James A. Baker III Institute for Public Policy
Rice University

Development and Climate Factors to Consider for the Successful Future of the Addicks Reservoir and Dam

By

Ronald L. Sass, Ph.D.

Fellow in Global Climate Change
James A. Baker III Institute for Public Policy
Rice University

September 12, 2011

A Major Rain Event

A Houston-area storm in 2009, one of the most intense and localized in recent memory, put the 50-year-old Addicks Reservoir to the test. Is this structure and other parts of the Harris County flood control system adequate for land-use and climate changes that will occur in the next half-century?

The rain began again shortly after midnight on April 28, 2009. It was the third time that month, starting on April 18, that the western end of Harris County, Texas, had experienced excessive rainfall after a relatively dry period earlier in the year. A large thunderstorm, originating in northwest Texas, had entered the area late in the afternoon of Monday, April 27. The storm remained over the Katy, Texas, area, pounding it with a heavy rainfall of 4–5 inches, resulting in extensive street flooding and complete ground saturation before moving offshore just before midnight.

Shortly after midnight on April 28, a second wave of storms developed over the area and remained nearly stationary until it weakened and moved off over the central part of the county. Heavy rains fell between 4:00 p.m. and 10:00 p.m. on April 27 and from midnight through 8:00 a.m. on April 28, producing a total of 9.0–11.5 inches of rain across the upper portions of the Addicks Reservoir watershed. Figure 1 shows a radar estimate of rainfall amounts over the Addicks watershed on April 28.

The highest short-duration period of rainfall occurred over the Addicks Reservoir itself and parts of Buffalo Bayou. Recorded at Addicks Dam, the maximum 30-minute rainfall was 2.9 inches, which is just short of the 100-year frequency. One-hour rainfall values were measured at 4.2–4.8 inches over Addicks Reservoir as well as over upper Brays Bayou and Upper Buffalo Bayou. These rain totals are somewhat higher than the 100-year storm frequency. Six-hour and 24-hour rainfalls over Addicks were in the range of a 10-year to 50-year event.

The Addicks Reservoir watershed spans 136 square miles or 87,040 acres. If we take the average rainfall on April 27 and 28 to be 10 inches over the entire watershed, the amount of rain that fell on the watershed during that event totaled 72,500 acre-feet. This value is dependent on the estimated rainfall derived from Figure 1b and does not include any contribution from neighboring watersheds that may have overflowed.

On April 30 and May 1, immediately after the rain event, the Addicks Reservoir contained a storage content of 60,190 acre-feet of water. The storage content on April 27, before the event, was measured at 5,860 acre-feet. Thus 54,330 acre-feet of runoff was collected from the watershed during the two-day storm, which was approximately 75% of the total precipitation. It is difficult to assign an error to this number, but it is probably within ±10%. It is also a quite reasonable runoff value for such an intense storm with high precipitation rates (Smith et al. 2000). However, each storm is unique and may have a different value for the runoff fraction. In general, the runoff fraction is dependent on the degree of saturation of the soil as well as the porosity of the surface. In addition, the runoff fraction depends on the rate and duration of the precipitation. In general, the more saturated the soil and the heavier the downpour, the greater is the runoff fraction.

Even though over 2,000 homes were flooded during the April 2009 storm, the floodwater was mostly due to overflow along lower portions of creeks feeding into the Addicks Reservoir and along Buffalo Bayou and its tributaries as well as the upper Brays Bayou. The reservoir did exactly what it was designed to do.

But can the reservoir be expected to work as well in future intense rainfall events?

The Addicks Dam

Construction of the Addicks Dam began in May 1946 and was completed in December 1948 at a cost of just over $4 million. The Addicks Dam is of earthen construction with a homogeneous core. The structure, modified in 1988, has a foundation of soil. Its length is 61,166 feet. Maximum discharge is 7850 cubic feet per second. Its capacity is 200,800 acre-feet. The dam was designed to hold sufficient runoff to raise the level of the water in the reservoir to a flood level of 109.6 feet. The highest water levels in the reservoir occurred on April 30, 2009, and

April 31, 2009, when it reached runoff storage of 60,190 acre-feet, with a water level elevation of 96.6 feet as measured by pressure transducer, or 100.02 feet as measured by radar sensor. At one other time, on March 8, 1992, the water level in the reservoir reached an elevation of 100.547 feet as measured by pressure transducer, with runoff storage of 57,870 acre-feet.

After the heavy rains of April 27-28, 2009, inspection by the U.S. Army Corps of Engineers revealed empty spaces in the foundation beneath the conduits, or tunnels, that control water flow into Buffalo Bayou. Officials blamed the seepage on the increased presence of stored water behind the structures—a result of more people, houses, and businesses both upstream and downstream of the dams. These findings led the Corps to designate the Addicks Dam and the nearby Barker Dam as "extremely high risk." Fearing the possible failure of the structure, the Corps has pumped polyurethane and grout into the foundation, increased monitoring of the outlet structures, and lowered the maximum reservoir pool elevation to 97.5 feet.

