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Impact of hurricane Harvey on the results of regional flood frequency analysis

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Abstract

Hurricane Harvey was an unprecedented event that resulted in immense damage to life and property. As a result, it is important to determine how this event, as well as past and future events like it, will impact engineering design equations that are based upon historical data, such as flood frequency analysis equations. This study seeks to contribute to this discussion by evaluating the extent to which Harvey influenced estimations of instantaneous peak discharges in rural ungauged basins in southeast Texas. Results indicate that Harvey significantly increased the computations of design floods using Log-Pearson Type III analysis (e.g., 3–55% for 2-year flood and 3–80% for the 100-year flood). This subsequently impacted the estimation of instantaneous peak discharges through regional flood frequency analysis by up to 28%. These results highlight the influence that

recent and future hurricanes can have on engineering design equations that are used for managing floodplains, assessing flood risk, and designing infrastructure such as levees, bridges, and culverts.

1 INTRODUCTION

In August 2017, Hurricane Harvey headed towards the Texas coast as it grew to Category 4 strength with maximum wind gusts of 241 km per hour and a storm surge of 3.7 m. It made landfall near Rockport, Texas on Friday August 25, 2017 and then moved inland and remained relatively stationary for 4 days before heading back out into the Gulf. Although it produced massive damage due to winds and storm surge, its greatest devastation was due to the extreme rainfall that produced unprecedented flooding in Houston and its surrounding areas. These areas received extraordinary rainfall totals, including a maximum total rainfall of 51.9 in. in Cedar Bayou in Houston (NOAA, **2017**), and a return period for the 3-day precipitation amount exceeding 1,000 year (750 mm over 3 days) over a large area (Van Oldenborgh et al., **2017**). This resulted in intense flooding that damaged or destroyed over 200,000 homes and businesses, displaced over 30,000 people, and caused 80 deaths, mostly as the result of drowning (NOAA, **2018**).

In the aftermath, many have asked what can be done to prevent widespread flooding during such an extreme event. Fortifying Houston to withstand the impact of Harvey is economically infeasible; however, including the risk of the hurricane within future engineering designs is a practical first step, and one that can and should be a critical piece of the solution moving forward. As engineers and researchers continue to consider the solutions to extreme flooding, part of the discussion will centre around the degree to which such storms might impact existing engineering design methodologies. In this study, we seek to contribute to that discussion by determining the extent that Hurricane Harvey has on the prediction of instantaneous peak discharges through regional flood frequency analysis of rural ungauged basins.

Flood frequency analysis uses records of annual maximum instantaneous peak discharge to estimate the magnitude and frequency of peak floods. These estimates can be applied within regional regression, along with basin characteristics, to develop equations that can estimate the magnitude and frequency of peak discharge at a stream site. These peak discharge estimates are critical for managing flood plains, assessing flood risk, and designing infrastructure such as levees, dams, roads, bridges, and culverts. Recommended procedures for regional flood frequency analysis are provided in Bulletin 17B, Guidelines for Determining Flood Frequency by the Interagency Advisory Committee on Water Data (1982). State-level agencies follow these guidelines, usually in partnership with the United States Geological Survey (USGS), to develop regional peak flow regression equations for use in state and local engineering procedures. While in use since 1982, updates to the regional flood frequency analysis methodology are currently being considered, including changes in how historical data and low outliers are treated (Thomas, **2016**). What is not firmly addressed within these updates are specific guidelines for how to consider the influences of non-stationarity or climate change on instantaneous peak discharges.

This is important, as regional flood frequency analysis is an empirical method that relies on historical data that have inherent limitations including the length of record and a non-stationary climate. Additionally, research has shown that climate change may alter the magnitude and frequency of extreme floods in the United States (Mallakpour & Villarini, **2015**). In fact, researchers have shown that Hurricane Harvey was intensified by about 15% due to global warming (Van Oldenborgh et al., **2017**). This suggests that historical records alone may not adequately capture future flood risks. Researchers have sought to address this shortcoming by evaluating how climate change will impact future peak flows and incorporating it into modifications to the flood frequency analysis methodology (Camici, Brocca, Melone, & Moramarco, **2013**; Gilroy & McCuen, **2012**; Kwon, Sivakumar, Moon, & Kim, **2011**; Stedinger & Griffis, **2011**); however, a consensus on how to do so has not been reached (England et al., **2015**).

