ADAPTING TO HYDROLOGIC NONSTATIONARITY IN ENGINEERING DESIGN

A Dissertation

by

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ABSTRACT

The engineering design discipline of hydrology and hydraulics has, for the past several decades, been largely based on probabilistic design techniques involving recurrence interval storm and flood events. The engineering design storm and design flood have been enduring concepts; however, recently the concept of hydrologic nonstationarity has gained a foothold in engineering theory.

An analysis of the annual maxima based method of predicting engineering design storms was conducted using multiple techniques to determine whether trends were detectable or prevalent. Analyses from over 300 rain gauge stations throughout the southeastern United States showed that over 40% had experienced some form of trending behavior over time. An analysis of tropical storm contributions to station annual maxima found that such events were not overly influential with regard to extreme event prediction. Furthermore, spatial trends were not detected. These findings showed that the engineering design storm is affected by hydrologic nonstationarity.

This research also investigated several other sources of hydrologic nonstationarity – specifically, contributions from rapid urbanization, topographic subsidence, and engineering design decisions. Changes in engineering design flows from urbanization result in designs that are quickly obsolete and prone to inundation. The decisions of a design engineer can result in design flows vastly different from those predicted by hydrologic models, even when taking into account effects of suburban development. Additionally, the impacts of urban development, precipitation increase,

and topographic subsidence were examined in concert in an attempt to quantify the individual impacts of each on potential flooded area. It was found that the three contributions of nonstationarity were individually quantifiable, and that the contributions from precipitation changes and topographic subsidence were the most significant sources. Land development was the least influential contributor, though still significant.

Engineering design under changing hydrologic conditions will be one of the major challenges for the industry in the coming decades. This research examined several design techniques available in the literature and subjected them to quantitative and qualitative assessment measures to determine their performance under prevailing design assumptions. The assessment measures tentatively indicated that modular designs and designs based on the theory of ecosystem services may be most suitable under potential future hydrologic conditions.

DEDICATION

This work is dedicated to my universally beloved Grandma – thank you for your example of pursuing your ambitions while being open to the Lord’s direction, putting family first, and always being yourself.

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NOMENCLATURE

AEP	Annual Exceedance Probability
ASCE	American Society of Civil Engineers
CFS	Cubic feet per second
CN	Curve Number
DEM	Digital Elevation Model
DOT	Department of Transportation
ENSO	El Niño - Southern Oscillation
EPA	Environmental Protection Agency
ESRI	Environmental Systems Research Institute, Inc., Redlands, CA
FAA	Federal Aviation Administration
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
GCM	General circulation model
GEV	Generalized Extreme Value
GHCN	Global Historical Climate Network
GIS	Geographic information system
GLM	Generalized Linear Model
GPS	Global positioning system
HCFCD	Harris County Flood Control District
HEC-HMS	Hydrologic Engineering Center Hydrologic Modeling System

HEC-RAS	Hydrologic Engineering Center River Analysis System
HSPF	Hydrological Simulation Program – FORTRAN
IBTRACS	International Best Track Archive for Climate Stewardship
IDF	Intensity-duration-frequency
IPCC	Intergovernmental Panel on Climate Change
ISODATA	Iterative Self-Organizing Data Analysis Technique
LOS	Level of service
n	Manning's roughness coefficient
NARSAL	Natural Resources Spatial Analysis Lab, University of Georgia
NASA	National Aeronautics and Space Administration
NAVD 1988	North American Vertical Datum of 1988
NCDC	National Climatic Data Center
NED	National Elevation Dataset
NGVD 1929	National Geodetic Vertical Datum of 1929
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service (formerly SCS)
NWS	National Weather Service
P	Normalized precipitation depth
PMP	Probable Maximum Precipitation
PRE	Proportional reduction in error
Q	Volumetric flow rate

R	Clark storage coefficient
SCS	Soil Conservation Service (currently NRCS)
SSE	Sum of squared errors
SSURGO	Soil Survey Geographic database
SWAT	Soil and Water Assessment Tool
SWMM	Storm Water Management Model
TNRIS	Texas Natural Resources Information System
TSARP	Tropical Storm Allison Recovery Project
TxDOT	Texas Department of Transportation
USACE	US Army Corps of Engineers
USDA	US Department of Agriculture
USGS	US Geological Survey

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1. INTRODUCTION

1.1 Infrastructure failures

An engineer's work must be accurate, effective, and economical. Any engineering failures must be taken seriously and put towards efforts to ensure no recurrences. Hydraulic failures are one common type of engineering failure, which include culvert washouts, bridge failures, and flood damage to infrastructure. Many studies have been done on floodplain development and management, but it is difficult to quantify the annual number of culvert washouts or bridge failures and the cost of the incidents. Wardhana and Hadipriono (2003) pointed out that there is currently no national database for keeping track of bridge failures, but a cursory survey of several states' data found that approximately 53% of all bridge failures in the studied area of the US between 1989 and 2000 were caused by hydraulic events including flooding, scour, and debris. Furthermore, the researchers found that the bridges failed primarily during their intended service life, indicating that age and deterioration played a minor role if any. An earlier study analyzed US bridge failures from 1951 to 1988, and attributed 37% of bridge failures to natural causes, including flood, scour, and wind (Harik et al. 1990). This study also concluded with a recommendation for a federal bridge failure database, stating that "[u]nlike the Federal Aviation Administration, which investigates every accident involving private and commercial airplanes, and the Federal Railway Administration, which investigates train accidents, the Federal Highway Administration … does not investigate every bridge failure in the U.S."

The difficulty of estimating the number or cost of all culvert washouts in the US is due in part to their ubiquity, and also a lack of information. Most culvert washouts are likely seen as a local problem and therefore not reported. According to the FHWA, circa 2001 over 2.5 million feet of pipe larger than 18 inches in diameter was installed per year on federally financed transportation projects (Kerenyi et al. 2005). This is not including field-cast structures or arch culverts. At the state level, data about culvert washouts are scattered and usually tied to large storm events. According to the Vermont Agency of Transportation, in 2011 Hurricane Irene caused over 1000 culvert washouts and damaged 300 bridges throughout the state of Vermont (Tetreault 2011). The New York DOT spends approximately $90 million per year maintaining existing culverts and installing new culverts (Esch 2013).

Other modes of transportation are not immune to flood failures. According to Brumbelow et al. (2012), railroad culvert and bridge washouts were responsible for 263 derailments and over $100 million worth of infrastructure damages in the past 30 years. The US DOT's Pipeline and Hazardous Materials Safety Administration reported at least one incident involving a pipeline washout in Alaska (Wiese 2012).

It has long been a complaint of engineers that current federal government policies for floodplain management actually do more harm than good by continually rebuilding in flood-prone areas, thus subsidizing development that is in a high-risk area (Loucks et al. 2006). Perhaps this critique can be extended to bridge and culvert design, since much of the transportation infrastructure is federally funded. In his book The Control of Nature, McPhee (1989) argued that once a public entity claims to have fixed a problem, such as Mississippi River flooding, the entity then becomes implicated in any repeat failures of the control system, which are truly inevitable since Nature has a way of confounding attempts to subjugate it. This creates a cycle of larger and larger infrastructure investment after each repeated failure, resulting in a vast amount of wasted resources.

1.1.1 What comprises a failure?

In the most archetypal sense within the sphere of civil engineering, an engineering failure is the total destruction or severe damage of a piece of infrastructure, rendering it unusable or unsafe without extensive repair or replacement. In practice, most such incidents are not the colossal disasters of legend, but smaller washouts that go unreported and are simply repaired at the next available opportunity. In another sense, a failure can be considered the point at which an item's performance goes below a previously defined threshold, which is generally expected to occur at the end of an item's design service life (Lemer 1996).

A secondary way of defining an engineering failure is the situation wherein the prescribed system design limits are exceeded. This is in essence a dichotomized occurrence, which may be called a probabilistic failure. A piece of infrastructure is typically designed such that the anticipated conditions will not be exceeded for a set percentage of the time of its anticipated design life; the proportion of time in which the conditions are exceeded can be called the "expected incapacitation", due to the fact that the occurrence was more or less eventually expected and the item is only temporarily unusable. This corresponding loss of opportunity may be considered a failure of the infrastructure to perform adequately when needed.

1.2 The state of the practice

The civil engineering design discipline referred to as "H&H" (hydrology and hydraulics) in its currently practiced form developed in the post-industrial era of infrastructure expansion, with the modeling component following closely behind in the computing era (Singh and Woolhiser 2002). Because a sizeable portion of the infrastructure in place today was constructed prior to the wide availability of high powered computers, any calculations or models used in the design would have necessarily been somewhat rudimentary, or based heavily on tabular and graphical reference materials. Klemeš (1997) pointed out that the phrase "hydrologic model" occurs only once in Ven Te Chow's seminal 1964 book, Handbook of Applied Hydrology. McEnroe (2009) summarized some early attempts at creating empirical formulas, including the Myers formula, Dun's table, and the early rational method, as well as some early critiques of said empirical formulas. He quoted an author writing in the 1886 Railroad Gazette, in a statement deriding attempts to oversimplify hydrologic design, saying "[i]t is well, however, to be certain that we are not simply making a rule where there is no rule, and so laying the foundation of future trouble…"

An example of such a method is the widely used combination of the Rainfall Frequency Atlas TP-40 (Hershfield 1961) with the former SCS, now NRCS documents TR-20 and TR-55 (NRCS 1986). Engineers calculated the likely magnitudes of storms of various probabilities, the assumption being that the weather patterns of the past were predictive of the future. Hydrologic estimation methods such as TR-55 were used to calculate tangible runoff amounts from land areas, which were then used to size hydrologic conveyance and storage structures. These documents and techniques filled an important position at the time, as they allowed engineers of all backgrounds to conduct analyses without access to mainframe computers or empirical data collection (Hawkins et al. 2009).

It is likely that the initial authors never intended their handiwork to be in widespread continued use after more than half a century (Lamont and Eli 2010); nevertheless, this is testimony to their impact on the field, not to mention the lack of other available methods. The NRCS Curve Number method was partially based on a prior document known as the National Engineering Handbook section 4 (NEH-4), which was not peer reviewed at the time of development and publication (Lamont and Eli 2010). Hawkins et al. (2009) stressed that ‘Q as a function of t’, that is to say, hydrographs, are a “giant conceptual leap” from the Curve Number method as originally conceived by the SCS. The authors further pointed out that one of the major factors in perpetuating the Curve Number method is the implied protection from liability that is afforded by using a well-known method from a government agency.

1.3 Defining potential nonstationarity

Nonstationarity in science can be defined as inconstancy of governing laws, as in a system having probability distributions and parameters that change with time, excluding those changes caused by oscillation patterns (Kundzewicz 2011). In a stationary system, past system data can be used to predict future system outcomes, as is the assumption with traditional frequency design. Using past data to estimate future flood magnitudes under an assumption of climate nonstationarity is, according to Kundzewicz, “mission impossible.” (p. 551)

The supposed death of stationarity in water resources was announced in the February 2008 edition of Science magazine (Milly et al. 2008), which ignited a vigorous debate on the subject (Villarini et al. 2009, Brown 2010, Galloway 2011, Hirsch 2011, Kundzewicz 2011, Matalas 2012). Galloway (2011) described the old assumption of stationarity as “doing the wrong thing more precisely,” and mentioned the history of Gilbert White and the National Flood Insurance Program. He argued that the 100-year flood was intended to be an opening approach revised over time; instead it has become the de facto standard for nearly all hydrologic design.

Contrasting viewpoints about widespread adoption of nonstationarity in hydrologic modeling are accessible in the literature; some authors have stated that adopting a design assumption of nonstationarity in engineering is problematic (Koutsoyiannis 2006, Lins and Cohn 2011). Because climatological averages may be changing, and at the same time an upward trend must be estimated, this situation results in a double extrapolation wherein one has to estimate both the new system parameters and the new trend magnitude and direction. Such authors have cautioned against wholesale adoption due to the potentially problematic situation of extrapolating both the time series values and the rate of change of the trends, which could introduce unwarranted uncertainty, while some argued that a better understanding of uncertainty in general is a better goal for current engineering practice (Al-Futaisi and Stedinger 1999);

stationarity is to be viewed as essentially a statistical tool rather than a natural process. Ultimately the authors concluded that stationarity and nonstationarity are simply statistical tools and modeling should always use the simplest possible configuration – in this case, retaining the assumption of stationarity with additional uncertainty (Montanari and Koutsoyiannis 2014, Serinaldi and Kilsby 2015).

1.3.1 Environmental nonstationarity

Generally, storm events have been, repeatedly and pervasively, defying conventional notions of return periods. For example, records show that the city of Houston received both the 100-year rainfall and the 500-year flood in recent years (Berger and Sallee 2006, AP 2012). In September 2009 the Atlanta, Georgia area received a flood estimated at 1 in 10,000 (USGS 2009). The climate of the earth itself hardly stays stationary for 10,000 years, making a claim for a 10,000-year flood very much context-dependent. The USGS tempered this estimate by stating that “the U.S. Geological Survey cannot accurately characterize the probability due to its extreme rarity.” (USGS 2009) Other guesses at probabilities stayed within the 100 to 500-year range. Western Tennessee likewise experienced catastrophic flooding in May 2010. According to the National Weather Service, the Cumberland River crested at a record post-dam level, and the 24-hour rainfall amount was the highest in the 139-year length of record for the area (NWS 2011). The NWS also estimated the recurrence interval for the 48-hour rainfall event, and found that some areas exceeded the 1000-year or 0.1% chance storm, according to current calculation methods.