The Corps of Engineers has made several upgrades and repairs at Addicks and counts it among its highest priorities. Both the Addicks and Barker dams have been identified as two of the nation's riskiest dams because of the potential inundation to low-lying and densely populated areas of Houston should they give way. But now, with the dams showing signs of fatigue due to increased runoff from upstream development, the Corps is reevaluating these structures with the idea of extending their lifetimes by an additional 50 years.

Future Considerations for the Addicks Dam

Several factors must be considered in evaluating the reservoir capacity and dam height that will be adequate for changing conditions over the next half-century. These changes include (1) increased runoff due to the addition of more impermeable surfaces derived from increased human development within the watershed of the dam and the Cypress Creek watershed to the northwest of the Addicks watershed, (2) the steady increase observed over the past 50 years in the intensity of heavy downpours during storms, and (3) the effect of climate change on the general intensity of storms in the future.

Increased Runoff From Property Development

We have seen above that the runoff ratio into Addicks Reservoir for the April 27-28, 2009, storm event was estimated as 75%. This ratio of precipitation to runoff is a complex function of a variety of parameters. One very important parameter is the fraction of the watershed that is covered by impermeable surfaces such as streets and parking lots. Such surfaces have almost no potential to adsorb the rainwater and its runoff will be at a ratio of close to 100%.

The Addicks Reservoir watershed covers 136 square miles with a population of approximately 150,000 people, yielding a population density of 1,100 people per square mile. This density could very well rise to a number closer to the population density of the city of Houston—3623 people per square mile—over the next several decades. Figure 2 depicts the rate of population growth in Harris County from 1960 to 2000. Between 1990 and 2000, Harris County's population grew by almost 21%, equal to a doubling time of approximately 35 years. Much of this growth could occur in the Addicks Reservoir watershed, raising the amount of runoff into the reservoir. An even greater change in population could also occur in the Cypress Creek watershed just to the north and extending west and east of the Addicks Reservoir (Figure 1a). Excess flooding from this watershed could easily affect the Addicks Reservoir that is down dip from it.

The Cypress Creek watershed extends into Waller County and includes the city of Waller as well as a small portion of the city of Houston. The watershed covers about 323 square miles and contains approximately 216,000 persons (Harris County only) with a population density of 669 persons per square mile. This watershed is thus roughly half as densely populated as the Addicks Reservoir watershed. The western portion of the watershed is either cultivated or rangeland. The central and eastern portion has been rapidly developing in recent years. New subdivisions in the western portion of the watershed are under construction, and large-scale land development projects are expected to continue. Continued residential development of this area will radically increase rainwater runoff due to the increase of homes, streets, parking lots, etc. Much of this runoff could easily enter the Addicks Reservoir. It is difficult to predict the increase in the water burden this will add to the reservoir, but it certainly will not be insignificant in the next several decades.

The Current Increase in Storm Intensity

The climate of the Texas Gulf Coast is uniquely warm and wet compared with the rest of the continental United States. The U.S. Global Change Research Program (USGCRP) has reported that for the southeastern United States, precipitation in the fall months has increased by 30% since 1901 while trends during the other seasons are less significant. Specific seasonal data are mapped in Figure 3.

The frequency of more intense storms has been steadily increasing since the construction of the Addicks Dam in 1948. And there is no indication that the steady trend in increasing storm intensity will stop or slow in the next 50 years of the dam's life. Karl and Knight (1998) suggest that precipitation events in the United States are changing disproportionately; the proportion of total precipitation derived from extreme and heavy events has become higher relative to more moderate events. An analysis of the percentage change in intense precipitation by Groisman et al. (2004) has been updated in a report by the U.S. Global Change Research Program (2009). The report states that in the United States, in general the amount of rain falling in the heaviest downpours has increased on average in the past century by approximately 20% in the southeastern U. S., including Texas, and this trend is very likely to continue. There has been little change or decrease in the frequency of light and moderate precipitation during the past 30 years, while heavy precipitation has increased as shown in Figure 4 for the years 1958 to 2007 (USGCRP 2009).

A very thorough analysis of the intensity of U.S. rain events was carried out by Travis Madsen (2007). His analysis of extreme precipitation frequency was based on a methodology developed by Kenneth Kunkel and Karen Andsager at the Illinois State Water Survey, with David Easterling at the National Climatic Data Center. The data used extended from 1948 to 2006, and included information from 3,445 weather stations in 48 contiguous states.

Storms with extreme levels of precipitation relative to the local climate were identified at each weather station by examining the frequency of 24-hour precipitation events with total precipitation magnitude with a one-year recurrence interval or larger. For a given weather station, the 59 largest one-day precipitation totals during the 59-year period of analysis were identified. The smallest of these values equaled the threshold for a precipitation event with a one-year recurrence interval. Any storm with a 24-hour precipitation total equal to or larger than this threshold was defined as extreme. Figure 5 graphically presents the local minimum thresholds that defined extreme precipitation (Madsen and Figdor 2007).