It is important to develop reliable and accurate predictions that account for climate uncertainty; however, little research have been done to evaluate the degree to which recent extreme events, such as Hurricane Harvey, influence design floods and subsequent regional peak flow regression equations. This knowledge is critical for contextualising the integration of non-stationarity into the existing flood frequency analysis methodology. It can also immediately help planners and engineers manage infrastructure and develop engineering designs with an accurate understanding of flood risks in light of current and future extreme events.

This study therefore seeks to (a) identify the impact that Hurricane Harvey had on flood frequency at gauges in southeast Texas and (b) the subsequent influence that this impact has on regional flood frequency analysis equations. In doing so, we hope to demonstrate the impact that recent and future extreme events, intensified by anthropogenic forces, may have on estimating flood risk with regional flood frequency analysis procedures outlined in Bulletin 17B. Finally, we discuss the implications that this has for application of the equations within engineering design.

2 METHODOLOGY

2.1 Study location

Harvey impacted the entire Texas and Louisiana coast; however, the area that received the greatest amount of precipitation was around the City of Houston in southeast Texas. A previous regional regression study defined common physiographic and climatic regions for the state of Texas (Asquith & Slade Jr, **1997**), with Region 11 encompassing Houston and its surrounding areas (Figure **1**). This region is therefore the focus of this study. Common physiographic regions, such as those shown in the figure, are developed within regional flood frequency analyses as a way to group gauges that are similar in hydrologic response. In the referenced study, regional boundaries for the state of Texas were developed based upon the density of the stations, watershed boundaries, and precipitation and evaporation patterns.

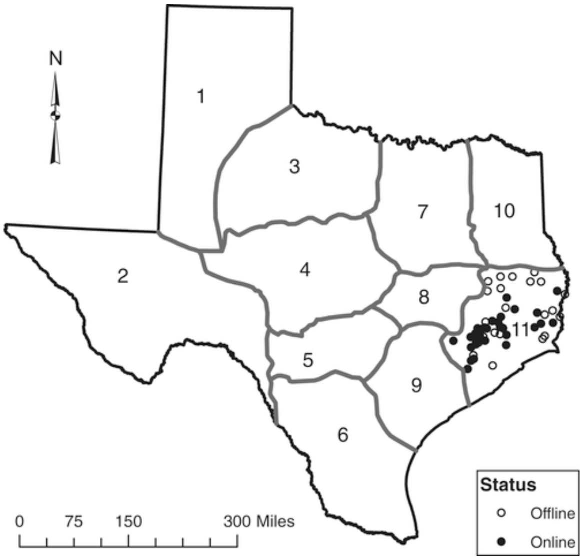

Figure 1 Case study region and gauges used in analysis in Southeast Texas; adapted from Asquith and Slade Jr (1997)

Within this region, 52 gauges were selected for analysis (Figure **1**). These gauges had to meet several criteria to be included in regional flood frequency analysis: they had to capture rural watersheds less than 10% developed, they had to be unregulated (i.e., no significant dams or impoundments), and they had to have at least 10 years of record, which is the minimum record length recommended for frequency analysis in Bulletin 17B. Of the 52 gauges, only 30 captured instantaneous peak discharge information from Hurricane Harvey. The remaining 22 gauges contained historical systematic years of record but were offline and therefore did not capture the impact of Hurricane Harvey. The watersheds of the 52 gauges ranged in size from 14 to 57,037 km^2, with a median of 237 km^2. The historical annual flood peak data from these 52 gauges were subsequently used in the Log-Pearson III flood frequency analysis.

2.2 Log-Pearson III analysis

Flood frequency curves were generated using USGS Peak FQ software (Veilleux, Cohn, Flynn, Mason Jr, & Hummel, **2014**) and followed the standard procedures as outlined within Bulletin 17B of the Interagency Advisory Committee on Water Data (**1982**). The Bulletin 17B procedures assume annual events are independent random variables that follow a Log-Pearson Type III probability distribution. Before developing the distribution, annual record flows were adjusted for outliers, historic peaks, and generalised skew. Low outliers were detected using the single Grubbs and Beck (**1972**) global Potentially Influential Low Flows test option. The weighted skew option within Peak FQ was used, which combines the station skew and generalised skew to create a more accurate measurement of the skew coefficient for a given watershed. Finally, Peak FQ generated quantiles of the Log-Pearson Type III distribution for selected exceedance probabilities (2, 5, 10, 25, 50, 100, and 200 year). The Log-Pearson Type III distribution was performed on two different sets of data: (a) those up to water year 2016 and (b) those up to water year 2017 (i.e., including Hurricane Harvey). The peak flow exceedance probabilities of the two data sets were compared in order to evaluate the effect that the inclusion of Hurricane Harvey has on the magnitude of the exceedance probabilities.