Research by Stedinger and Griffis involved incorporating nonstationarity into the Bulletin 17B method, another example of a widely used government document, intended for estimating flood risk (2005, 2007a). This approach involved taking existing statistical models and adding to them additional parameters intended to incorporate climate variability, using Bayesian statistical theory where applicable. Beginning with a detailed description of the method (2007b), the authors continued to a review and analysis of the parameter estimation methods (2007c), and concluded with a discussion of the skew parameters (2009). The researchers conducted tests of the modeling ideas on several sites in South Carolina (2007d). Continuing along the same research path, Griffis and Kashelikar (2008) examined adding parameters intended to capture climate variability into Bulletin 17B, including such effects as ENSO. The reimagined Bulletin 17B approach is very flexible, but the authors cautioned against adding uncertainty without having any form of defensibility in terms of either climate data or other physical parameters. Additionally, the authors spoke frankly about the current state of frequency estimation: "Although the climate may be changing making the future less certain, even without a changing climate we cannot honestly claim to know the 100-year flood with much precision." (Stedinger and Griffis 2011) Stedinger and Griffis (2008) recommended widespread adoption of a revised Bulletin 17B, stating that "[w]hile those procedures have survived the test of time and use, the time has arrived to update [the statistical methods.]" Additional researchers concurred with the recommendation to update the method (Dawdy et al. 2012). Similarly, Gilroy and McCuen (2012) took a stationary flood frequency analysis and applied “multinonstationarity” in an attempt to determine the differences in results from the two assumptions.

Probabilistic hydrologic modeling entered the common arsenal of industry techniques upon the advent of capable computing resources. This technique involves treating hydrologic model inputs as probability distribution functions and allowing the resulting outputs to represent a wide range of probable outcomes (Marco et al. 1989). Probabilistic hydrology is often contrasted with deterministic hydrology of the type popularized by Ven Te Chow and his collaborators (Delleur 2014). General adoption of probabilistic risk based analysis by entities such as the US Army Corps of Engineers (Wurbs et al. 2001) represented the acknowledgement of the fact that natural processes are inherently difficult to predict and therefore present unique challenges for designing civil infrastructure. In a probabilistic analysis combining many sources of hydrologic uncertainty with potential flood damage, Toneatti (1996) found that a risk-based approach to estimating potential flood damage gave a more accurate representation of the consequences of extreme hydrologic events.

Accurate estimation of precipitation extremes remains a challenge for hydrologic modeling. Katz et al. (2002) discussed the history of precipitation extreme estimation, notably the work of Emil Gumbel, whose work was established on the assumption of stationary climate and stationary watershed. Katz (2010) pointed out that extreme value theory in statistics has evolved since Gumbel did his groundbreaking work, and concluded that “it continues to be argued that shifts in extremes can be more reliably derived indirectly from changes in the overall probability distribution of a climate variable (e.g., shifts in the mean and standard deviation) than through direct statistical modeling of extremes.” Furrer and Katz (2008) proposed using stochastic weather data generation methods in order to improve extreme precipitation estimates.

1.3.2 Anthropogenic nonstationarity

It is a well-established fact that land use changes result in changes in stream flow as a result of changed runoff patterns; so too with geomorphological changes and human use patterns. The influence of land surface changes on stormwater peak flows has been appreciated for decades (Leopold 1968) as have geomorphological changes, including both natural and anthropogenic influences (Price 2011). Research on stream flow in the Maryland Piedmont area using GCMs and growth predictions suggested that climate and land use changes work together to create long-term stream flow changes, with precipitation changes being the apparent dominant driver (Hejazi and Moglen 2008). Gross and Moglen (2007) examined dams in Maryland, specifically the effects of the dams on stream peak flows, and found that a dam’s influence is limited and quantifiable. Additionally, Mejia and Moglen (2010b, 2010a) found that the spatial distribution of urban development in a watershed, along with the spatial distribution of storm events, had an effect on the runoff hydrographs produced by the area.

Humans frequently relocate water to suit their own needs, including groundwater pumping, groundwater recharge (intentional or not), and location transfers. Some researchers term this as “hydromorphology” (Vogel 2011), defined as “the dynamic morphology of water resource systems caused by both natural and anthropogenic influences.” While this concept is currently not widely adopted, according to Vogel it is "an active paradigm that accepts anthropogenic impacts on the hydrosphere as being both integral and inseparable within the context of the hydrologic cycle[,]" and therefore desirable as a way of understanding the physical world.

1.4 Toward a new design theory

The philosophical contemplation of design theory is usually the realm of structural and mechanical engineering, not to mention architecture and its related disciplines. The nature of civil engineering design as a one-time event may contribute to the phenomenon, but perhaps more importantly is the fact that much of civil engineering design requirements are heavily codified and regulated, whether or not the requirements are effective or superior. Olenik (1999) gave the example of stormwater "micro-management", wherein stormwater control regulations on a site-scale level have resulted in very dispersed infrastructure and questionable benefits to the environment.

Return-period or exceedance probability design can be considered an attempt at risk equity, such that all road crossings are theoretically designed for similar levels of overtopping probability, regardless of the relative level of importance of the road. In practice, this is not always ideally accomplished, considering individual engineers tend to make decisions about each project independently, and codified design standards are subject to frequent revision. However, despite the availability and mandatory status of these precisely calculated design probabilities, infrastructure management entities seldom enact any form of insurance or contingency planning based on these values. Therefore, the contribution of this concept to infrastructure management is questionable.

It appears that due to the large number of recent record-breaking hydrologic events, the increased understanding of climate variability, and repeated failures of existing infrastructure, the logical next step is to reexamine, revise, and replace the existing hydrologic design paradigms with new methods that produce the right infrastructure that is needed for the current world. Hawkins et al. (2009) described both the Curve Number method and the Manning's Equation as "a semi-empirical engineering method", developed under a specific set of conditions, but widely used and extrapolated well beyond its theoretical limits. Perhaps return-period precipitation based design should be seen in a similar light, relegated to those methods used essentially to please governing agencies and avoid lawsuits.

1.5 Research inquiries

This research focused on answering three basic questions about hydrologic design as currently practiced. First, are precipitation events a significant source of nonstationarity? Second, what other sources of nonstationarity can be quantified? Third, what can we do differently as engineers and designers in order to effectively construct cost-effective long-lasting infrastructure for future generations?

This study first examined the role of precipitation events in hydrologic nonstationarity, specifically with regard to the traditionally incorporated engineering design storm. The study assessed the accumulative quantile estimate of the 100-year storm event, the role of tropical storms in determining annual maximum precipitation events, the occurrence of two-year storms per year, and the possible presence of spatial trending in precipitation behavior.

The role of land-based and design-based contributions to hydrologic nonstationarity was examined, both in conjunction with precipitation based nonstationarity and without. Contributions from land development and topographic subsidence were quantified to determine the relative impact of various sources of hydrologic nonstationarity. Additionally, the decisions of a design engineer can have a lasting effect on the performance of an individual piece of infrastructure, leading to the possible conclusion that design decisions may themselves be a source of hydrologic nonstationarity.

To conclude, this study examined design techniques for culverts and small bridges based on ideas from the engineering literature. These design techniques were modeled and evaluated using an ad hoc quantitative assessment technique with three performance criteria for optimization. The techniques were also assessed qualitatively using a custom ranking system. These assessments allowed recommendations to be made on which techniques are appropriate for further consideration or adoption.

2. CONTRIBUTION OF PRECIPITATION TO HYDROLOGIC NONSTATIONARITY

2.1 Introduction

Return-period based risk assessment has been the de facto design standard for most civil engineering projects that involve some rarely-occurring natural event such as a heavy rainfall. In hydrology, the concept of the engineering design storm has, from the standpoint of contemporary engineering design techniques, a long history in which it endured relatively little alteration to its basic conceptual matter (Watt and Marsalek 2013). As the hypothesis of nonstationarity in climatic systems gained traction, it was inevitable that this concept would eventually descend upon the preexisting civil engineering hydrologic design paradigms (Barros and Evans 1997).

In the US, the job of predicting the engineering design storm has traditionally fallen to federal or state government agencies. The widely distributed 1961 Rainfall Frequency Atlas of the United States, also known as TP-40, was at the time of publication intended to collect and standardize several publications of smaller areas (Hershfield 1961). It remained in wide use for several decades, and although gradually superseded once again by several smaller area publications, remains in circulation.

The US National Weather Service is in the midst of a multi-year effort to revise and update precipitation frequency documents for the US; this effort remains ongoing (Bonnin et al. 2006a). The rainfall frequency atlas has the advantages of a greater period of record, improved spatial statistical technology, and newer regional frequency analysis methods, specifically the use of L-moments. Additionally, the methodology provided confidence intervals computed with non-parametric simulations. An analysis of the potential impacts of climate change on the recurrence interval storm revealed “little consistent observable effects of climate change on the annual maximum series…” according to the authors (Bonnin et al. 2006a).

Angel and Huff (1997) studied extreme precipitation trends over the US Midwest and found statistically significant increases, leading the authors to suggest that an assumption of stationarity may be invalid. Chen and Rao (2002) analyzed hydrologic time series in the US Midwest for change points intended to detect nonstationarity, and found some evidence thereof. Villarini et al. (2011a) examined annual maximum daily rainfall for the US Midwest and found slight annual maximum increases and some possible change points. Findings of nonstationarity were echoed for a broader area of the US by Heineman (2012).

Bonnin (2010) examined linear trends in threshold exceedances over several areas of the US and found mixed increases and decreases of varying statistical significance. Similar results were found for Spain and Portugal (García et al. 2007, Rodrigo and Trigo 2007) and for the French Mediterranean coast (Pujol et al. 2007). A study of precipitation trends in the South Pacific showed a spatial significance in relation to existing oceanic weather patterns (Griffiths et al. 2003). In Austria, Villarini et al. (2011b) examined both annual maxima and peaks-above-threshold daily data for possible trends but were ultimately unable to make conclusive assertions regarding stationarity. A study of Westphalia, Germany, by Einfalt et al. (2011) examined rainfall data from 1950 onward, and found numerous significant trends, leading to the authors' call for more flexible urban hydrologic design techniques. In Denmark, researchers studying an update to regional IDF curves found increases in intensity, especially for large recurrence interval events (Madsen et al. 2009).

Cislaghi et al. (2005) examined data in four major Italian cities and found decreasing rainy days in conjunction with increasing rainfall intensity. Crisci et al. (2002) examined design storms in Tuscany and found evidence of increasing extreme events large enough to potentially influence design. Conversely, Gemmer et al. (2011) examined annual data in southern China and found few significant temporal trends and no significant spatial trends. In northern China, Liang et al. (2011) found overall decreasing precipitation trends and some possible climatological change points.

In New England, Douglas and Fairbank (2011) studied whether extreme hydrologic events were becoming more extreme, and found mixed increases and decreases in comparison to existing published exceedance frequency depths. Klein Tank and Können (2003) examined climate indices over a large swath of Europe and found both precipitation increases and decreases at various stations, as did Smith and Lawson (2012) for Manchester, England. A study of rainfall return periods for a portion of Australia found a significant difference in the 1% storm between two periods separated by a change point (Li et al. 2005). Also in Australia, Westra and Sisson (2011) studied daily and sub-daily precipitation data and found increases in short-duration storms but no significant changes in annual maxima.

Is the 100-year storm of today passably similar to the 100-year storm estimate posited in the 1960s? If not, are there discernable trends in the available data? These and other questions repeatedly arise in civil engineering, especially after news of infrastructure failures or catastrophic storm events. In engineering, infrastructure failure of any form must be taken seriously, and professional practice must adapt to learn from past circumstances and avoid repeat failures.

In this section, four analysis methods were employed to test the concept of stationarity with regard to the return period engineering design storm. First, the concept of the 100-year quantile estimate was examined due to its prevalence as a standard design storm, using a Monte Carlo technique to generate confidence intervals in order to test for trending behavior. This allowed any temporal trends to surface if the existing time series was outside the generated confidence intervals. Second, the influence of tropical storm activity on annual maximum precipitation events was examined in the interest of determining whether these warranted a separate analysis. Third, a peaks above threshold analysis was conducted using a time series analysis technique likewise to uncover any potential trends. Fourth, of the resulting data sets were examined for spatial trends using geographic data analysis techniques to explore any spatial relationships. These analyses provided insight on the relative stationarity of the engineering design storm as commonly conceived.

2.2 Annual maxima analysis

Engineering design storm magnitudes are calculated by combining all available data at the time of analysis, fitting a probability distribution, and determining the appropriate precipitation event. The type of probability distribution used can vary based on convention or data characteristics. This empirical technique is common in textbooks and engineering education. For this analysis, the 100 year quantile estimate storm was assessed because of its prevalence in both design and analysis, and its nature as a sufficiently but not exceedingly extreme event from which to assess the behavior of extreme quantile analysis in general. This analysis examined whether the described technique is sensitive to nonstationarity.

The area of interest for this study included a broad area encompassing the entire southeastern United States because the area is sufficiently humid – i.e. it has a sizeable number of rain storm events – from which to draw conclusions. Additionally, the region is sufficiently insusceptible to frequent winter storm events, which simplified the analysis by assuming that snowfall can be excluded. The NCDC Global Historical Climate Network daily data (24 hour) was selected as the data source for this research (NCDC 2011a) due to the available length of record and the broad geographical coverage for the area of study. The specific weather stations selected were required to display three key attributes: a) the station's time series had to begin in the 1930s at the latest and end in 2000 at the earliest; b) the station needed at least 79 years with at least 90% completion (329 days of record); and c) the station's time series could not have gaps larger than 10 years. Upon combining the area of interest with the data quality standards, this resulted in 332 rain gauge stations across 18 states and Puerto Rico, shown in Table 1.

Table 1. Area of study coverage.

State/Territory	NOAA climate divisions	Number of stations used
Alabama	8	11
Arkansas	9	27
Delaware	2	1
Florida	7	17
Georgia	9	20
Kentucky	4	14
Louisiana	9	20
Maryland	8	6
Mississippi	10	24
Missouri	6	32
New Jersey	3	10
North Carolina	8	33
Oklahoma	9	27
Puerto Rico	6	5
South Carolina	7	16
Tennessee	4	20
Texas	10	27
Virginia	6	9
West Virginia	6	13
Total		332

Temporal trends in an engineering design storm estimate were assessed with a plot of the 100-year storm estimate versus time. The analysis technique used can be termed an ‘accumulative’ quantile estimate, which differs from the commonly employed moving quantile estimate in that at each data point, the estimate uses all the available data rather than just the predefined analysis window. The GEV distribution maintains wide acceptance in the field of climatological and hydrologic extreme value analysis (Martins and Stedinger 2000, Bourque et al. 2002, Coles et al. 2003), and thus was selected as the appropriate method for computing the 100-year storm estimate.