For each weather station, the annual frequency of storms with extreme levels of precipitation was calculated. The average for each weather station over the period of analysis was defined as “1.” If no change in frequency was detected, the trend in annual major storm frequency was set to zero. A significant positive or negative slope would indicate a change in the annual frequency of major storms over time or an increase or decrease in storm intensity. To calculate the trend in major storm events over time, data based on station location were aggregated. The presence of a trend was tested using standard least-squares regression analysis. To determine statistical significance of the resulting trend, a two-tailed t-test at the 95% confidence level was used (Madsen and Figdor 2007). A graph of an analysis similar to this is shown in Figure 6, where the annual average frequency of storms with extreme precipitation is combined for every station in the United States from 1948 to 2006.

In this study, the country was divided into several regions and average frequencies were calculated. Texas was considered to be in the west-south-central region of the country. The overall average change in extreme precipitation frequency reported for this region between 1948 and 2006 was 24% with a 95% confidence interval ranging from 20% to 27%. The change in extreme precipitation frequency for the same time period reported by the state listed Texas at 28% with a 95% confidence interval ranging from 22% to 33%. Most important for our purposes, for statistically significant changes in extreme precipitation frequency by metropolitan area (1948-2006), the study lists the Houston-Galveston-Brazoria complex as having a change in extreme precipitation frequency of 49%, with a 95% confidence interval ranging from 20% to 78%. Thus we can consider the distinct possibility of an increase of nearly 50% in intense storms between 1948 and today in the area of the watersheds of the Addicks Dam and Cypress Creek.

In addition, Keim et al. (2008), in a report for the U.S. Department of Transportation, assessed how the Gulf Coast climate is changing. This study generally corroborates the other work reported above. Keim et al. report that the empirical record of the central Gulf Coast region for the past century shows an annual precipitation record that suggests a trend toward increasing values. The study also modeled a long-term trend of increasing annual runoff region-wide. Over the entire record since 1919, there was an increase in rainfall that provided an estimated 36% increase in precipitation runoff. The model input was primarily an increase in soil moisture content due to heavier precipitation; it did not take into account the increase in impermeable surfaces due to a steady rise in residential land development.

The Effect of Climate Change on the General Intensity of Storms in the Future

The historical steady increase in the intensity of severe storms is real and observable and must be accepted regardless of cause. One explanation is that these increases are consistent with climate change brought about by anthropogenic input of greenhouse gases into the atmosphere. Climate scientists anticipate that global warming will be manifest in a variety of changes in precipitation patterns throughout the world. In the United States, many areas will receive more amounts of rain and others will receive less. In Texas, it is expected that the western part of the state will become drier and the eastern part will become wetter. All across the country, however, the scientific consensus is that rainstorms and snowstorms will be more intense, with increasing risk of flood and other impacts.

Changes in climate and related factors have been observed in the United States and were recently enumerated by the U.S. Global Change Research Program (USGCRP) in *Global Climate Change Impacts in the United States* (2009). The findings include the following:

- U.S. average air temperature increased by more than 2°F over the past 50 years, and total precipitation increased on average by about 5%.
- Precipitation patterns have changed. Heavy downpours have become more frequent and more intense. The frequency of drought has increased over the past 50 years in the southeastern and western United States, while the Midwest and Great Plains have seen a reduction in drought frequency.
- The frequency of large wildfires and the length of the fire season have increased substantially in both the western United States and Alaska.

In the chapter dealing with the U.S. national climate change, the USGCRP notes that the amount of rain falling in the heaviest downpours has increased approximately 20% on average in the past century. It is predicted that this trend will very likely continue with the most intense storms continuing in areas where they currently form.

One of the most easily recognized precipitation patterns is the increasing frequency and intensity of heavy downpours. There has been little change or decrease in the frequency of light and moderate precipitation during the past 30 years, while heavy precipitation has increased. In addition, while total average precipitation in the nation as a whole rose by about 7% in the past century, the amount of precipitation falling in the heaviest 1% of rain events increased nearly 20% (Kunkel et al. 2008).

Climate models project continued increases in the heaviest downpours during the 21st century, while the lightest precipitation is projected to decrease. Heavy downpours that are now 1-in-20-year occurrences are projected to occur about every four to 15 years by the end of this century, depending on location, and the intensity of heavy downpours is also expected to increase. The 1-in-20-year heavy downpour is expected to be 10% to 25% heavier by the end of the century than it is now (Kunkel et al. 2008). These trends are graphically represented in Figure 7. The figure shows projected changes in the average in the amount of precipitation falling during light, moderate, and heavy events in North America from the 1990s to the 2090s. Projected changes are displayed in 5% increments, from the lightest drizzles to the heaviest downpours. As shown in the figure, the lightest precipitation is projected to decrease, while the heaviest will increase, continuing the observed trend. The higher emission scenario yields larger changes. Projections are based on the models used in the Intergovernmental Panel on Climate Change's (IPCC) *2007 Fourth Assessment Report* (Gutowski et al. 2008).