2.3 Flood frequency curve considerations and limitations

The Log-Pearson III distribution has been in use by U.S. Federal agencies since 1967 (USWRC, **1967**) and is the recommended procedure within Bulletin 17B. It is also the distribution of choice in the United States going forward as the work group tasked with revising Bulletin 17B has recommended continued use of the Log-Pearson III distribution based upon robust testing (Cohn et al., **2014**; Griffis & Stedinger, **2007a**) and numerous case studies over the past five decades (Thomas, **2016**). Having a national standard for flood frequency analysis is advantageous because it provides objectivity; however, it precludes optimal fitting of the distribution for a particular basin. To this end, there are many other distributions that are used in flood frequency analysis, such as the Generalised Extreme Value distribution, which is adopted by many European Countries (e.g., Sutcliffe, **1978**), and other less common distributions such as Gumble EV1, Weibull, Generalised Pareto, and Generalised Logistic (Kidson & Richards, **2005**; Stedinger, **1993**). These methods are classically applied to annual peak flows, but alternative partial duration series approaches, such as peaks over thresholds, can be used that include every event over a certain threshold in the analysis. These provide more control over the selection of what is considered a flood in the analysis; however, drawbacks include how to pick a threshold and selection criteria for including flood peaks (Lang, Ouarda, & Bobée, **1999**).

Regardless of the statistical approach, there are limitations to fitting a statistical distribution to a set of peak flow records. For example, limited records at a gauge could introduce error due to sampling because the estimated flood probabilities are greater than the period of record. Short gauging records may not adequately represent long-term conditions if they only capture a wet or drought period, or if it is known that substantial storms happened before or after the period of record at the station. As such, it is generally known that the error increases as both the return period increases and the period of record decreases (McCuen & Galloway, **2010**).

Specifically, when a flood return period represents a longer time frame than the gauging record, that flood can have a significant impact on the fitting of the flood frequency distribution (i.e., the station skew coefficient). The station skew coefficient represents asymmetry of the probability distribution and is highly sensitive to peaks in the upper tail of the distribution; therefore, it is difficult to obtain accurate skew coefficients for stations with small sample sizes. Furthermore, the flood frequencies may be significantly impacted by peculiarities of the peak flows at a site. These issues can be accounted for by using a weighted skew coefficient that combines the station skew with regional skew information, which in turn improves the accuracy of the estimated skew coefficient (Griffis & Stedinger, **2007b**). Alternatively, the period of record could be extended through continuous physically based models or by combining data from regional gauges with longer periods of record (Hirsch, **1982**).

As mentioned, in this case study we follow Bulletin 17B procedures and therefore apply a Log-Pearson III distribution. By using the nationalised standard, we do not evaluate the annual peak flow records against all possible distributions; however, we use a weighted skew coefficient to improve the fit of the flood frequency distribution. For many gauges Harvey was an extraordinary flood, or the largest magnitude flood at the gaging station, and therefore Harvey may have a significant impact on the fit of the distribution. To this end, we evaluated the extent to which Harvey's exceedance probability, derived from Log-Pearson III analysis, exceeds the period of record for gauges in the study. In addition, we evaluated the correlation between the period of record, and the extent that Harvey influenced design floods. In doing so, we attempt to shed light on the limitations of evaluating an extraordinary flood that is constrained by periods of record shorter than its exceedance probability under Bulletin 17B procedures.