Taking the first 30 years of each annual maxima time series, this beginning portion of data was used to compute the 100-year storm event. The 31st year was added, and the 100-year storm was recalculated, etc., until the end of the series, resulting in the so-called accumulative quantile estimate. To test for significant trending behavior, the data was checked for whether the quantile time series exceeds the 95% confidence interval. Because parametric methods of computing quantile confidence intervals are known to be problematic when estimating high quantiles, the confidence intervals for this analysis were computed by use of a non-parametric Monte Carlo bootstrapping technique partially based on Mahajan et al. (2011), with the number of Monte Carlo realizations determined after review of recommendations by Morgan et al. (1990). (See also Kysely (2010) for a discussion of nonparametric bootstrapping techniques.) The resulting data was then plotted as in Figure 1 to show the time series of quantile estimates, recalculated each year, plotted against a gradually converging 95% confidence interval produced from 1000 random reshuffling realizations of the annual maxima data, employing the same accumulative quantile algorithm.

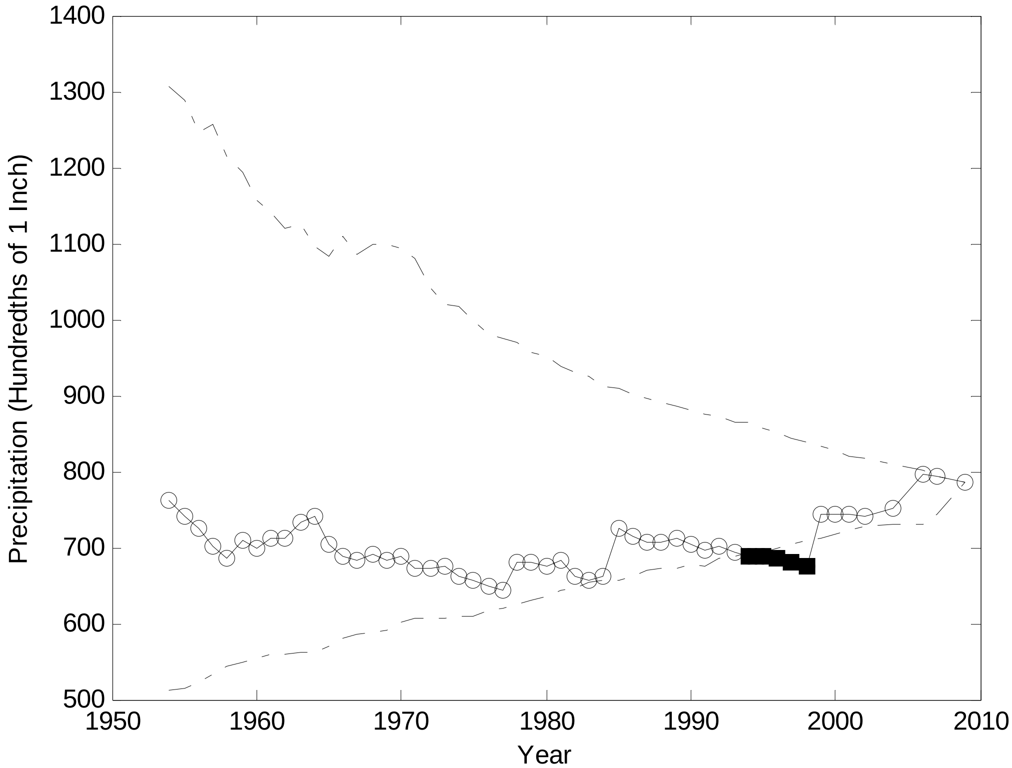

Figure 1. Accumulative quantile estimate analysis of Hopewell, VA (Station ID #444101)

Of the 332 stations analyzed, 151 exhibited behavior wherein at some point within the available time series, the quantile estimate went outside the 95% confidence interval estimate. However, actual directional trend evidence was much more obscure, as station time series often exhibited multiple and varying trend directions. Rather than using a quantitative measure of trend, each station was rated using a categorical rating system which qualitatively indicates the type and magnitude of the exhibited nonstationary behavior (see Figures 2, 3, and 4). Using this rating system, there appeared to be a 45% rate of trend significance. Under the null assumption of a stationary time series, one would expect a few stations to exhibit significant trend behavior based on random chance; however, these results show more than 5% rate of trend significance, which appears to indicate possible nonstationarity of precipitation time series. It is worth noting that this conclusion assumes independence of both individual annual maxima data points and independence of each weather station. In actuality, each station exhibits autocorrelation within its own time series and with other surrounding stations; thus, all conclusions should be considered with these limitations in mind.

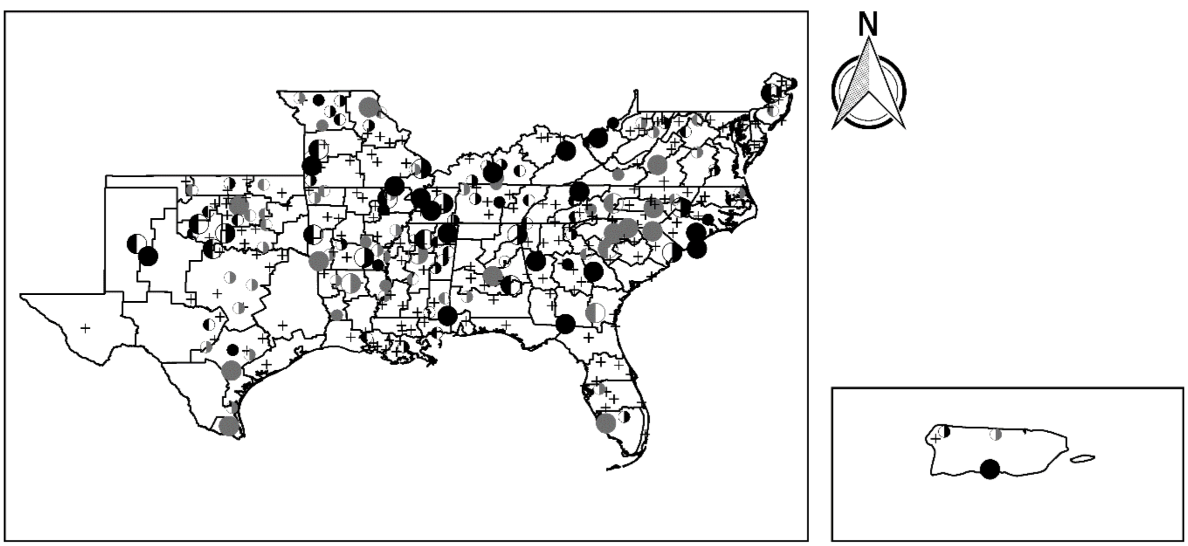

Figure 2. Categorical rating system (not to scale) (Basemap via NCDC 1991)

Rating	Symbol	Description
1	+	Does not cross 95% confidence interval
2	◐	Crosses lower interval <10 times during the first half of the graphed data
3	◐	Crosses lower interval >10 times during the first half of the graphed data
4	◑	Crosses lower interval <10 times during the second half of the graphed data
5	◑	Crosses lower interval >10 times during the second half of the graphed data
6	●	Crosses lower interval <10 times during both halves
7	●	Crosses lower interval >10 times during both halves
8	◐	Crosses upper interval <10 times during the first half of the graphed data
9	◐	Crosses upper interval >10 times during the first half of the graphed data
10	◑	Crosses upper interval <10 times during the second half of the graphed data
11	◑	Crosses upper interval >10 times during the second half of the graphed data
12	●	Crosses upper interval <10 times during both halves
13	●	Crosses upper interval >10 times during both halves
14	⊙	Crosses both confidence intervals

Figure 3. Categorical rating system legend

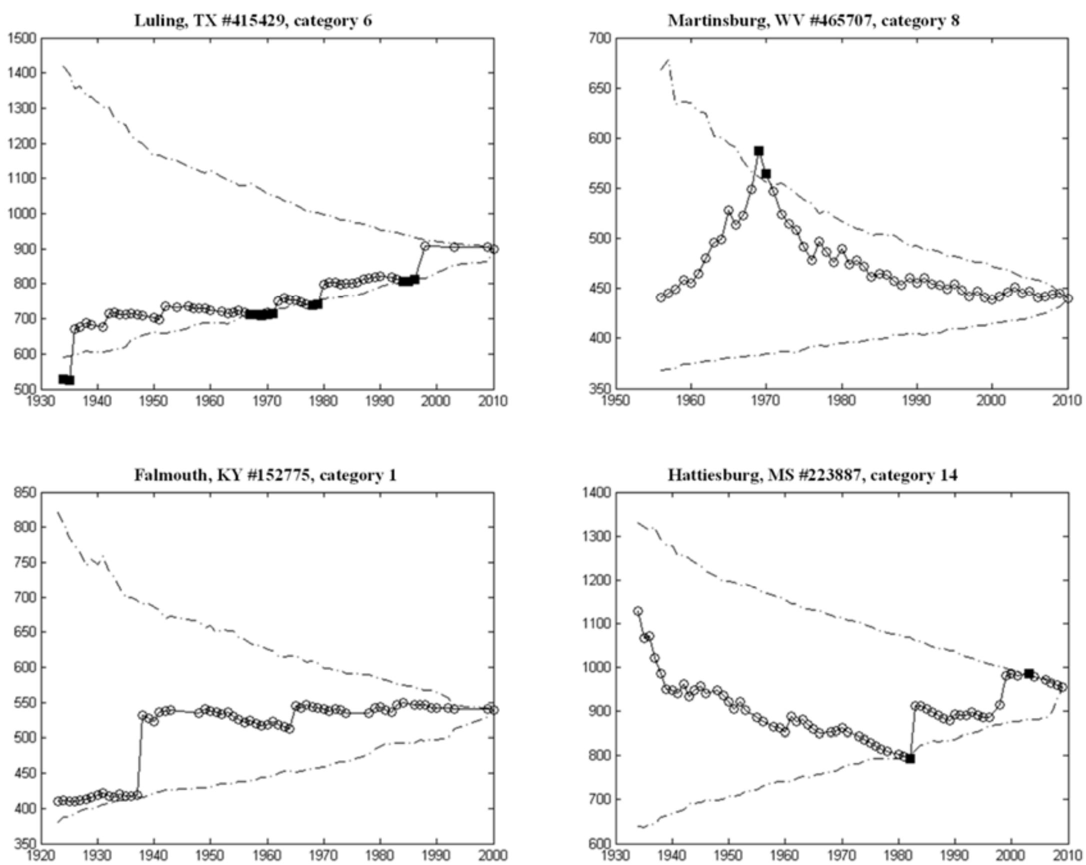

Figure 4. Example station plots

2.3 Tropical storm activity

The North American Atlantic and Gulf Coast areas are prone to tropical storm activity, which possibly contributes to the annual maximum values for each weather station; concern arises over whether tropical depressions have a disproportionate impact on the annual maximum values. This finding could have ramifications on how any high outliers are treated in each time series. To definitively peg the exact contribution of tropical weather patterns, a simple date and location matching algorithm was devised, wherein each annual maxima was compared to the IBTRACS database (NCDC 2011b), which covers known tropical storms from 1850 to present. If the date of an annual maximum data point matched a data point date from IBTRACS, and the location of the IBTRACS data point was within 60 miles of the weather station in question, then the annual maximum was considered to have been produced by a tropical weather event.

First, the analysis counted how many and what proportion of the annual maxima found at each weather station had in fact been caused by tropical storms. This count found that on average, 5% to less than 10% of all annual maxima events were caused by tropical storms at each station. Some stations had fewer than 5% but none had more than 10% of its annual maxima events caused by tropical storms. Apparently, although tropical storms are undoubtedly a presence in the time series, they are not a disproportionate influence in terms of total data points. The next question was whether or not tropical storms constituted a disproportionate influence on the upper tenth percentile of each station’s annual maxima data points. It was found that approximately two to three upper tenth percentile storms (out of 79 or more data points) were found to coincide with tropical storms. Therefore, tropical storms do in fact appear in the upper tenth percentile of each station's annual maxima but do not displace other types of storms. Then it was considered whether tropical storms constituted a disproportionate number of station-record worst-ever events. It was found that station record maximum values most often did not correspond to a recorded tropical storm event, even in relatively hurricane-prone areas such as Florida. Based on these statistical findings, all high outlier storm events were included in the data set without special consideration, based on the conclusion that hurricanes and tropical weather events do not disproportionally affect station annual maximum values.

2.4 Peaks above threshold analysis

A peaks above threshold analysis was conducted because potential nonstationarity of the engineering design storm may occur in the form of certain probability events occurring more frequently than their supposed probability implies. Analyzing a partial duration series in addition to an annual maxima series can result in a more complete picture of a station's characteristics (Martins and Stedinger 2001). Using the same NCDC data set, the occurrences of two-year storms per year were considered. The two-year storm was selected because it is a commonly used engineering design parameter, and it occurs at a sufficient frequency such that adequate data points can be produced from the existing available time series. The seasonality of two-year storm occurrences emerged from simple histogram bins (the two-year storm estimate having first been calculated using the GEV distribution). The distribution of the histogram bins showed a clear difference between cool season and warm season precipitation events, as more two-year storms appeared to be occurring in warm months. It was determined that the months could be divided into “frontal-dominated” and “convective-dominated” weather patterns (Nov-Apr and May-Oct, respectively), and should be analyzed separately, a process similar to that employed by Keim and Faiers (1996) and Baigorria et al. (2007).

The occurrence of two-year storms per year was analyzed by the use of a Poisson process in various cases (Olsen et al. 1998, Martins and Stedinger 2001). Additionally, a chi-square goodness of fit test effectively showed that, for the data in question, a Poisson distribution assumption for the rate of two-year storm exceedances per year could not be rejected in approximately 93% of cases. To discern whether the two sets of months were indeed two separate populations, a Kruskal-Wallis test was applied to the populations’ means. The test for different populations was significant in approximately 63% of test cases, and the occurrences of significance were highly spatially correlated as explained in the discussion of spatial trends to follow.