In a study of climate change and variability along the coast of the Gulf of Mexico for the U. S. Department of Transportation (Climate Change Science Program 2008) it was observed that a lack of horizontal resolution limits the ability of the current generation of climate models to simulate individual storms. A simple theoretical argument presented by Allen and Ingram in 2003 concludes that extreme precipitation events should become more intense as the climate warms (Keim et al. 2008). As reported above, the IPCC (2007) observed that the frequency of heavy precipitation events had increased over most areas during the 20th century and concluded that a continued increase in heavy precipitation events is very likely during the 21st century. The Clausius-Claperyon relationship dictates that as the air temperature increases, the atmosphere has the ability to hold more water vapor. For example, at ambient temperatures, a 2°C to 3°C (3.6°F to 5.4°F) rise in the temperature of the Gulf of Mexico increases the equilibrium water vapor pressure above it by 10% to 15%. As the air temperature above the ocean rises even higher, saturation conditions can hold even higher amounts of water vapor. Hence, in a warmer climate, it is quite likely that specific humidity will increase both on average and in extreme saturation conditions. Extreme-value analysis of model output for daily precipitation in the Gulf states region, similar to the analysis discussed above with daily surface air temperatures, reveals a predicted increase of around 10% in the 20-year return value of the annual maximum of daily average precipitation. The coarse horizontal resolution of the climate models used in this analysis results in an underestimation of extreme precipitation events (Wehner 2005). The increase in precipitation during intense storms will likely be much higher than predicted by Gutowski et al. (2008). Heavy downpours that are now 1-in-20-year occurrences are projected to occur about every 4 to 15 years by the end of this century, depending on location, and the intensity of heavy downpours is also expected to increase. The 1-in-20-year heavy downpour is expected to be 10% to 25% heavier by the end of the century than it is now, as indicated by Figure 7 (Kunkel et al. 2008).

Conclusion

The Texas Gulf Coast has two very important natural aspects; it is very flat and it characteristically has very heavy precipitation events. These two features combine to produce frequently flooding. In Harris County, as in other coastal locales, much effort and money are spent to control the precipitation and runoff so as to reduce flooding. One way is to create, at the bottom of natural watersheds, retention reservoirs, such as the Addicks Reservoir in the northwest part of the county. The Addicks Reservoir and Dam were designed and constructed in 1948 to retain an amount of water similar to that which fell on the 136 square-mile Addicks watershed on April 27, 2009, and April 28, 2009.

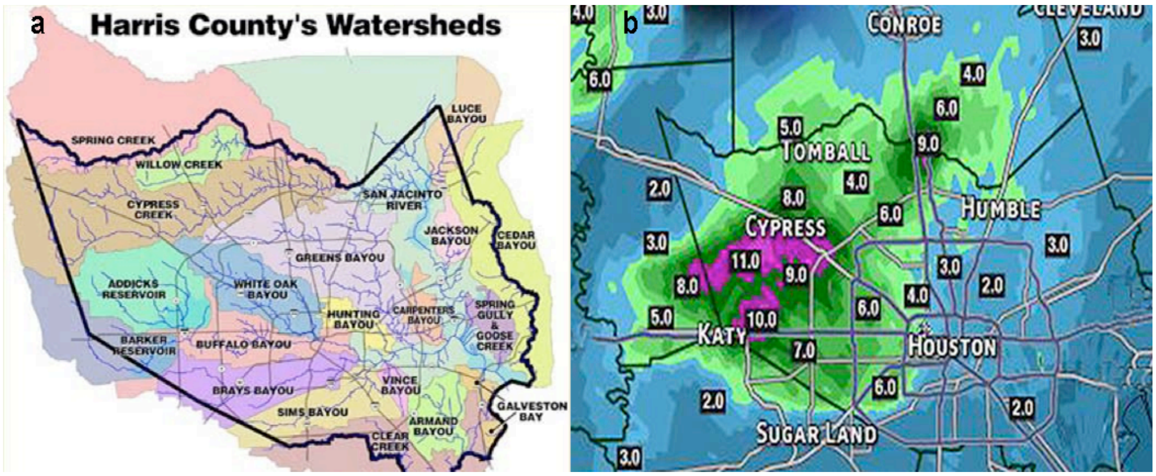
Now, with the dam showing signs of age, the Army Corps of Engineers is looking to ensure that the structure will do its job for another 50 years. It is important that the Corps consider every aspect of change in the hydrology of the area in order to assure the renovated dam will indeed be adequate for the job it is meant to do: manage the total amount of runoff precipitation that may occur at any time during the next 50 years of its lifetime. To do that, the Corps needs to have an accurate assessment of the highest amount of water that may drain into the reservoir in a manner that limits downstream flooding.