2.4 Non-stationarity tests

As mentioned, researchers have shown that Harvey was intensified by about 15% due to global warming (Van Oldenborgh et al., **2017**), which raises concerns about the validity of the stationarity assumption in annual peak flows. We therefore checked this assumption in the flood peak record through the detection of abrupt changes and monotonic trends using non-parametric tests. Abrupt changes in the mean of the flood peak distribution for each gauge were detected using the Pettitt test (Pettitt, **1979**). The Pettit test is an adaptation of the rank-based Mann–Whitney statistic that tests whether two samples come from the same population and is effective at detecting abrupt changes in the mean of flood peak distributions (Barth, Villarini, Nayak, & White, **2017**; Villarini, Smith, Baeck, & Krajewski, **2011**). If no change point is present, monotonically increasing or decreasing trends were detected using both the Mann–Kendall and Spearman's rho tests. In the case that a change point is detected, these tests were performed on subsets of data before and after the change point. The Mann–Kendall and Spearman's rho tests are commonly used to detect monotonic trends in flood peaks (Helsel & Hirsch, **2002**) and using both can provide clearer evidence of a trend or lack thereof in the flood peak records (e.g., Villarini, Serinaldi, Smith, & Krajewski, **2009**). The significance level for all tests was set to 5%. While we focus this study on abrupt changes and monotonic trends, we recognise that other types of trends may also be present.

2.5 Regional flood frequency analysis

The USGS Weighted Multiple Linear Regression (WREG) software was used to perform weighted least squares (WLS) regression. Details on the procedure used by WREG software can be found in the user's guide (Eng, Chen, & Kiang, **2009**). Variables considered were drainage area, basin shape factor, and stream slope, as these were the variables considered in the original regional flood frequency study (Asquith & Slade Jr, **1997**). Drainage area (DA) represents the contributing drainage area in square miles, the basin shape factor (SH) is the ratio of the square of the stream length to the drainage area, and the stream slope (SL) is the slope in feet per mile of the longest flow path of the drainage area. Traditional regional flood frequency analysis methods determine a final set of parameters by first generating a large set of candidate parameters, determining those that exhibit statistical significance, and evaluating parameters for multicollinearity. However, because the referenced study performed this on the same watersheds, and the focus of this study is not on the parameterization, the variables considered in the referenced study (DA, SH, and SL) were used as a final set of parameters.

These variables were developed using the following datasets. Gauge locations, as well as instantaneous peak flow values, were obtained from the USGS Surface Water Data from the Nation (**http://waterdata.usgs.gov/nwis/sw**). Digital elevation data from National Elevation Dataset (NED) was obtained from the USGS National Map Download Platform (**http://viewer.nationalmap.gov/viewer**). Using these datasets, drainage area, basin SH, and SL were computed using ESRIs ArcMap software.

Finally, WLS was performed on two sets of data (a) all gauges up to water year 2016 and (b) all gauges up to water year 2017. The purpose of this comparison was to ultimately evaluate how Hurricane Harvey would impact the development of flood frequency equations.

3 RESULTS AND DISCUSSION

3.1 Log-Pearson III analysis

3.1.1 Influence of Harvey

Log-Pearson III analysis was performed on instantaneous peak stream gauge data both with and without Hurricane Harvey, and it was found that Harvey significantly influences peak discharge exceedance probabilities. Figure **2** illustrates the percentage change of the estimated design floods as a function of the exceedance probability or return period. As illustrated, Harvey has a significant impact on computation of design floods. For example, there was a median difference of 27% for the 100-year flood at the 31 active sites. An illustration of where these occurred is shown in Figure **3**, which maps the percentage change of the 100-year flood at each gauge location. As illustrated, a significant portion of the gauges were impacted in and around Houston, as well as the surrounding areas.

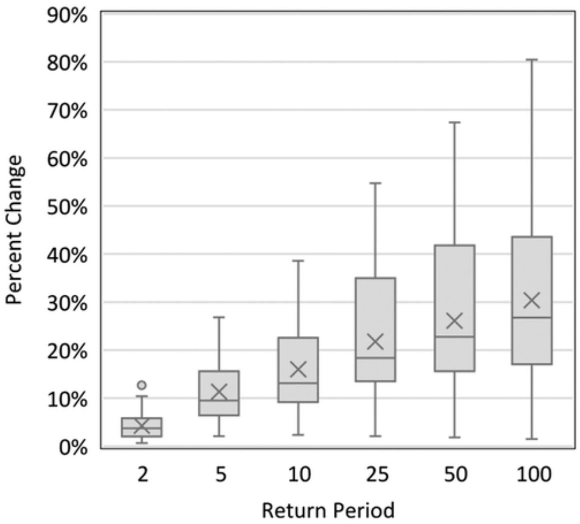

Figure 2 Percentage change in the return period from the inclusion of hurricane Harvey using LPIII analysis