A separate Poisson parameter was calculated for each year of data to check for trends in the rate of two-year storm exceedances per year. Additionally, a similar analysis was conducted using the rate of two-year storm exceedances per decade due to the previously described maximum 10-year gaps in the time series data. The 95% confidence intervals in both cases were calculated for the Poisson distribution and plotted as in Figure 5. A careful examination of resulting graphs indicated there were no discernable trends or significant nonstationary behavior in either the rate of exceedances per year or the rate of exceedances per decade.

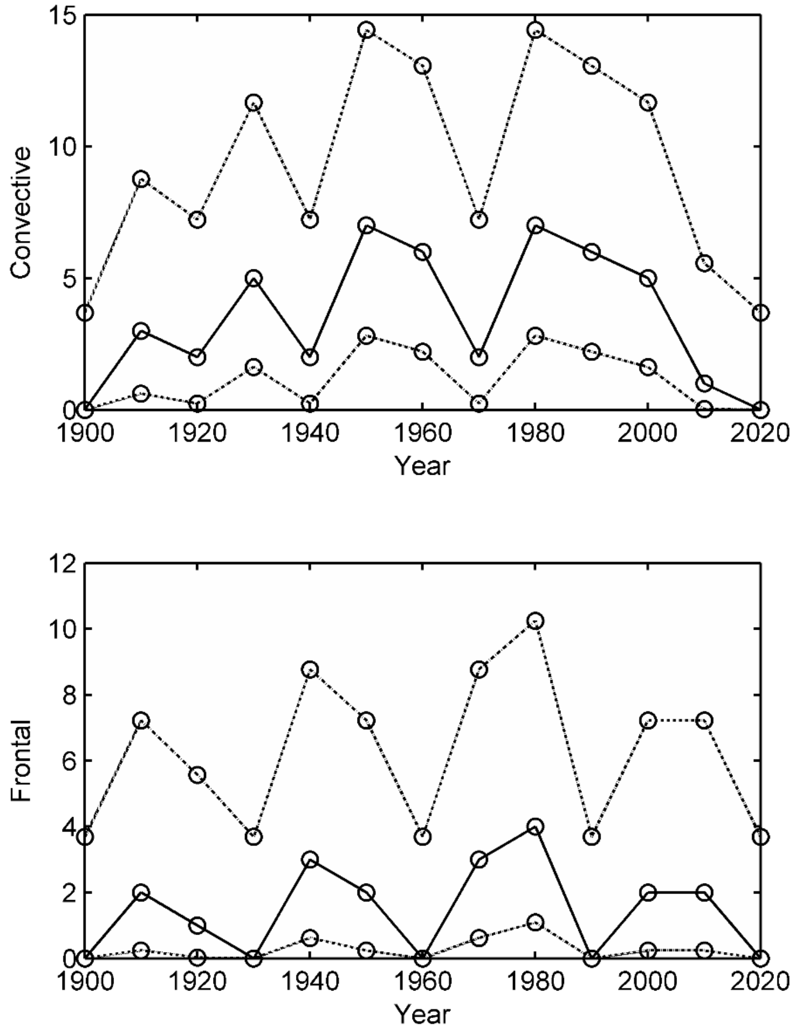

Figure 5. Example plot of two-year storm exceedances per decade of Luling, TX (Station ID #415429)

The peaks above threshold analysis as conducted was unable to discern whether two year storms are occurring more or less frequently over time. There is variability in the number of occurrences but no obvious temporal shifts in either direction. In this case, the null hypothesis was not rejected and it appears that the number of two year storms per year are neither increasing nor decreasing for these particular stations.

2.5 Spatial trend analysis

Because engineering hydrologic design work is predominantly conducted via precipitation quantile estimates from rainfall frequency atlases and similar publications, it is advantageous to analyze precipitation data from a spatial standpoint. Atlases are common as is spatial averaging and trend prediction; a determination of spatial trend may assist with the usage, revision, and creation of new rainfall frequency atlas data. The results from the previous tests were applied to geographic information to ascertain whether any spatial trends were present.

For the annual maxima analysis, the qualitative categorical rating system used in the trend study lends itself to a cluster analysis rather than a quantitative spatial trend calculation. A Voronoi polygon map was constructed with the station rating values as shown in Figure 6, which did not reveal any obvious clustering phenomena. Additionally, when applying a simple linear regression to the annual maxima time series data to obtain a net directional slope, a comparison between this net slope and the qualitative rating system also did not reveal a discernable spatial relationship, other than a majority of net positive directional slopes, significant or otherwise.

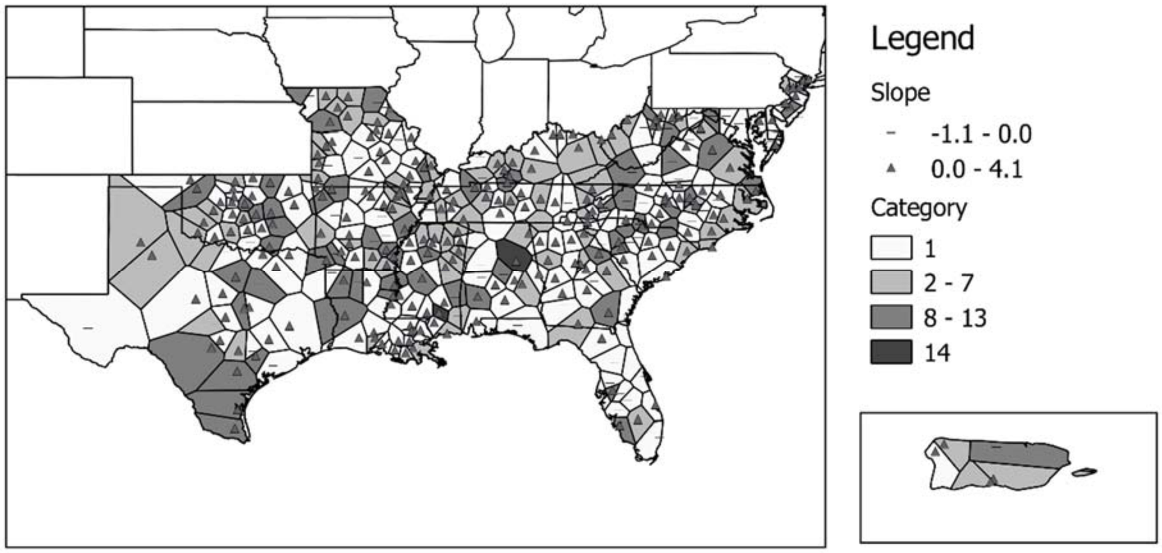

Figure 6. Categorical clustering analysis versus linear slope (not to scale) (Basemap via U.S. Census Bureau 2010)

For the peaks above threshold analysis, there was not significant trending behavior with which to conduct a spatial analysis; instead the exceedance rate and significance of seasonal variation was analyzed. In general, the rate of two-year storm exceedances per year without seasonal consideration was relatively uniform throughout the data set, on target with expected values, and did not exhibit significant spatial correlation. The significance of the Kruskal-Wallis test showed a large amount of significant clustering in the Mississippi River valley and Ozark Plateau areas as shown in Figure 7, which was echoed in comparison to the ratio of convective to frontal storms; the ratio was closer to 1 in those areas where the Kruskal-Wallis test was not significant.

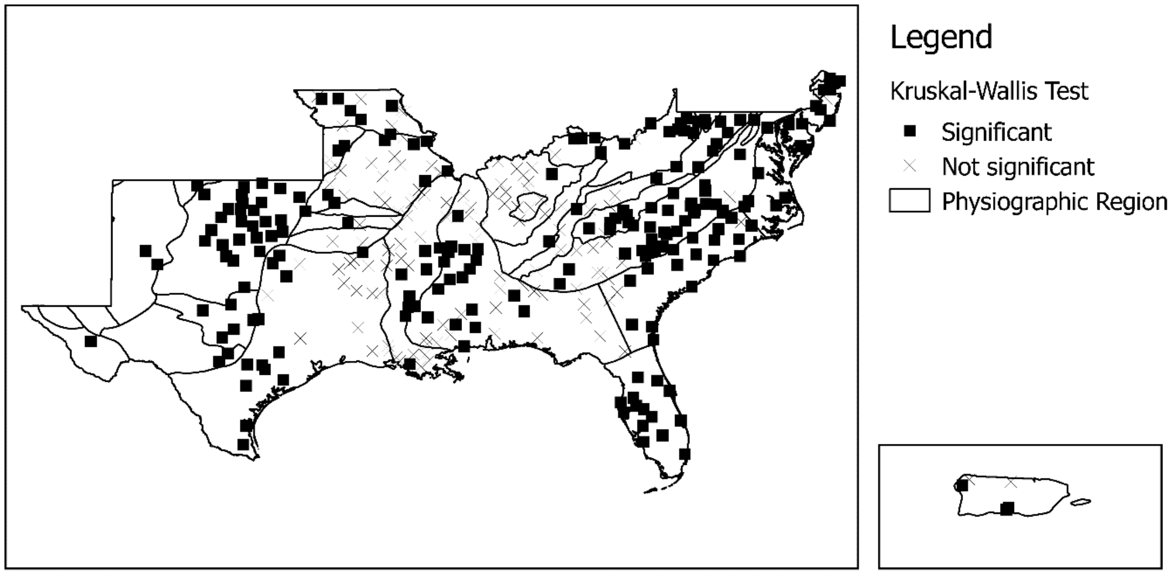

Figure 7. Significance of Kruskal-Wallis test for two populations compared to physiographic regions (not to scale) (Basemap via Fenneman and Johnson 1946)

2.6 Conclusion

Drawing on data from 332 rain gauge stations in the southeastern US, this section used four trend testing techniques to examine the concept of nonstationarity in the engineering design storm as currently used by the industry. This research applied an accumulative quantile estimate technique and applied a nonparametric bootstrapping technique for detecting potential nonstationarity. According to the analysis, the estimate of the 100-year (1% exceedance) engineering design storm depends upon where in the time series the estimate was conducted. When shuffling was performed to eliminate sampling bias, it was found that the best industry estimate of the engineering design storm using all available weather data is often outside the 95% confidence limit. Tropical storms were not found to overly influence station annual maxima. Furthermore, trends in the rate of two-year storm exceedances were undetectable, as were spatial correlation of the quantile estimate trends. Temporal trends in the rate of exceedances per year and per decade were not detected, but a test of the validity of using a Poisson distribution for exceedances showed a clear spatial relationship.

These findings raise questions about the inherent accuracy and usefulness of using an accumulative design storm quantile estimate and spatial estimation procedures, essentially the status quo for engineering design storm calculation. This research showed that there ultimately was not a strong signal or trend from climate change on the estimated return period precipitation, but rather the methodology had inherent problems that were camouflaged by the spatial averaging technique commonly employed in statistical hydrology. To the design engineer, it matters little whether the variation is due to so-called “real” or “apparent” nonstationarity; that is, variation caused by climatological factors or simple misestimating due to human mathematical limitations and lack of data. If a best estimate of the current 100-year storm is inaccurate, perhaps designers are better off forgoing the traditional techniques and focusing on methods that can more adequately withstand potential hydrologic events.

3. CONTRIBUTIONS OF LAND USE AND GEOMORPHOLOGY TO HYDROLOGIC NONSTATIONARITY

3.1 Introduction

Engineering hydrology and hydrologic design represent a unique opportunity to examine the effects of various processes on the flow of water downstream, as each new infrastructure design must ideally be built to reflect anticipated future conditions over the expected life of the facility. This portion of the research examines several possible sources of hydrologic nonstationarity, combined with the conventional engineering design return period rainfall-runoff methodology, in order to provide guidance for the field of civil engineering design under the assumption of nonstationarity.

Nonstationarity can result from change in climatological or geomorphological processes or from changes in human land and water use patterns, among other phenomena. Several researchers have attempted to quantify the impacts of these various sources. Ferguson and Maxwell (2012) studied the influence on a stream of nonstationarity due to climate change versus human-caused water relocation, namely pumping for irrigation, and found that the quantities of the impacts were somewhat comparable, but that climate change could additionally impact water availability if the two forces coincided. Vegetation change can affect both stream base flow and water quality (Cheng et al. 2007); similarly, Gallart and Llorens (2003) studied the impact of forest cover to water availability and concluded that forest uptake is a contributor to hydrologic nonstationarity. Lin et al. (2012) studied a watershed in Taiwan under several development and climate change scenarios and found that reduced development increased a watershed's ability to adapt to climate change.

States Luna Leopold, the originator of the study of geomorphology, "Of all land-use changes affecting the hydrology of an area, urbanization is by far the most forceful." His 1968 planning document goes on to enumerate several ways that anthropogenic land morphology systematically affects hydrologic regimes, contending that urbanization accelerates otherwise natural processes as the stream attempts to accommodate the drastically altered flows (Leopold 1968). Using the science available at the time, Leopold systematically establishes changes to event peak flow, total runoff volume, water quality, and general river morphology which he terms "hydrologic amenities." Several studies have looked at predicted land development patterns in combination with climate change scenarios and their effects on watershed hydrology (see Table 2), with many results agreeing that the effects of climate change were slightly greater than the effects due to land use alone, and combined effects surpassing each factor in isolation.

Table 2. Studies of climate and land use effects on watershed hydrology

Reference	Modeling technique	Model type
Best et al. (2003)	Statistical analysis	Flow duration
Knebl et al. (2005)	HEC-HMS/RAS	Rainfall-runoff/hydraulic
Hejazi and Moglen (2008)	McCuen & Snyder	Flow duration
Amini et al. (2011)	HEC-HMS	Rainfall-runoff
Du et al. (2012)	HEC-HMS	Rainfall-runoff; continuous simulation
Tong et al. (2012)	HSPF	Continuous simulation; water quality
Shi et al. (2013)	SWAT	Continuous simulation
Yan and Edwards (2013)	SWMM	Rainfall-runoff

Saghafian et al. (2008) found that a watershed's hydrograph peak flow was more sensitive to land cover change than the total runoff volume of the same event. Forsee and Ahmad (2011) studied a watershed in Nevada under several climate change models and found a wide range of possible outcomes. They concluded that precipitation predictions for the sake of engineering design should include a wider range of possible future climate scenarios. Otherwise, applying the concept of the conventional engineering design storm to modern infrastructure will eventually result in existing infrastructure becoming overwhelmed by new hydrologic regimes (Moglen and Rios Vidal 2014).

