller JP, Brown DW, Paul EM. 1987. Hydrologic data for urban studies in the Houston metropolitan area, Texas, 1984. Austin (Texas): U.S. Geological Survey. Report No. 86-608.

Liscum F, Massey BC. 1980. Technique for estimating the magnitude and frequency of floods in the Houston, Texas, Metropolitan Area. Austin (Texas): U.S. Geological Survey. Report No. 80-17.

Lucena Z, Lee MT. 2017. Characterization of streamflow, suspended sediment, and nutrients entering Galveston Bay from the Trinity River, Texas, May 2014–December 2015. Reston (Virginia): U.S. Geological Survey. Report No. 2016-5177.

Maestre-Valero JF, Martínez-Granados D, Martínez-Alvarez V, Calatrava J. 2013. Socio-economic impact of evaporation losses from reservoirs under past, current and future water availability scenarios in the semi-arid Segura Basin. Water Resources Management. 27(5):1411-1426.

McKean JR, Johnson DM, Johnson RL, Garth Taylor R. 2005. Can superior natural amenities create high-quality employment opportunities? the case of nonconsumptive river recreation in central Idaho. Society & Natural Resources. 18(8):749-758.

Merz B, Elmer F, Thieken AH. 2009. Significance of "high probability/low damage" versus "low probability/high damage" flood events. Natural Hazards and Earth Systems Sciences. 9(3):1033-1046.

Niemczynowicz J. 1999. Urban hydrology and water management – present and future challenges. Urban Water. 1(1):1-14.

Null SE, Medellín-Azuara J, Escriva-Bou A, Lent M, Lund JR. 2014. Optimizing the dammed: water supply losses and fish habitat gains from dam removal in California. Journal of Environmental Management. 136(Supplement C):121-131.

O'Connor JE, Costa JE. 2004. Spatial distribution of the largest rainfall-runoff floods from basins between 2.6 and 26,000 km2 in the United States and Puerto Rico. Water Resources Research. 40(1).

O'Connor JE, Duda JJ, Grant GE. 2015. 1000 dams down and counting. Science. 348(6234):496.

Pinter N, Thomas R, Wlosinski JH. 2001. Assessing flood hazard on dynamic rivers. Eos, Transactions of the American Geophysical Union. 82(31):333-339.

Poff NL, Hart DD. 2002. How dams vary and why it matters for the emerging science of dam removal. BioScience. 52(8):659-668.

Schumann GJP, Frye S, Wells G, Adler R, Brakenridge R, Bolten J, Murray J, Slayback D, Policelli F, Kirschbaum D et al. . 2016. Unlocking the full potential of Earth observation during the 2015 Texas flood disaster. Water Resources Research. 52(5):3288-3293.

Sharif HO, Jackson TL, Hossain MdM, Zane D. 2015. Analysis of flood fatalities in Texas. Natural Hazards Review. 16(1):04014016.

Sivapalan M, Samuel JM. 2009. Transcending limitations of stationarity and the return period: process-based approach to flood estimation and risk assessment. Hydrological Processes. 23(11):1671-1675.

Slade Jr. RM, Patton JM. 2003. Major and catastrophic storms and floods in Texas: 215 major and 41 catastrophic events from 1953 to September 1, 2002. Reston (Virginia): U.S. Geological Survey. Report No. 2003-193.

Stafford E, Fey N, Vaske JJ. 2017. Quantifying whitewater recreation opportunities in Cataract Canyon of the Colorado River, Utah: aggregating acceptable flows and hydrologic data to identify boatable days. River Research and Applications. 33(1):162-169.

Tobin GA. 1995. The levee love affair: a stormy relationship? Journal of the American Water Resources Association. 31(3):359-367.

Tortorelli RL, McCabe LP. 2001. Flood frequency estimates and documented and potential extreme peak discharges in Oklahoma. Reston (Virginia): U.S. Geological Survey. Report No. 2001-4152.

Veenhuis JE, Gannett DG. 1986. The effects of urbanization on floods in the Austin metropolitan area, Texas. Austin (Texas): U.S. Geological Survey. Report No. 86-4069.

Veilleux JC. 2013. The human security dimensions of dam development: the grand Ethiopian renaissance dam. Global Dialogue (Online). 15(2):42.

Wilson MA, Carpenter SR. 1999. Economic valuation of freshwater ecosystem services in the United States: 1971–1997. Ecological Applications. 9(3):772-783.

Winters KE. 2012. Floods in Central Texas, September 7-14, 2010. Texas Water Journal. 3(1):14-25.