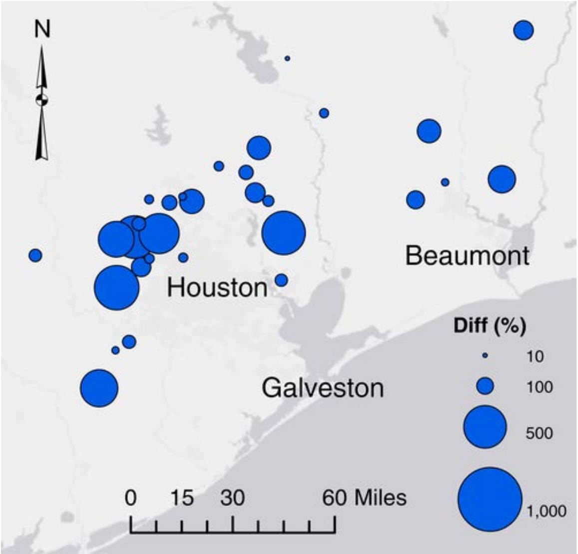

Figure 3 LPIII 100-year flood increase due to hurricane Harvey

It is known that the period of record used in a flood frequency analysis can significantly affect the results, and that shorter periods of record may tend to overestimate design flows (Victorov, **1971**) and result in greater error of the estimates (McCuen & Galloway, **2010**). Therefore, to investigate how record length may impact the fitting of the flood frequency distribution, we sought to evaluate the strength of the relationship between record length and Harvey's impact on return period peak discharges. This is illustrated in Figure **4**, which plots the percentage difference in peak discharge of the 2- and 100-year floods computed before and after Harvey, as a function of the years of record at a gauge. From this figure, it is clear that the percentage difference for the 2- and 100-year floods decreases with increasing years of record. This trend may be due to a greater error of the estimates among gauges with shorter periods of record, which would suggest that stations with longer years of record are helpful for contextualising extreme floods, as they seem to be less influenced by Harvey. Even so, the percentage change in the 100-year return flood for those with more than 75 years of record ranged between 15 and 21%.

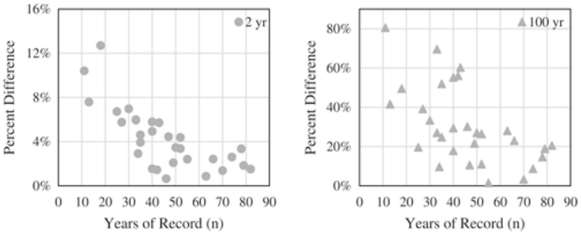

Figure 4 Percentage change in the return period (2 and 100 year) as a function of the years of record (*n*) at the stream gauge

The Log-Pearson III analysis was also used to evaluate Harvey's instantaneous peak discharge return period at the gauges. Using an analysis with records up to 2017, it was found that the instantaneous peak discharge produced by Harvey had a median return period of 77 years (Figure **5**). The estimated return period of Harvey was greater than the number of annual peaks for 83% of the gauges. In addition, the instantaneous peak discharge during Harvey was the greatest on record for 63% of the gauges used in the analysis. Other floods of significance that were the greatest on record for many of the remaining gauges include Hurricane Rosa (1994), Tropical Storm Allison (2001), Memorial Day (2015), and Tax Day (2016).