Geomorphological forces are known to have a lasting impact on hydrologic behavior. In Georgia, Magilligan and Stamp (1997) used rainfall-runoff modeling to examine the response of a watershed from the cotton-production era through eventual reforestation and found that the changes impacted the two-year storm more than the 100-year storm. Additionally, the watershed's sensitivity to erosion caused by farming continued long after agricultural activities ceased. Meyer and Prager (2004) enumerated a list of potential stream impacts from urbanization and acknowledged the disconnect between regulatory design flows and the true behavior of urban streams. In a meta-analysis of impacts to stream base flow behavior, Price (2011) found that the greatest influences on watershed behavior involved the slope, topographic relief, and the basin's drainage density.

Nonstationarity in engineering hydrology should be considered a design constraint and is confounded by the fact that multiple sources can exist to varying degrees in any one location. For an engineer to understand how a particular watershed will react to sources of change in the future, a process to analyze relative effects of nonstationarity in isolation and in concert is necessary.

3.2 Case study of Sweetwater Creek, Georgia

Sweetwater Creek is a 260 square mile watershed northwest of the Atlanta Metro Area, Georgia, located in in the Apalachicola-Chattahoochee-Flint drainage basin (see Figure 8). The basin drains south to the Chattahoochee River, and ultimately to the Gulf of Mexico at Apalachicola, Florida. The creek was used as a source of textile mill power in the early industrial era of Atlanta, but now is mainly used for recreation. The Atlanta area is known to receive severe flood events, of which the record flood occurred in September 2009 (Bowers 2009), therefore the creek is well monitored with seven stream gauges and several precipitation gauges as shown in Figure 9.

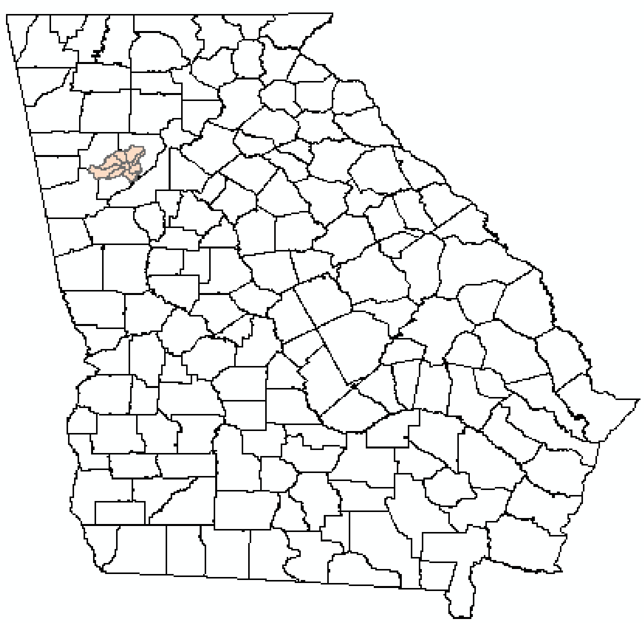

Figure 8. Location of Sweetwater Creek in Georgia (Basemap via U.S. Census Bureau 2012)

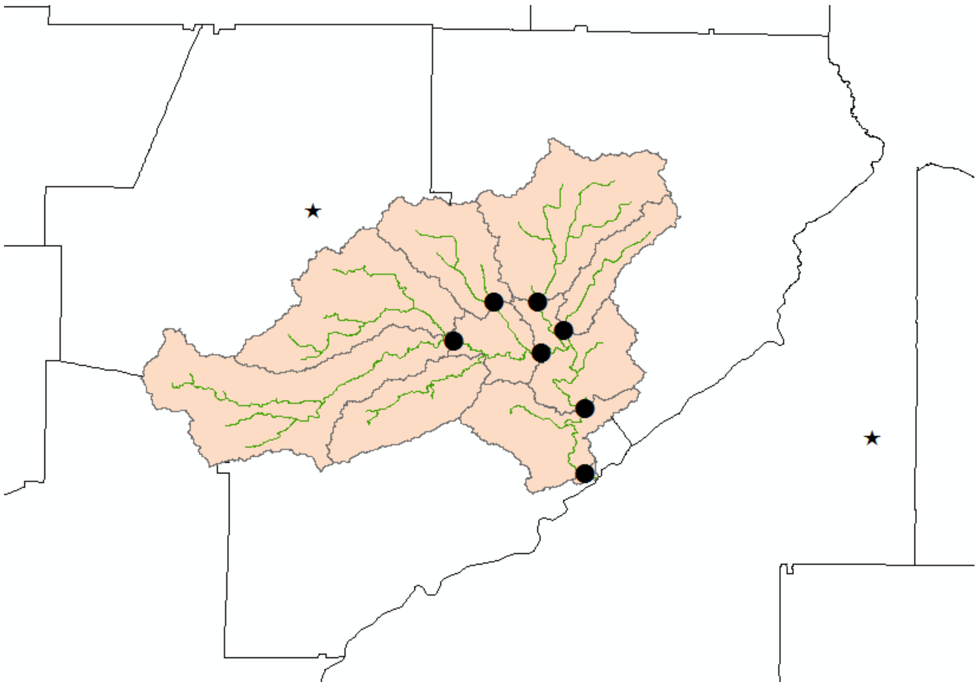

Figure 9. Location of rain gauges (star) and stream gauges (circle) within watershed

The Sweetwater Creek watershed has seen significant urban/suburban development over the past several decades, which has impacted stream flows in the area (Peters and Rose 2001). It is possible that this development may have worsened or adversely impacted the flooding during the catastrophic event. This widespread urbanization may have had the potential to impact flood severity and contribute to infrastructure failures within the watershed. In this analysis, the potential contribution to hydrologic nonstationarity by the increased development was quantified using hydrologic modeling.

3.2.1 Hydrologic model

A hydrologic model of the watershed was constructed using HEC-HMS and available digital input data. For topographic data, 10-meter topographic Digital

Elevation Models and stream location files were obtained from standard USGS elevation and hydrography products (Gesch et al. 2002), with additional geographic information obtained from the USGS' study of the 2009 flood event (Musser 2012). Soil information was obtained from the USDA soil type database (Soil Survey Staff 2013). Engineering design storms were obtained from NOAA Atlas 14 (Bonnin et al. 2006b). The HEC-HMS model was constructed using Curve Number loss, Clark unit hydrograph transform (Sabol 1988), Muskingum-Cunge reach routing, and recession base flow methods.

Land cover data for the watershed was obtained from the Georgia Land Use Trends dataset issued by the University of Georgia (NARSAL 2010). The land cover data set was constructed using Landsat Thematic Mapper images at a 30-meter resolution. The classification of the Landsat images into land use type was conducted using winter images (without foliage) and the ISODATA unsupervised classification algorithm. These were then double checked using spring images and black and white images for accuracy. Land cover raster data was available from 1974 to 2008, allowing a comparison through time for the past several decades. These land cover rasters were converted into curve number rasters by an ad hoc reclassification technique using NRCS (1986).

The hydrologic model was calibrated using stream flow data from the USGS National Water Information System and gage precipitation from the National Climatic Data Center using a storm event from April 2014. Calibration was achieved using a custom abstraction value and manually adjusted Clark Unit Hydrograph storage coefficients. The calibrated model performed well in comparison to actual stream gage values, achieving a correlation value of 0.90.

3.2.2 Hydrologic analysis

A hydrologic analysis of Sweetwater Creek was conducted using the 25-year and 100-year engineering design storms and the available land cover raster data sets to examine whether the increased urbanized area had impacted the flows resulting from the standard design storms. As shown in Table 3, the urbanization had a large impact on design flows for both the 25-year and 100-year storm events.

Table 3. Results of hydrologic analysis

Year	25-year	100-year
2008	19,199 CFS	25,380 CFS
2005	18,200 CFS	23,961 CFS
2001	16,282 CFS	21,500 CFS
1991	14,768 CFS	19,536 CFS
1985	14,293 CFS	18,866 CFS
1974	13,277 CFS	17,562 CFS

The results of this analysis showed that infrastructure can become obsolete quickly due to land use change, often in less than 10 years and much more quickly than what could be considered a standard design life for a piece of civil infrastructure such as a bridge or river crossing. Having infrastructure with greatly reduced capacity can hinder the ability of an area to endure catastrophic flood events. Furthermore, rapid development can complicate engineers' ability to accurately design infrastructure that will remain in service throughout its design life. Designers are often faced with the choice of either designing a piece of infrastructure that will quickly become obsolete, or attempting to guess at the future design flows of a stream under the prevailing environment.

3.3 Case study of Armand Bayou, Texas

Armand Bayou, formerly called Middle Bayou, is a 60 square mile watershed located in southeast Harris County, Texas (see Figure 10). The watershed is home to NASA's Johnson Space Center as well as Ellington Field Air Force base. The low-lying and swampy watershed is typical of coastal East Texas, in that it has seen considerable suburban development and subsidence in the past 100 years, both of which could have influenced the overarching hydrologic scheme of the bayou. The stream outlets to Clear Lake, which is hydrologically connected to Galveston Bay. The main channel is influenced by tidal cycles, and as such the inundated portion of the channel is referred to as "Mud Lake", indicating a level of turbidity typical of semi-stagnant water. The stream has several tributaries, among them Horsepen Creek, Willow Creek, and Big Island Slough. For the sake of brevity, the tributaries were excluded from this study.

Figure 10. Location of Armand Bayou study area (Basemap via TNRIS 2012)

Information on the bayou and its tributaries is relatively abundant. The area has been regularly mapped by the USGS since the advent of the topographic mapping program circa 1906, enabling the use of the old topographic quadrangles as a form of verification of existing conditions. Additionally, the watershed is mapped and modeled by the Harris County Flood Control District, which allows public use of the available models. The bayou does not contain any volumetric gauging stations; however, both the main bayou and its tributaries contain several stage gauges. The elevations of the stage gauges have shifted as the watershed has experienced subsidence, so numerical rectification was required before the stage hydrographs could be used for calculation purposes. One should observe the difficulty of accurately identifying the exact elevation of “sea level” in this case, not to be confused with elevation zero (Gabrysch 1982). First, the national standard shifted from NGVD 1929 to NAVD 1983 during the study period of this project; however, according to NOAA the difference between the two is nearly negligible in this location, at less than one tenth of one foot (Mulcare 2004). Furthermore, the original 1906 USGS topographic land survey was likely conducted using a local tidal datum, the exact identity and elevation of which has been lost to the ages. Additionally, a NOAA sea level gauge is located nearby at Galveston Pier 21. An examination of the sea level data set from this gauge showed that while sea level has indeed risen in Galveston Bay, it is difficult if not impossible to separate the rise due to climatological forces and the relative rise due to land subsidence (Turner 1991, Kolker et al. 2011). Therefore, climatologically-caused sea level rise was neglected for this analysis.

3.3.1 Armand Bayou hydrology

Armand Bayou and the surrounding areas have proven to be an interesting hydrologic case study in several theoretic topics, including storm surge, land development, and coastal flooding. Houston experienced destructive flooding in 1929 and 1935, which led to the creation of the Harris County Flood Control District in 1937. Heavy urbanization throughout the 20th century led to even more flood damages, and the HCFCD realized that the city would need to move beyond the typical flood control strategy of channelization and levees, so began to focus more on regional planning. The catastrophic flooding caused by Tropical Storm Allison accelerated this effort, leading to the buyout of many flood prone properties and implementation of the Tropical Strom Allison Recovery Project (TSARP). This project saw the creation of new hydrologic and hydraulic models and new floodplain maps with more realistic estimations of flooding potential. (White et al. 2008)

Brody et al. (2013) conducted a flood loss study of the 100 year flood plain of the Clear Creek watershed and concluded that the 1% return period flood metric is inadequate due to faulty estimates of the potential for flood losses. Holder et al. (2002) studied the effects of Tropical Storm Allison on Brays Bayou and analyzed the effects of hydraulic tailwater on a flood wave. The research found that increased tailwater reduced the Brays Bayou outfall capacity by as much as 60%. Ray et al. (2009a) and Ray et al. (2009b) used a combined hydrologic-hydraulic model to emulate Hurricane Ike and Tropical Storm Allison storm surge conditions on the Horsepen Creek portion of Armand Bayou and found that coinciding rainfall and storm surge peaks caused an approximate increase of 0.5 feet of water surface elevation. Additionally, significantly more area was flooded due to the flat topography of the watershed. Warner and Tissot (2012) examined the combined effects of sea level rise and storm surge in Galveston Bay and estimate water level probability exceedance distributions for several possible scenarios.

The Armand Bayou watershed was studied in this analysis using a combined hydrologic-hydraulic model in order to examine the effects of various hydrologic influencing factors on the engineering design storm. Analyses are conducted to represent conditions at three historical points – 1929, 1973, and 2011. The dates of the study points were chosen to represent the initial start of subsidence activity, a median subsidence condition, and modern conditions as-is.

3.3.2 Texas coastal subsidence

Subsidence has long been a thorn in the side of Harris County's many residents. Harris County lies atop the Gulf Coast aquifer which is composed of the Chicot, Evangeline, and Jasper aquifers, all of which have seen significant water withdrawals and depletion, which in turn led to the large-scale subsidence problem. As early as 1894, city utilities began pumping groundwater for public municipal utility use, but intense groundwater extraction accelerated in the 1930s-40s during rapid economic expansion (Gabrysch and Bonnet 1975). It is difficult to place the exact date of problematic subsidence. The first known case of large-scale land subsidence was at the Goose Creek oil field, which had subsided by over three feet in elevation due to oil and gas extraction, but until the 1930s subsidence was thought to be highly localized. Land surveys of the area were conducted in 1906, 1918, and 1932, at which time significant discrepancies in elevation were noted across a wide swath of the county (Gabrysch and Bonnet 1975).