Several existing and new sources of water that need to be included in the evaluation are:

- Increased runoff from property development, both in the already highly developed Addicks watershed and in an area that is experiencing an even greater change in population: the Cypress Creek watershed just to the north and extending west and east of the Addicks reservoir. This development could increase the runoff into the Addicks Dam during a very intense storm by as much as 10% to 20%.
- The current increase in storm intensity that has been observed. Precipitation in this area has increased by 30% since 1901 and the frequency and intensity of heavy rainfall storms has been increasing since the Addicks Dam was constructed. One of the clearest precipitation trends in the United States is the increasing frequency and intensity of heavy downpours.
- The effect of future climate change on the general intensity of storms. The scientific consensus across the country is that rainstorms and snowstorms will be more intense, with increasing risk of flood and other impacts. This increase in storm intensity has been predicted to be from 10% to 45% depending on the temperature rise in the source water (i.e., the Gulf of Mexico), the air temperature rise, and the characteristics of the storm itself.

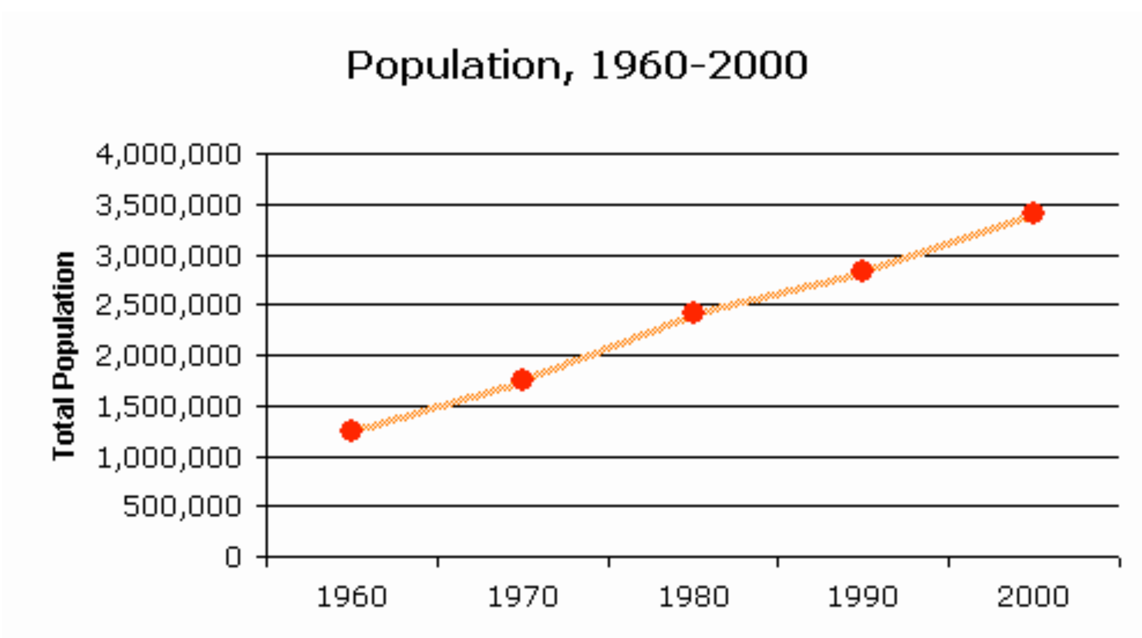
Taken together, these three factors could combine to require that the water retention requirement of the reservoir and the integrity of the dam be increased by as much as 50%. And that figure may be too conservative. The future will place a significantly larger demand on this very important part of the flood control system of Harris County. In upgrading it, we cannot afford to err on the low side.

Figure 1a. Watersheds in Harris County, Texas. **Figure 1b. Radar-based estimate of total rainfall in Harris County, April 27-28, 2009**. Both figures show a heavy black outline of Harris County as well as major area roads. Note that the heaviest amounts of rainfall fell directly over the watershed of the Addicks Reservoir.