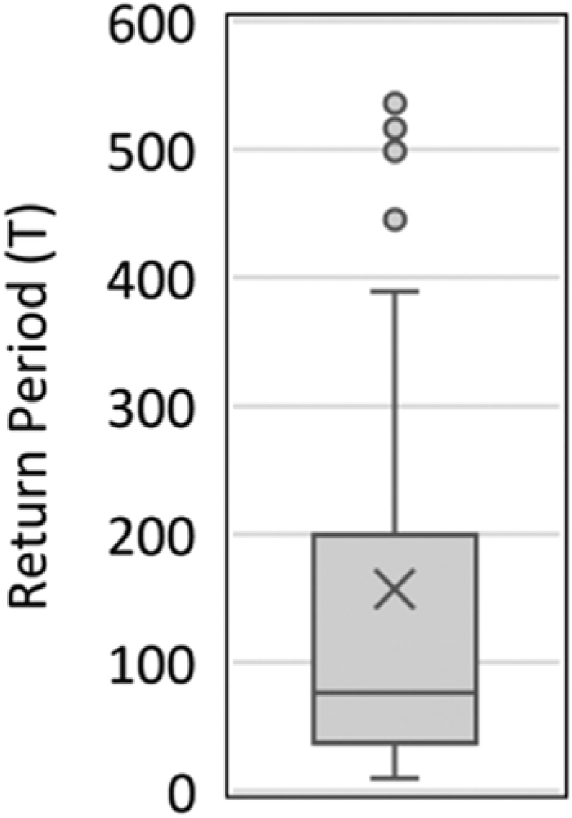

Figure 5 Return period of instantaneous peak discharge attributed to hurricane Harvey for the active gauges

3.1.2 Non-stationarity tests

The annual peak flow records were tested for abrupt changes using the Pettitt test and for monotonic trends using the Mann–Kendall and Spearman's rho tests. Of the 52 gauges used in the analysis, five gauges indicated either a change point or an increasing monotonic trend in annual peak flow records. We examined the USGS metadata (i.e., peak streamflow and gauge height qualification codes) at these gauges to determine if any changes to the gauge sites may have influenced their measurements. The metadata from two of these gauges, USGS 08072730 and 08072760, indicated that the base discharge and gauge datum changed, after which both gauges showed statistically significant abrupt changes (Pettitt $p < 0.0001$). Of the three remaining gauges, two had metadata that indicated a change in base discharge. The results from the monotonic trend test on these gauges as well as from the subset of annual peak flows before and after the change points for 08072730 and 08072760, are provided in Table 1. While five gauges indicated a violation of the stationarity assumption, four of the five may be due to changes in base discharge and/or gauge datum rather than climate or land use changes, and the clear majority showed no stationarity violation. To this end, although Harvey was found to be influenced by global warming (Van Oldenborgh et al., **2017**), based upon this analysis it does not appear that global warming exhibits a significant influence on the stationarity of annual peak flows in this region.

Table 1. Non-parametric monotonic trend test results

USGS gauge	*S*	M-K	Gauge code
08072730a	0.02	0.012	D, 6
08072760a	0.027	0.02	D, 6
08072760b	0.028	0.025	D, 6
08029500	0.039	0.031	
08074020	0.015	0.021	D
08115000	0.042	0.039	D

Note. S: Spearman's rho *p*-value; M-K: Mann–Kendall *p*-value; D: Base Discharge changed; 6: Gauge datum changed.

[a] Record after change point.
[b] Record before change point.

3.2 Regional flood frequency analysis

A regional flood frequency analysis was performed on the full set of 53 gauges using two sets of data (with and without Harvey) and it was found that Harvey increased the estimated flow rate of the regression equations by up to 28%. The regional regression equations that estimate return period floods as a function of geomorphologic basin characteristics are shown in Tables 2 and 3 for return periods 2–100 years. A graphical comparison of these equations is shown in Figure 6. This figure demonstrates the change in peak flow between the equations with (Table 3) and without (Table 2) Harvey as a function of the drainage area; the peak flows in this figure were computed using the physical characteristics of the 53 basins used in the analysis. As illustrated, this percentage change in peak flow due to Harvey increases from the 2- to 100-year storm. For example, the percentage change for a drainage area of 100 km^2 differs between 1% for a 2-year storm and 19% for a 100-year storm.

Table 2. Regression results for annual peak flows up to 2016

Equation	Sp(%)	Pseudo R^2	SME (%)
Log10(0.5 peak) = 2.492 + 0.613*Log10(DA) - 0.372*Log10(SH)	49.4	84.18	47.7
Log10(0.2 peak) = 2.736 + 0.508*Log10(DA)	55.31	79.98	53.99
Log10(0.1 peak) = 2.549 + 0.558*Log10(DA) +0.333*Log10(SL)	57.67	79.09	55.59
Log10(0.04 peak) = 2.607 + 0.568*Log10(DA) +0.448*Log10(SL)	62.47	76.55	60.13
Log10(0.02 peak) = 2.649 + 0.572*Log10(DA) +0.519*Log10(SL)	66.74	74.37	64.17
Log10(0.01 peak) = 2.688 + 0.576*Log10(DA) +0.580*Log10(SL)	71.51	72.03	68.69

Note. DA: drainage area (km^2); Sp: average standard error of prediction; SME: standard model error; Sp, pseudo-R^2, and SME computed using Log10(peak); peak flows given in ft^3/s.