The 1950s saw slightly decreased rates of subsidence as utility managers began to seek alternate sources of water, but in the 1960s, rates of subsidence and pumping increased again due to population pressure. Circa 1970, 80% of withdrawals from the area within Houston were conducted by the City of Houston in response to population pressure on surface water resources. Groundwater in the Pasadena area was mostly withdrawn for industrial purposes, and in Baytown-La Porte, withdrawals were evenly split between residential and industrial uses (Gabrysch 1982). The 1960s saw the advent of subsidence monitoring in order to better track larger areas of subsidence (Gabrysch and Bonnet 1975). The Harris-Galveston Coastal Subsidence District was formed by the

Texas legislature in 1975 with the goal to reduce dependence on groundwater (Kasmarek et al. 2012) and began monitoring water levels in 1976. The subsidence has caused additional submerged coastal land and caused new areas to be subjected to flooding from both storm surge and heavy rainfall events (Holdahl et al. 1991).

Research on the Harris County subsidence issue remains ongoing. New measurement technologies such as radar interferometry (Buckley et al. 2003) and GPS techniques (Engelkemeir et al. 2010) allow for more precise measurement of vertical movement as well as fault mapping. Briaud et al. (2002) studied the San Jacinto Monument in Galveston Bay and found that settlement had exceeded the engineer's original settlement calculations from the 1930s due to both incorrect soil assumptions as well as general subsidence trends in the area. Paine (1993) studied Pleistocene era subsidence of the Texas coast and concludes that recent subsidence rates exceed prehistoric subsidence rates. Kasmarek (2012) used the groundwater modeling program MODFLOW to simulate land surface subsidence over a large scale area of coastal Texas and was able to replicate the approximate subsidence from 1891-2009, as well as to evaluate predictions as far as 2050 (Kasmarek et al. 2005). Optimistic groundwater withdrawal scenarios show that future subsidence can be very nearly arrested if aggressive groundwater controls are in place. Pessimistic scenarios show as much as 10 additional feet of subsidence at worst by 2030 (Kasmarek et al. 2005).

3.3.3 Hydrologic model

In order to estimate the hydrologic effects of changes in climatological forces and land development for the three selected study points, a hydrologic model of the watershed was constructed using HEC-HMS, for which the watershed delineation was conducted with Arc Hydro tools. Detailed LIDAR DEMs were available for the watershed (Gesch et al. 2002), as were maps of subsidence amounts throughout history (Gabrysch and Bonnet 1975, Kasmarek et al. 2005, Kasmarek et al. 2012). In order to test whether the subsidence had an impact on the general drainage area of the bayou, the watershed delineation was conducted several times using synthesized DEMs that had been modified to represent several subsidence scenarios. These tests showed that land subsidence did not appear to impact the overall watershed drainage area in a significant way. Therefore it was assumed that the watershed bounds were more or less constant throughout the period of study. The HEC-HMS model used Curve Number loss, Clark unit hydrograph transform, Muskingum-Cunge reach routing, and recession base flow methods.

Land cover input to the hydrologic model for the year 2011 was obtained from available NLCD rasters for 2011. The inputs for 1973 and 1929 were obtained by the use of a Markov transition model, which is well supported for use in lumped parameter hydrologic modeling (Mitsova et al. 2011, Du et al. 2012, Tong et al. 2012, Alexakis et al. 2013). The National Land Cover data set has land cover rasters available for 2011, 2006, and 2001. For 1992, the data set has an available raster of somewhat reduced accuracy. To improve the comparison between the data sets, the NLCD also has issued a set called the 1992 retrofit raster, which “was developed to provide more accurate and useful land cover change data than would be possible by direct comparison of NLCD

1992 and NLCD 2001" (Fry et al. 2009) according to documents published by the USGS.

The Markov transition matrix was created by comparing land use raster cell changes between the 2011 and 2001 data sets, using fixed roadway raster cells and semi-fixed water raster cells, due to the perceived behavior of actual land development patterns. The Markov chain process was then tested for its interpolation and extrapolation accuracy using the 2006 and the 1992 retrofit data sets, respectively. The process performed adequately for both the tests, so was then used to create land cover data sets for 1973 and 1929. These simulated land cover rasters were then converted into Curve Number rasters for input into HEC-HMS. The resulting Curve Numbers were examined against old USGS topographic quads in order to determine whether the values generated were reasonable considering the amount of development and land cover characteristics at the time. Again, the simulated rasters performed adequately.

The 100-year storm and corresponding flood was selected as the study point due to its conventional use in the industry and regulatory sectors. Precipitation input for 2011 was obtained from Asquith and Roussel (2004), and for 1973 from the classic TP-40 Rainfall Frequency Atlas publication due to its widespread use in the previous century of civil engineering design (Hershfield 1961); the intent was to emulate how an engineer in the mid-century period would have calculated precipitation. The return period precipitation estimates for Armand Bayou increased between the two publications, and a study of several surrounding precipitation gauges indicated a general modest increase in return period storm estimation based on annual maximum precipitation (Faloon et al.

2013), so a simple linear extrapolation procedure was used to obtain return period precipitation values for 1929. These were input into HEC-HMS using the frequency storm input function, which results in an alternating block balanced triangular distribution hyetograph. Storm area reduction factors were used to correct for the large area of the watershed. These three design storms are ultimately hypothetical but conform to conventional industry practice standards.

Because the watershed is essentially ungauged, base flow was estimated on a flow per unit area basis, based on values from the Clear Creek watershed, an adjacent gauged watershed of similar soil and land cover type. Due to the lack of publicly available flow gauges and the relative difficulty of accurately calibrating a hydrologic model to stage gauge data, the model was instead calibrated against HCFCD's official return period flow values, themselves obtained from a calibrated hydrologic model from the TSARP project. Although not ideal, the use of so-called "soft" hydrologic data, that is, data derived from models, in model calibration is somewhat substantiated by Seibert and McDonnell (2013). The hydrologic model input variables are shown in Table 4.

Table 4. Hydrologic model input sources

Hydrologic model input	Sources
Land cover	NLCD (Vogelmann et al. 2001, Alfieri et al. 2007, Homer et al. 2007, Fry et al. 2009, Fry et al. 2011); calculated
Soil types	USDA SSURGO (Soil Survey Staff 2013)
Topography	NED 3 meter DEM (Gesch et al. 2002)
Clark R storage coefficient	Sabol (1988)
Design storm	Asquith and Roussel (2004); Hershfield (1961); calculated
Calibration values	HCFCD (2015)

3.3.4 Hydraulic model

A dynamic routing model in HEC-RAS was used in order to capture the influences of both stormwater runoff and tidal processes on the water surface elevation and potential flooded area. The basis of the dynamic routing model was the TSARP HEC-RAS model available from HCFCD, which was constructed using surveyed channel cross sections and elevations and calibrated according to industry standards (HCFCD 2008). Available data showed subsidence up to about 12 vertical feet in the watershed's headwaters and about 6 vertical feet at the stream outlet (Kasmarek 2012) (see Figure 11). To adjust the stream elevations to simulate the three subsidence scenarios, interpolation of available subsidence data was used to create a line of continuous change in elevation along the stream bed. Due to this change in elevation, the tidal limit of the stream had moved upstream over time, resulting in a changed hydrologic regime (see Figure 12). Although the mouth of the stream at Clear Lake had always been tidal, the upper limit of the tidal influence had moved upstream. This was accounted for by taking an existing tidal stream stage gauge and translating it along the calculated energy grade line to a point at which the tidal influence was estimated at the selected points in history. The 2011 tidal limit location was set at the official EPA regulatory tidal limit (Guillen 2010), and the previous locations of the tidal limits were estimated from historical USGS maps and aerial photos. Initial conditions for the dynamic routing model represent the start of the simulated storm event from HEC-HMS – effectively the first hydrograph point. The hydraulic model input variables are summarized in Table 5.

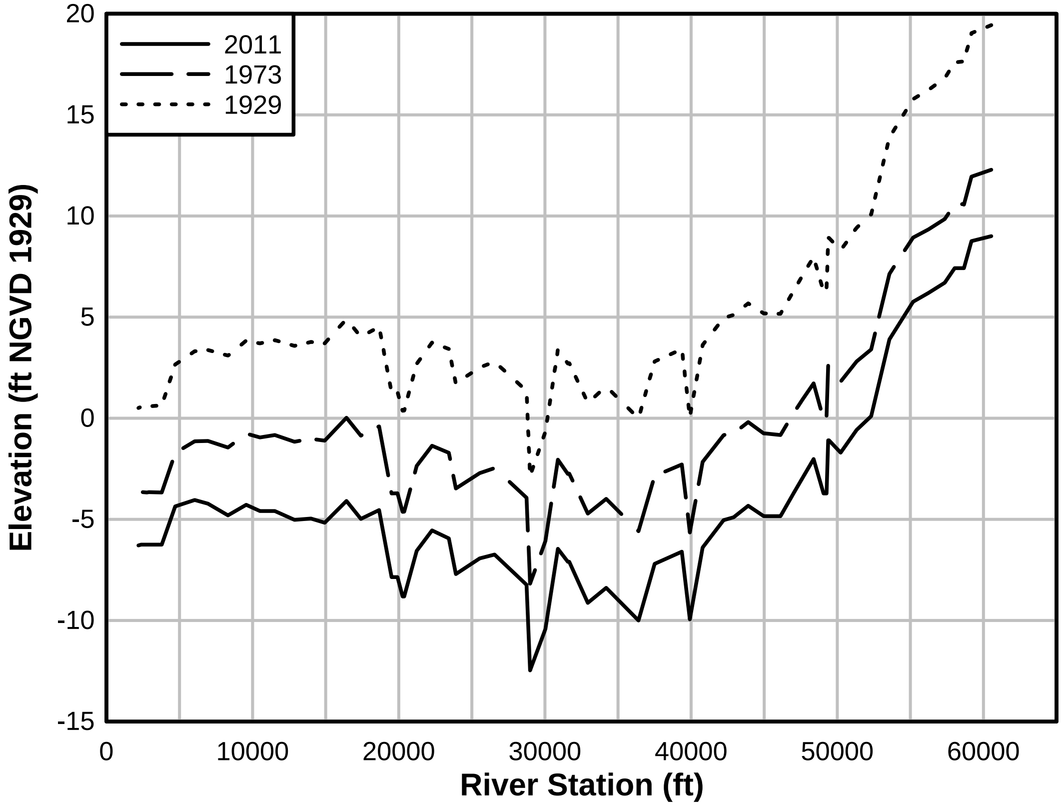

Figure 11. HEC-RAS model channel bottom elevation

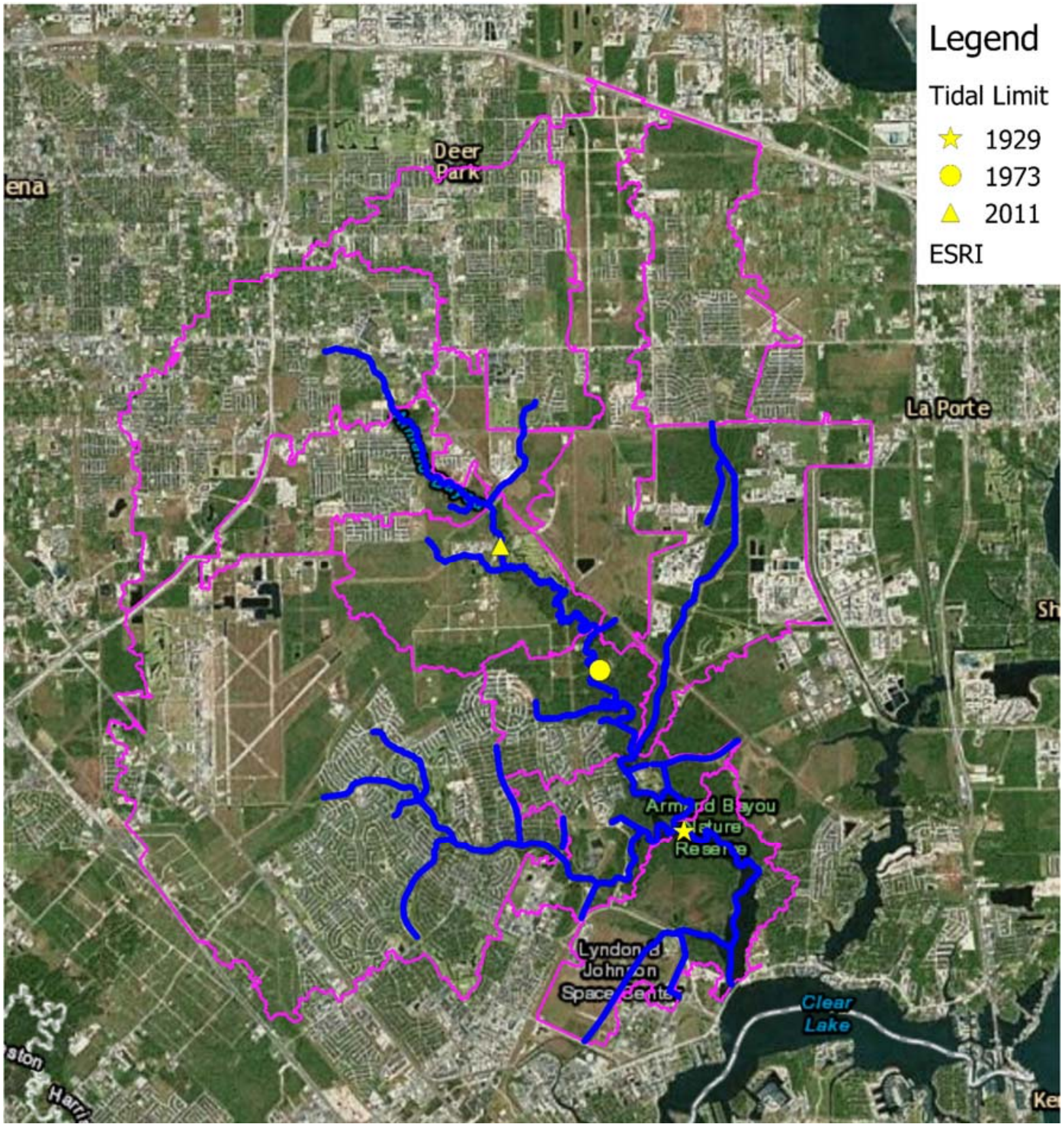

Figure 12. Armand Bayou watershed (Basemap © ESRI (2014) Esri Digital Globe, Geo Eye, i-cubed, USDA, USGS, AEX, Celmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

Table 5. Combined hydrologic-hydraulic model input data

Year	Land Cover	Return-period Precipitation	Subsidence Conditions
1929	Simulated	Calculated	Gabrysch and Bonnet (1975)
1973	Simulated	TP-40 (Hershfield 1961)	Gabrysch and Bonnet (1975)
2011	NLCD (Jin et al. 2013)	Asquith and Roussel (2004)	Kasmarek (2012)

3.3.5 Results

The resulting model was run with each of the three separate inputs to land cover conditions, return period precipitation, and land surface subsidence. All combinations of the nine input variables results in a total of 27 different combined hydrologic-hydraulic simulations. Model output was obtained of both maximum water surface profile elevations and total flooded area as computed by HEC-RAS integrated GIS tools. The results were ranked, and statistical tests were conducted to determine the magnitude of the impacts of each input variable. Perhaps unsurprisingly, the condition with the greatest amount of flooded area was the entirely modern scenario, and the entirely early period scenario had the least.