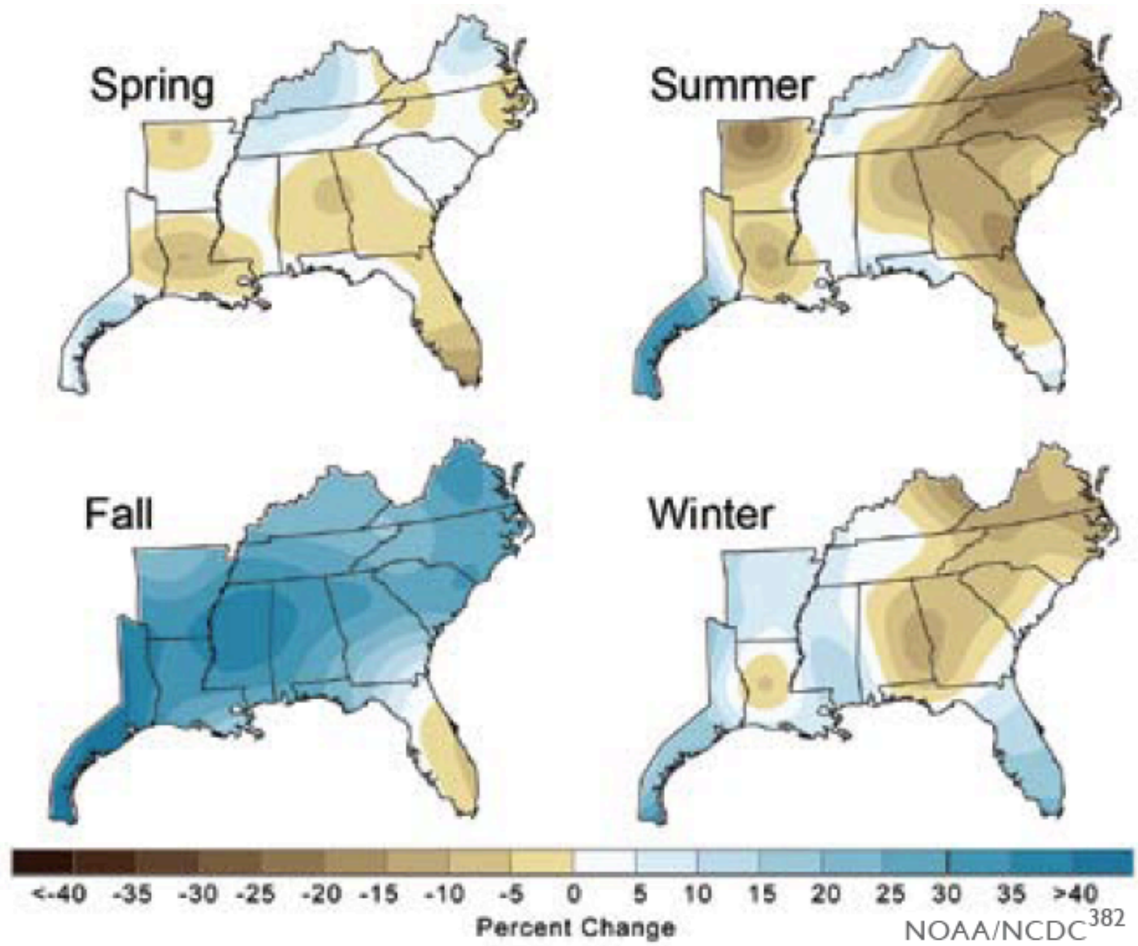
Source, Figure 1a: Harris County Flood Control District. Source, Figure 1b: KTRK-TV, Houston

Figure 2. Increase in the total population of Harris County, Texas, 1960-2000



Source: CensusScope,org (http://www.censusscope.org/us/s48/c201/chart_popl.html)

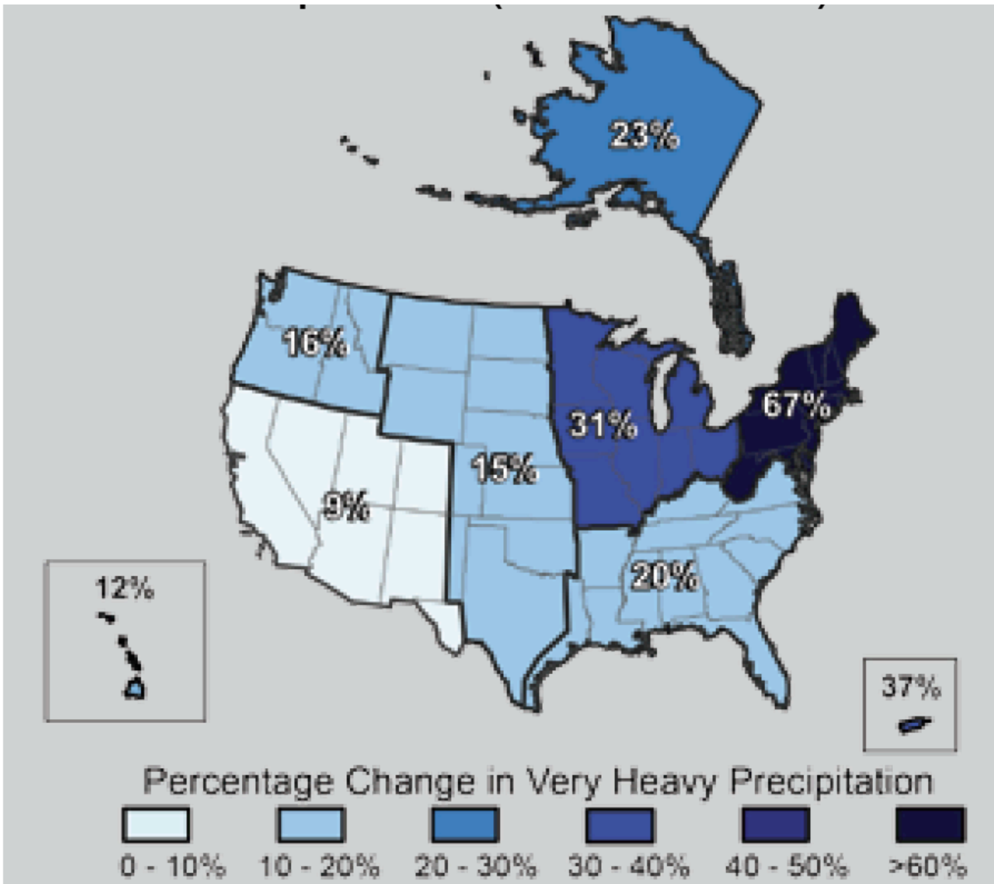
Figure 3. **Observed changes in precipitation, 1901-2007**. Precipitation along the Texas Gulf coast in the fall months is shown to have increased by more than 40% since 1901. Increases during other seasons are not as dramatic but are significantly positive.