Table 3. Regression results for annual peak flows up to 2017 and including hurricane Harvey

Equation	Sp(%)	Pseudo R^2	SME (%)
Log10(0.5 peak) = 2.511 + 0.604*Log10(DA) -0.358*Log10(SH)	50.03	83.57	48.32
Log10(0.2 peak) = 2.791 + 0.496*Log10(DA)	55.78	78.98	54.45
Log10(0.1 peak) = 2.620 + 0.542*Log10(DA) +0.337*Log10(SL)	58.5	77.54	56.39
Log10(0.04 peak) = 2.704 + 0.546*Log10(DA) +0.451*Log10(SL)	64.07	74.1	64.66
Log10(0.02 peak) = 2.763 + 0.547*Log10(DA) +0.522*Log10(SL)	69.07	71.17	66.41
Log10(0.01 peak) = 2.819 + 0.547*Log10(DA) +0.584*Log10(SL)	74.67	68.05	71.72

Note. DA: drainage area (km^2); Sp: average standard error of prediction; SME: standard model error; Sp, pseudo-R^2, and SME computed using Log10(peak); peak flows given in ft^3/s.

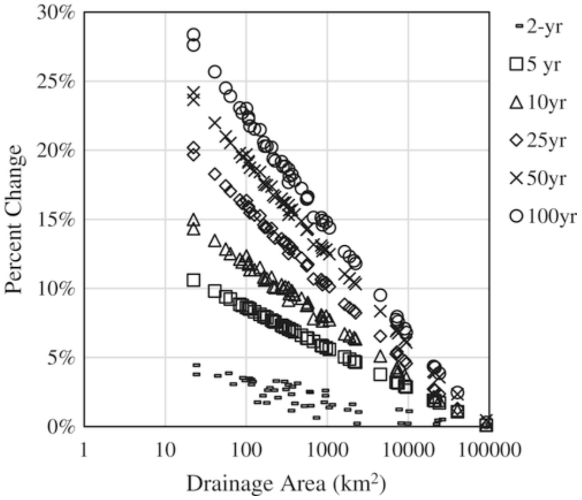

Figure 6 Percentage change in peak flow as a function of the drainage area for the 2- to 100-year design floods

This increase in estimated peak flows is significant, especially considering that 42% of the gauges used in the regional regression analysis were offline. This means that 42% of the dependent variables in the regional regression analysis (i.e., peak flow exceedance probabilities) were developed without considering Harvey. It may be assumed that in regions where the percentage of online gauges is greater, the influence of recent extreme events on a regional regression analysis will be greater as well. This highlights a limitation of the analysis and suggests that it could underestimate the impact that Harvey has on design equations. Therefore, this may suggest that for regions subject to large extraordinary floods and gauging records of various lengths, it is prudent to apply record extension methods for those gauges that are offline or have limited records (e.g., Hirsch, **1982**; Vogel & Stedinger, **1985**).

Figure 6 also illustrates that the percentage difference in peak discharge decreases as the drainage area increases. This relationship is clear when comparing the regression equations. For example, the 0.2 peak flow equations that are single variable in Table 3 have a higher intercept and lower slope. Therefore, there is a point at which the equations in Table 2(without Harvey) will predict higher peak flow rates than for those in Table 3 (with Harvey). However, such a point may be beyond the maximum drainage area of the basins used in the analysis. In any case, regional regression equations should always be used with caution for drainage areas exceeding those of the basins used to develop them.