Assigning each input value a categorical variable classification allows for a categorical statistical analysis of the output. The modern condition is designated as category 1 and the mid-era and initial conditions given category 2 and 3, respectively. The flooded area sorted by rank was found to be approximately linear and normally distributed (see Figure 13); therefore a Generalized Linear Model is appropriate for analysis.

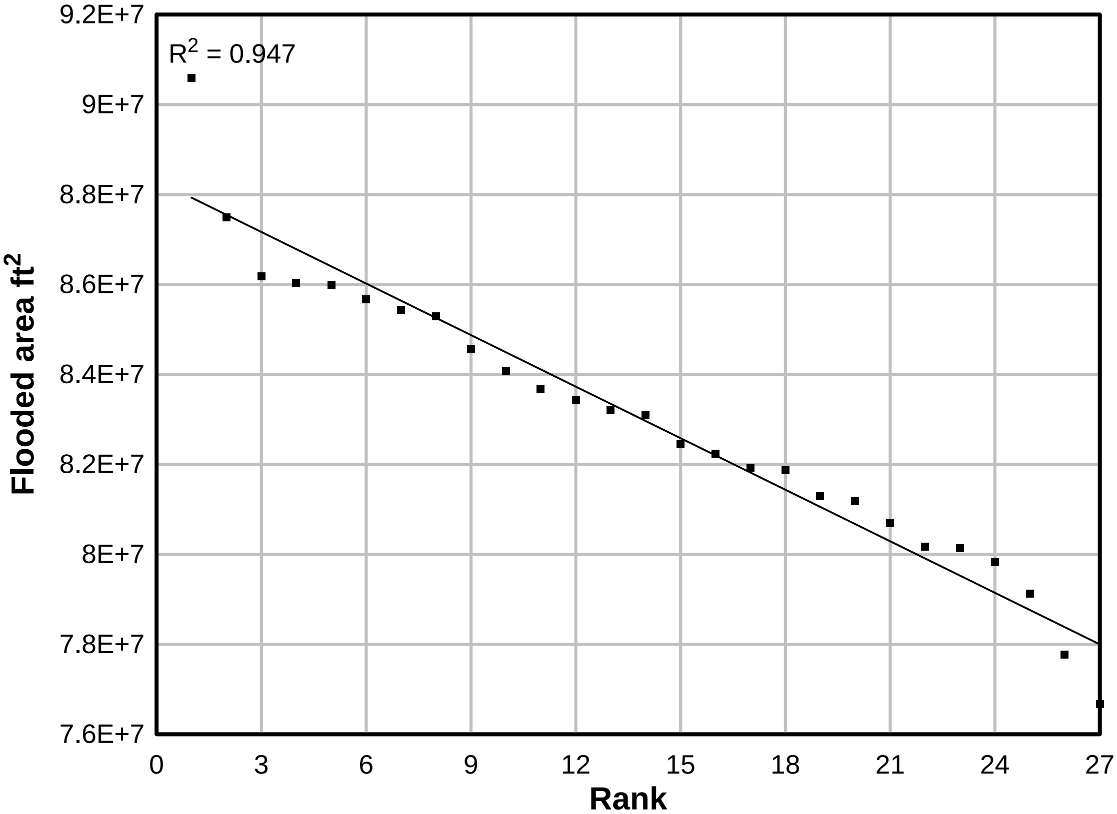

Figure 13. Linear trend line of ranked data

The GLM of the flooded area as predicted by the categorical variables resulted in a very high adjusted coefficient of determination (R^2) of 0.965 (see Figure 14). Because all variables were significant at the 95% level, the comparative impacts of each input variable were assessed using the Proportional Reduction in Error value (PRE) after Judd et al. (2009). The PRE value was calculated as $PRE = (SSE_1 – SSE_0) / SSE_1$, where SSE_0 represents the Sum of Squared Errors of the full model with all predictors and SSE_1 represents the Sum of Squared Errors of the model without the predictor in question. The predictors representing return period precipitation input and topographic subsidence variables were nearly identical, each having PRE values of 0.94. The impact from land surface change was found to be least influential at 0.54, although this value is still considered a significant contributor (see Figure 15).

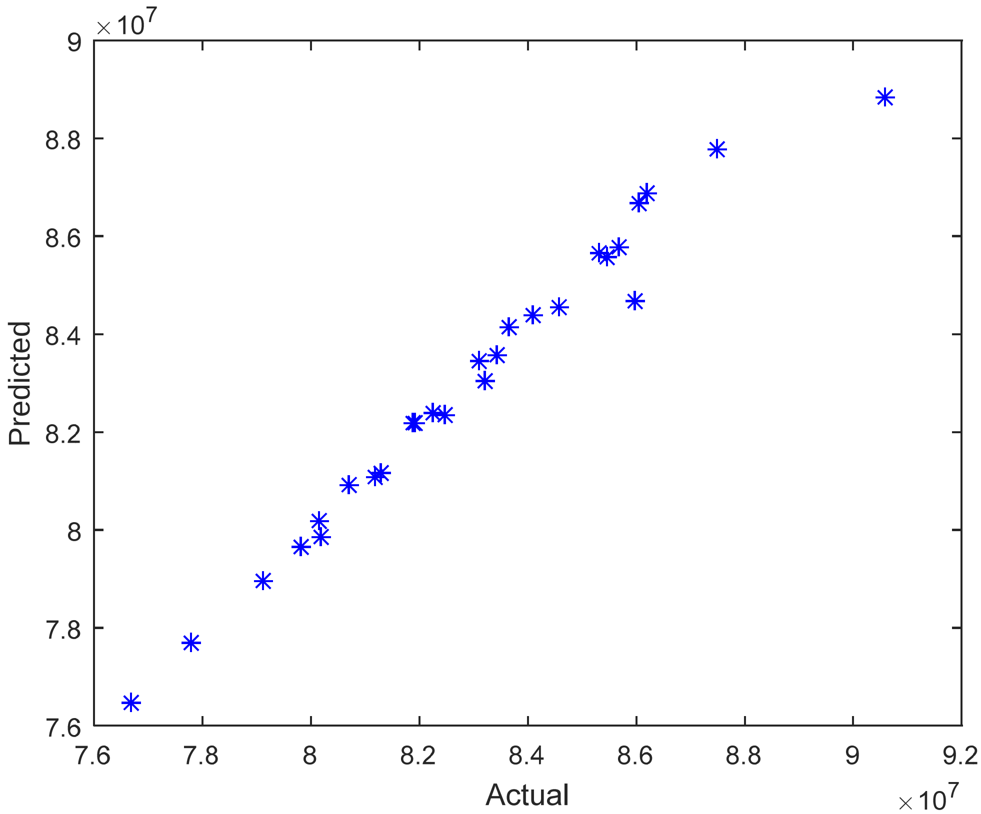

Figure 14. Predicted by observed values from Generalized Linear Model

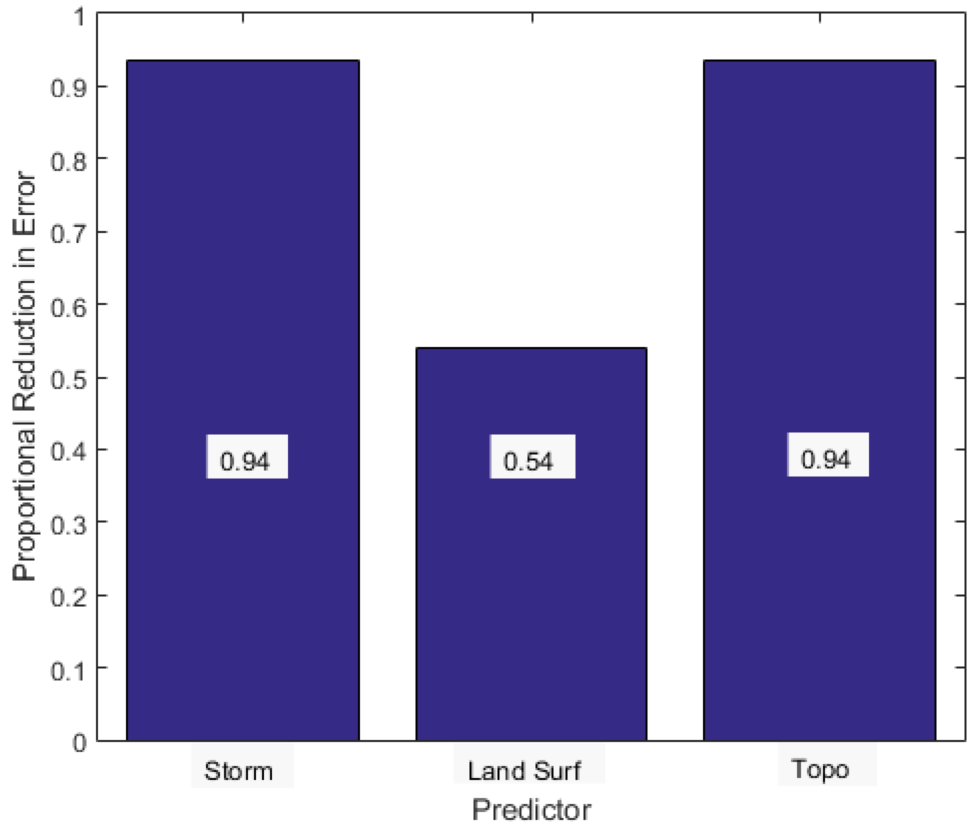

Figure 15. Proportional Reduction in Error values for predictors

3.3.5.1 Limitations

Use of a Generalized Linear Model of this nature has several possible limitations. The model was constructed using only categorical data, which eliminates random variation within each input variable; this is more or less true regardless of whether the input variables consist of ordinal numbers or actual hydrologic-hydraulic model input values. Correlation tests between the categorical variables are essentially meaningless due to the nature of the data and the analysis, and adding additional interaction variables between the predictors likewise did not significantly improve the model. Evaluation of the model at only three points in time excludes any differential rates of change in the three types of input values within the specified time periods. A categorical model lacks any numerical predictive power and can only be used to make qualitative inferences about the relative magnitudes of impact of geophysical forces on the flooded area potential. Furthermore, other factors may be at work in producing hydrologic nonstationarity, which may have affected some or all of the model input values and are not accounted for in this analysis.

Modeling techniques are obviously important to examining hydrologic nonstationarity, due to their varying sensitivities to input variables. The NRCS Curve Number approach remains popular due to its accessibility, but must be used with adequate knowledge of its strengths and weaknesses (Hawkins et al. 2009). Karamouz et al. (2012) performed an uncertainty analysis on a rainfall-runoff model of a basin in Iran and found that the watershed was more sensitive to changes in Curve Number than to time of concentration, and the frequency of extreme events appeared to decrease under simulated climate change conditions. Similarly, Kousari et al. (2010) performed a sensitivity analysis of the NRCS Curve Number method and found the effect of the curve number parameter to be the most pronounced of all the variables. Additionally, studies comparing distributed and lumped parameter hydrologic models for their ability to predict the impact of land use change on hydrographs conclude that lumped parameter models are less accurate (Ogden et al. 2011, Paudel et al. 2011). Betson et al. (1985) evaluated the industry acceptance levels of several models for quantifying hydrologic impacts of land use change in uncalibrated situations and found that acceptable results can be obtained but caution against putting too much faith in any model just because of consensus or the image of authority or knowledge.

This research project involved creation of a hydrologic model based on hypothetical rainfall events and simulated land use conditions, calibrated to regulatory return-period flow values, and then input into a calibrated hydraulic model to estimate inundated area. A model based on models and simulated conditions will have more uncertainty than a model based solely on measured inputs. However, the practice of hydrology often lacks adequate observation data, and relies heavily in empirically derived models to estimate ungauged values. These empirical models are sensitive to input parameter variation as previously discussed. Although the models in this research were constructed according to allowable methodologies described in regulatory codes, the theoretical nature of the analysis should not be understated.

3.3.6 Conclusion

The combined hydrologic-hydraulic dynamic routing model of Armand Bayou showed that the hydrologic regime of the stream had changed significantly over the 82-year period of analysis. The results were then analyzed using a qualitative Generalized Linear Model. When including all variables in the model, the potential influences from the return-period design storm and the topographic subsidence outweighed the influence from land surface change, but all values were considered significant contributors.

The Armand Bayou area and Harris County as a whole have made large decisions in past decades on two of the three potential sources of nonstationarity. The region has invested billions of dollars in infrastructure to reduce groundwater withdrawal and arrest subsidence. Furthermore, authorities in the area have followed a very pro-development philosophy that has invited significant land use changes in the form of increased urbanization and hydrologic modification. The region still struggles significantly with flood frequency and intensity and the resulting property damage, which is exacerbated by increased property value in the area. By qualitatively demonstrating which factors have the greatest influence on stream flows in the area, this analysis can help inform policy decisions with regard to flood zoning and development choices. Climatological sources of nonstationarity remain outside the control of local authorities. Development authorities in the region would do well to take heed of the fact that one of the greatest influences on flooded area cannot be legislated away; any strategies for coping with increased flooding should incorporate this knowledge.