[382]

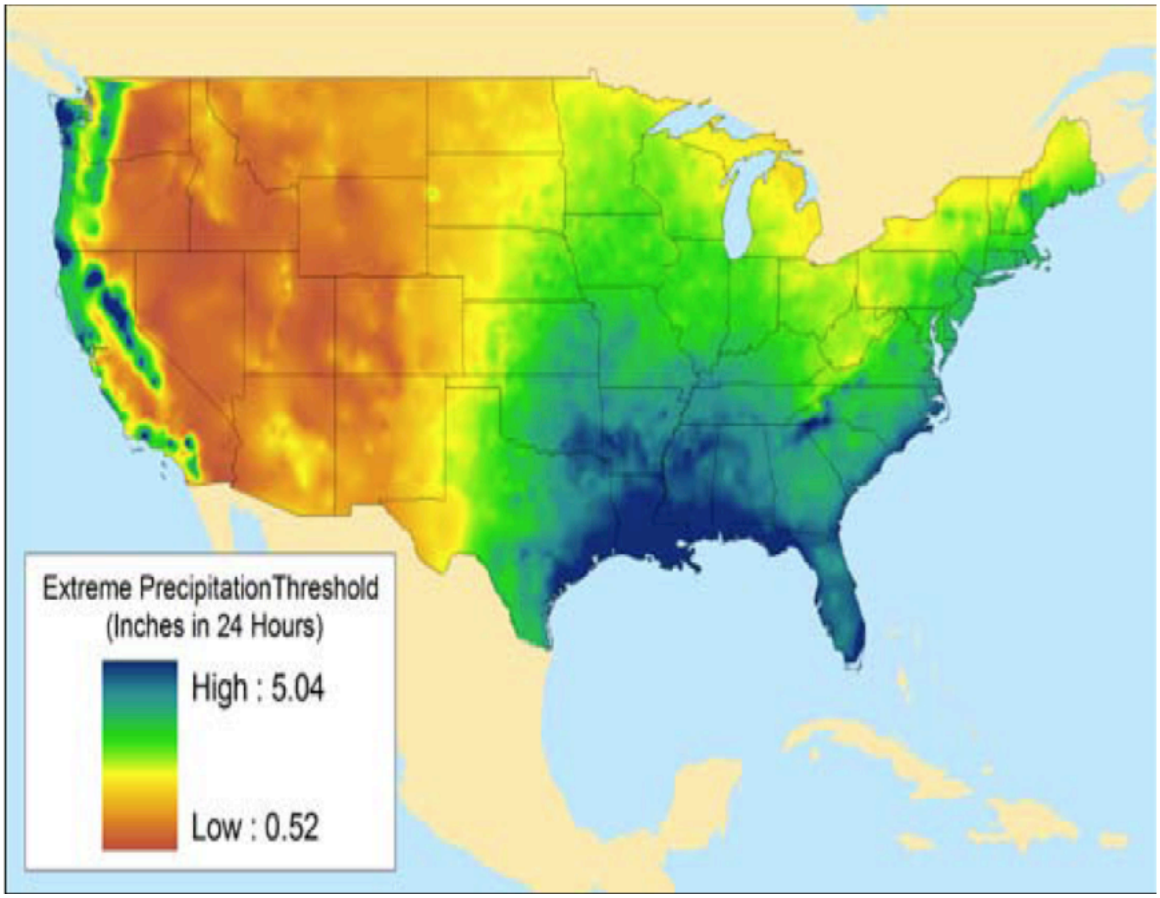
Source: Climate Change Science Program, 2008

Figure 4. **Increases in very heavy precipitation, 1958-2007**. The map shows the percent increase of rain during very heavy precipitation events (defined as the heaviest 1% of all daily events) for each region in the U. S. The Houston area falls in the 20% category.