3.3 Implications

The degree of the influence of Harvey—as represented in Figures 2 and 6—is significant for a number of reasons. The first is that it suggests recent events, such as Harvey that are intensified by global warming (Van Oldenborgh et al., **2017**), may have a significant influence on the development of design floods. It therefore supports the claims that non-stationarity should be considered within flood frequency methodologies. The second is that it indicates that recent extreme precipitation events, such as Hurricane Harvey, can significantly alter the estimation of peak discharges. As shown previously in Figure 2, the design floods for individual stream gauges are altered significantly by Harvey; furthermore, Figure 6 illustrates that this alteration affects the estimation of peak discharges using regional flood frequency analysis. This indicates that the regression equations used to design infrastructure, manage flood-hazard areas, and define flood plains prior to Harvey may now be under-designed. All of this leads to two important questions: (a) what is the most appropriate way to evaluate flood risk with regional flood frequency methodologies in light of both current extreme events and global warming and (b) how do we deal with infrastructure that now may be undersized?

To the first question, these results suggest that recent events, exacerbated by global warming, can have a considerable influence on the development of regional flood frequency equations. How to appropriately consider this risk within flood frequency analysis methodology is a pressing concern. At minimum, what Harvey demonstrates is the need to consistently update flood frequency equations that are used in engineering design when events of such magnitude occur. Updated equations will help to ensure that infrastructure, which serves the public, is designed with the most recent systematic data. However, even if equations are updated, current methodologies do not consider the influence of global warming. As mentioned previously, there are several emerging methods that have been suggested to consider the impact of global warming, such as those that apply climate models (e.g., Camici et al., **2013**; Gilroy & McCuen, **2012**; Kwon et al., **2011**), and these results suggests this is a critical area of research that deserves further attention.

In addition, these results indicate that infrastructure designed prior to Harvey may now be undersized. For example, the Texas Department of Transportation Hydraulic Design Manual (Garcia, **2016**) recommends that culverts designed for local roads using regional flood frequency equations are designed to handle the 10-year flood. For a culvert designed to handle runoff from a 10 square mile watershed, the peak flow it would need to convey would now be almost 15% greater when considering Harvey. Depending upon the hydraulics of the site, the culvert could now be undersized. This highlights the importance of adaptive engineering designs that minimise damage due to conveyance failure and suggest that in some cases detention storage or drainage capacity may need to be expanded to account for this increase in design flood magnitude.

We recognise that there are many other factors that contribute to floods including land use change, food mitigation strategies, and development regulations, among others. This analysis was restricted to rural watersheds (<10% developed), and therefore does not consider the impact of Harvey on the urban environment in Houston, where the effects of Harvey were felt the greatest. Even so, there may be smaller land use changes and development within these watersheds that has affected their hydrology. The strength of this analysis, however, is that it removes the influence of other non-stationary factors to a large degree; the assumption of precipitation and climate as the main drivers of change are stronger for rural watersheds than urban watersheds that are subject to continual development. To that end, the non-stationarity tests indicated that there are no large violations of stationarity among the annual peak flow records in this region. Therefore, conclusions that Harvey is the main driver of change in these design equations largely holds true.

4 CONCLUSIONS

In summary, we have presented a case study that demonstrates the impact that Hurricane Harvey has on flood frequency and regional annual peak flow regression equations. Flood frequencies were computed for the stream gauges in the geomorphologic region around Houston using systematic records that both excluded and included Harvey. The results showed that Harvey influenced the design equations on average between 4 and 30% for the 2- and 100-year floods, respectively. The peak exceedance probabilities were used in a regional flood frequency analysis to predict the magnitude and frequency of peak discharges, and the results indicate that Harvey influenced the estimations of the 100-year flood on average by up to 28%. This study has therefore provided an example of the impact that Harvey has on flood frequencies and regional regression design equations. The results suggest that events like Harvey, magnified by global warming, will have a large impact on existing flood frequency analysis results; therefore, further research that seeks to account for similar future events is prudent.

As scientists and engineers, we try to design infrastructure considering risk to the best of our abilities, but we can never get it perfect. Resource constraints will limit the number and length of record of continuous stream gauges, and there are uncertainties in transferring information from one gauged location to an ungauged location based upon shared basin characteristics. In addition, climate is non-stationary, and changes in climatic and physiographic (i.e., land development, land use change, etc.) forces make predictions based upon past observations inherently unreliable. Any solution to this must be able to consider the true influence of these storms. As demonstrated, the impact of Harvey on engineering design equations was significant, suggesting that future hurricanes intensified by global warming may have similar influences.

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