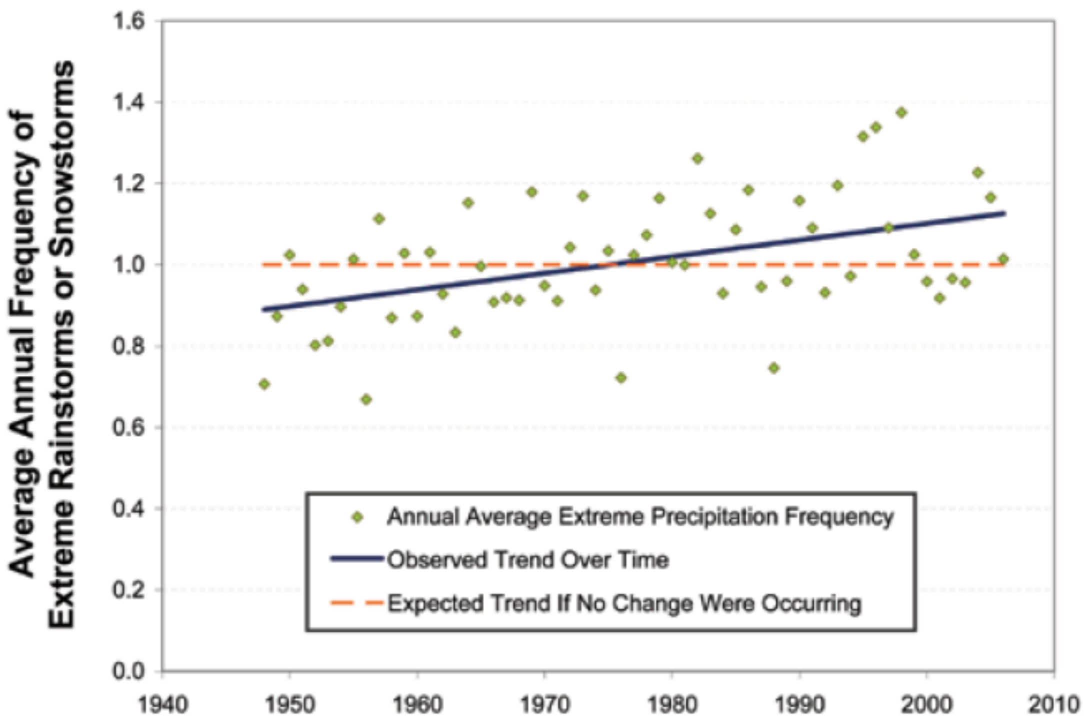
Source: Climate Change Science Program, 2008

Figure 5. **Local minimum thresholds for definition of extreme precipitation**. Note that the threshold value for the area including Harris County, Texas, 5 inches rainfall in 24 hours, is among the highest amounts in the nation. Thus, a given percentage increase has a higher absolute value than for most other areas.



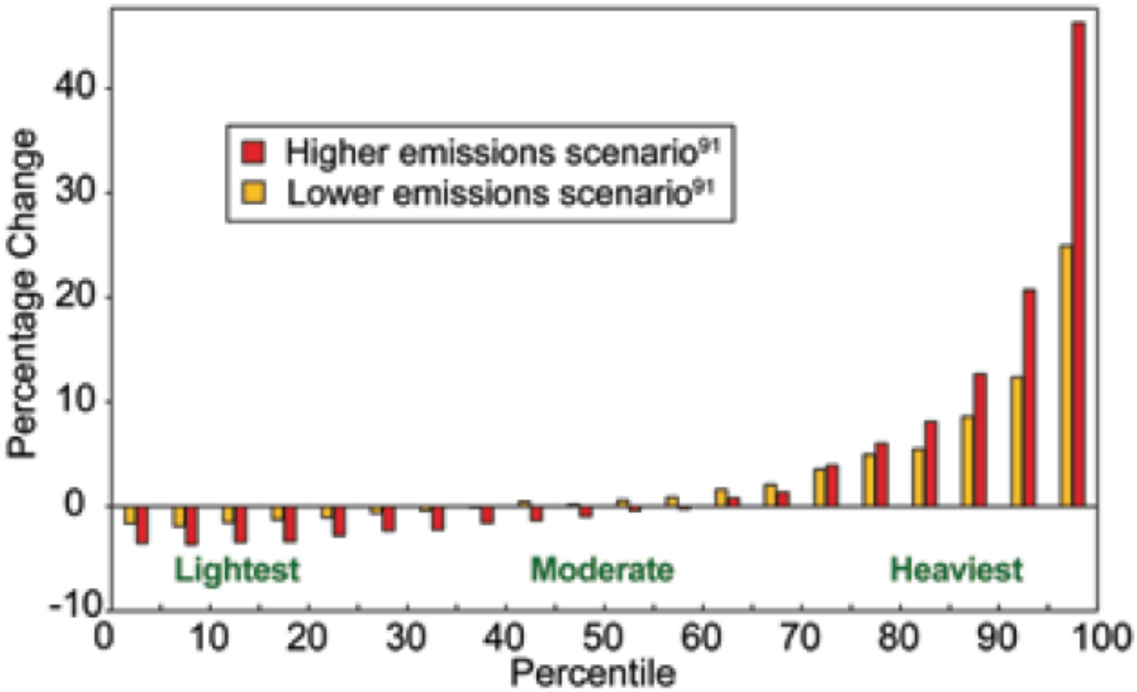
Source: Madson and Figdor 2007

Figure 6. **Average annual frequency of storms with extreme rain or snow in the United States, 1948-2006.** Analysis of the slope of this graph shows that storms with extreme levels of precipitation have increased in frequency by 24% across the continental United States over this time period. With 95% confidence from the t-test, the average increase in extreme precipitation frequency lies between 22% and 26%.



Source: Madsen and Figdor, 2007

Figure 7. Projected changes in light, moderate, and heavy precipitation in the United States by 2090



Source: U.S. Global Change Research Program

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