An analysis such as this can be applied to other watersheds in order to show what can be expected from the future and which sources of nonstationarity can be expected to have the greatest impacts. Design engineers may have to prepare for the prevailing assumption of hydrologic nonstationarity to take root in the near future. In order to design infrastructure to adequately perform under future hydrologic conditions, engineers must be aware of all potential sources of hydrologic nonstationarity and their relative influences on possible future stream flow. Many engineers are likely aware of the potential for nonstationarity in the design storm estimate and the influences of the change in land cover. However, larger geomorphologic changes such as large-scale subsidence can have an impact as well.

4. IMPACT OF DESIGN DECISIONS ON HYDROLOGIC NONSTATIONARITY

4.1 Introduction

It is a situation that many consulting engineers know all too well: a project involves a preexisting piece of infrastructure whose design values, upon further inspection, do not seem sensible. A bridge should have been designed to a known specification, but appears to be deficient or incorrectly sized. The as-built drawings are straightforward on the surface, and the calculations are mathematically correct; however, the missing piece of evidence is the original engineer's professional judgment. The temptation to throw accusations of error or incompetence can emerge, but a professional should never make those claims lightly. In the absence of an explanation from the original designer, an apparent miscalculation might in fact be an unconscious, undocumented decision process rather than malice or ignorance. Perhaps tapping into instinctive engineering judgment can have the potential to reshape how engineers look at hydrologic design.

Most hydrologic structures are designed and regulations are written based on the concepts of risk of failure and return period of hydrologic events, collectively known as frequency-based design. Design storms have existed in theory since approximately 1889 (Watt and Marsalek 2013), with the more recognizable forms appearing in about 1935 (McEnroe 2009). In a study of historical engineering design theories, McEnroe (2009) traced the development of culvert design from empirical techniques to worst-case scenarios to some form of cost-benefit design that is more familiar to modern-day engineers.

Reevaluation of the concept of return period design or annual exceedance probability continues today (Watt and Marsalek 2013, Stewart and Deng 2014). The 100-year flood technique has long been criticized from a flood mitigation perspective, mainly because it usually assumes stationarity of the time series, independence of events, and homogeneous sampling. Nevertheless, Miller et al. (2000) stated that discarding the technique entirely would be impractical, and that human experience and local conditions should have a much larger role in hydrologic engineering judgment. The US Federal Government has long required cost-benefit analysis for structural flood control measures, along with enhanced support for nonstructural measures (Wurbs 1983). Stewart and Deng (2014) suggested that current methods of measuring climate risk inadequately account for cost and probable risk, and recommended the use of a more complex system of measuring risk, costs, and benefit of certain mitigation and adaptation strategies for coping with extreme weather. Brown (2010) suggested infrastructure should be designed to dynamically accommodate all flood or drought events rather than just 99% of them and encourages moving beyond the concepts of risk and return period altogether.

It is all too easy to blame design woes on inadequate models or lack of mathematical proficiency, although Alvi (2013) suggested that most structure failures are due to accumulations of smaller, diverse human decision errors rather than errors due to poor or incorrect modeling. With regard to hydrologic modeling specifically, a large source of potential uncertainty comes from the model parameter input values. Kousari et al. (2010) performed a sensitivity analysis on the commonly used SCS Curve Number method and found that the curve number value was the model input that had the largest influence on peak discharge because of its effect on both runoff and time of concentration, a finding also shown by Hawkins et al. (2009); the second most influential variable for the Curve Number method was the amount of precipitation.

Some authors have suggested that difficulties with estimating extreme events can be attributed to lack of correct mathematical procedures or use of oversimplified calculations. Much work on applying different statistical techniques has been done over the years (Fernández and Salas 1999a, 1999b, Stedinger and Griffis 2008, Salas and Obeysekera 2013), including the addition of terms intended to compensate for nonstationary time series. Şen (1999) assumed hydrologic processes are dependent rather than independent, and Salas et al. (2013) attempted to quantify hydrologic uncertainty of a river in Switzerland, and in the process to distinguish between the difference between the return period of an event and the return period (failure risk) of a structure. Dawdy and Lettenmaier (1987) explored the concept of rare flood risk and its relation to infrastructure design, mainly in relation to dam break analysis, and analyzed several existing techniques for estimating risk of failure. Among the techniques examined were parametric and nonparametric exceedance probability theories, probable maximum values, and enhanced consideration of historical events in paleohydrology. Additionally, the addition of a cost-benefit scenario to the statistical analysis of a flood control project was promising (Tung 1992).

Recent developments in hydrologic engineering have included the concept of climatological nonstationarity, wherein future events cannot necessarily be inferred from past events due to changing probability distribution functions. The assertion that nonstationarity should be the default assumption has taken hold (Milly et al. 2008, Galloway 2011, Hirsch 2011, Kundzewicz 2011), though some authors believe that stationary statistical methods are sufficient (Koutsoyiannis 2006, Lins and Cohn 2011). Al-Futaisi and Stedinger (1999) conducted several cost-benefit analyses of flood control projects and concluded that a more robust understanding of project uncertainty is warranted. In this study, it is worthwhile to note that nonstationarity within hydrologic models can occur from more than just climatological sources (Lins and Cohn 2011).

Tragically, the failure of hydrologic structures including bridges is familiar to the practice of civil engineering design. It is difficult to estimate the scope of this systemic problem, since data on bridge failures is scarce and incomplete (Wardhana and Hadipriono 2003). Stearns and Padgett (2011) analyzed influences behind numerous bridge failures in Texas following Hurricane Ike and found that scour and hydrologic forces were the main causes of structural failure. Failure can be defined as the point at which performance goes below an acceptable threshold. Lemer (1996) attempted to define obsolescence and service life of infrastructure, for which one needs adequate standardized measures of performance. Lemer also suggests designing infrastructure with inherent flexibility if possible, in order to meet unforeseen future conditions – in effect, targeting higher levels of optimum performance. Another possible remedy for obsolescence could include refurbishing and retrofitting infrastructure early in its lifespan, when future conditions are first foreseen.

A discussion of engineering design theory would not be complete without a look at the ethics and judgment required to practice the profession. Bulleit et al. (2014) analyzed the role of models in engineering design and suggest that model output needs to be taken with more critical skepticism. The authors contrasted purely systematic analytical design approaches to perceptive design marked by intentionality and consideration much like an art, while cautioning against trusting too much in intuition without experience to reinforce it. In a deeper analysis of engineering decision making, Elms and Brown (2013) contrasted teleological and causative decision making strategies and compared the contributions of both to various stages of an engineering project. Knoll (2014) suggested a blurred line between error and conscious or unconscious risk taking, all of which are usually spurred on by financial factors, but concluded that as with traditional gambling, intentional engineering risk taking is an overall losing proposition. Tillman (1990) analyzed the ethical orientation of a population of novice engineers and found that the engineers began their career primarily oriented towards rule-following behavior but gradually transitioned to judgment-based ethics as they gained experience. Klein et al. (2003) explored the concept of infrastructure resilience in a meta-analysis, and Möller and Hansson (2008) analyzed the concept of inherently safe design under probabilistic assumptions and concluded that it is possible to account for epistemic uncertainty in engineering design.

The case study of one particular bridge in Texas represents a unique opportunity to observe the interactions between hydrologic design, nonstationarity, and professional decision-making. The bridge in this case shall remain unnamed, in order to avoid the appearance of casting professional aspersions since that is not the intent of this observational exercise. Constructed in 1996 and demolished in 2014 as part of a road-widening project, the bridge was ostensibly designed using regional regression equations to allow a 25-year storm runoff event to pass, but was later found to be undersized. The bridge did not experience any failure in its lifetime, and the reduced cost of the bridge would likely have been a boon to the public taxpayers. In spite of the fact that hydrologic design has been governed by the recurrence interval or design storm method for the better part of the past century, the combination of nonstationarity, model uncertainty, and economic reality in this case study seem to indicate that the design of a small bridge can succeed without following the prescribed method.

4.2 Case description

"Anonymous Bridge" was a narrow two-lane stream crossing in a residential area of Fort Bend County, Texas on a state road where the design procedures are subject to Texas Department of Transportation policies. The bridge was designed in 1996 to replace an existing structure as part of a small TxDOT state highway project consisting only of the bridge and approaches. The 45-foot long span was constructed of 16" pre-stressed concrete piles with concrete abutments, pre-stressed concrete slab beams, and a poured concrete slab. The stream channel was at the time lined with grass and a course of riprap under the bridge deck to anchor the 1.5:1 max channel side slope.

The 1985 Bridge Division Hydraulic Manual (TxDOT 1985) was in effect at the time of the bridge design, which required design at minimum for the 10-year storm and desirable design for the 50-year storm, with consideration given to anticipation of land use change over the design life of the structure. The engineer ostensibly designed the bridge to pass an estimate of the 25-year storm event with plenty of clearance above the water surface, and to pass the 100-year storm event at an elevation equal to the bottom of the support structure, without overtopping the structure. According to the design documents, these flows were calculated according to the regional regression equations valid at the time of design. The state of Texas was divided into six regions, with each region having several regression equations for different recurrence interval peak flows. The method is simple to use but errors inherent are quite large (see also Schroeder and Massey 1977).

Upon closer inspection of the watershed, the flow amounts for the two design storms seemed to have been underestimated, considering the overall hydrologic characteristics of the watershed. At first, it was assumed that increased development throughout suburban Fort Bend County had resulted in higher modern peak flows, so that the older design values were small by comparison. Another working theory was that the Manning's n value used in computing the rating curve had been overestimated, or perhaps another coefficient or lookup value had been altered elsewhere in the calculations.

4.3 Hydrologic analysis

A typical modern hydrologic analysis was conducted to verify the design of the bridge in accordance with current TxDOT regulations, which require new and replacement bridges to pass an annual exceedance probability storm without overtopping, the probability of which depends on the size of the waterway and the traffic volume of the road. Small bridges on minor roads are recommended to pass the 4% storm, with an additional evaluation of the 1% storm for review purposes (TxDOT 2014a §4.6).

The watershed above the bridge is approximately 1.9 square miles, largely composed of a small historic downtown and suburban area with numerous institutional facilities. Like much of East Texas, the soils are clay and alluvial deposits with low infiltration capacity, prone to erosion and shrink-swell cycles. The stream is ungauged, so no model calibration was performed. TxDOT guidance documents allow for the use of rainfall-runoff calculations in order to determine annual exceedance probabilities for ungauged streams, preferably using a 24-hour duration storm event (TxDOT 2014a §4.13). HEC-HMS was selected for the analysis due to its widespread use and acceptance in both consulting and conceptual modeling (Fleming 2009, Dhami and Pandey 2013). The sources of hydrologic model input data are listed in Table 6.

Table 6. Hydrologic model input data sources

Item	Source
Elevation	10 meter DEM (TNRIS 2013)
Land Cover	NLCD, TxDOT (Vogelmann et al. 2001, Homer et al. 2007, Fry et al. 2009, Fry et al. 2011, Jin et al. 2013, TNRIS 2014)
Soil Data	USDA SSURGO (Soil Survey Staff 2013)
Precipitation	Asquith and Roussel (2004)

In order to assess whether increased development has resulted in larger peak flows at present than at the time of the bridge's construction, it was necessary to estimate land cover input variables for the years in question. Publicly available land use raster data is available from 2001 at the earliest, with a less accurate set available from 1992. For conditions earlier than 2001, simulated land surface data rasters were produced using the available land use data sets and a Markov chain process similar to Mitsova et al. (2011). The Markov transition matrix was constructed by creating a probability table of land use raster cell changes between the 2001 and 2011 NLCD raster surfaces. Raster cells near the edge of developed areas were more likely to transition between developed and undeveloped conditions, so separate probability tables for edge cells were developed differently from those representing cells surrounded by similar cells. Since development typically occurs in close proximity to transportation infrastructure, the positions of the roads on the raster were fixed in place using a TxDOT shape file. To a lesser extent, the positions of the cells containing open water were fixed using a conditional placement statement in the model code.

The Markov process was tested for accuracy using the 2006 land use raster and performed adequately, with all land use categories achieving minimum 90% similarity between simulated and actual conditions, and most categories achieving 95% or better. To test for extrapolated accuracy, the simulated and actual rasters for 1992 were compared against each other. A direct comparison with the 1992 NLCD raster data set achieved less confidence, so the simulated raster was compared against the 1992 retrofit raster, which according to the USGS, "was developed to provide more accurate and useful land cover change data than would be possible by direct comparison of NLCD 1992 and NLCD 2001." (Fry et al. 2009) This comparison performed adequately for undeveloped conditions, but the comparison of developed areas between these two years' data sets was complicated by the lack of sub-categorized developed area in the 1992 data set; however, the total sum amount of all developed areas was within acceptable tolerance limits as shown in Table 7. Therefore, it can be assumed that the Markov process performs adequately for both interpolated and extrapolated simulated land use rasters.

Table 7. Markov chain process error

Item	**Percent difference between estimated and actual 2006**	**Percent difference between estimated and actual 1992**
Water	-2.3%	-1.4%
Meadow	-0.6%	-0.6%
Forest	8.5%	10.2%
Open-space developed	-6.1%	n/a
Low-density developed	-3.3%	n/a
Medium-density developed	6.3%	n/a
High-density developed	-7.1%	n/a
Total developed	n/a	-6.2%
Roadway	-0.7%	-0.7%

In order to completely assess the impact of land development on the hydrology of the watershed through time, several land use simulations were performed, dating as far back as 100 years prior to 2011. Simulation of the approximate 1911 condition eventually results in an apparent asymptotal limit of approximately 82 CN, or that of a D soil undeveloped field, as shown in Figure 16. Upon entering these values into HEC-HMS, the model results showed that the difference in flow due to the original 1995 design calculations was much greater than the difference in flow due to the estimated change in areal land development. Additionally, for 1996 conditions, using a standard SCS Curve Number runoff analysis, HEC-HMS gives peak flows on the order of twice the original design capacity (see Table 8).

Table 8. Designed conditions versus actual conditions, 1996

Storm Event	Designed	Simulated
25 year	522 CFS	1097 CFS
100 year	701 CFS	1576 CFS

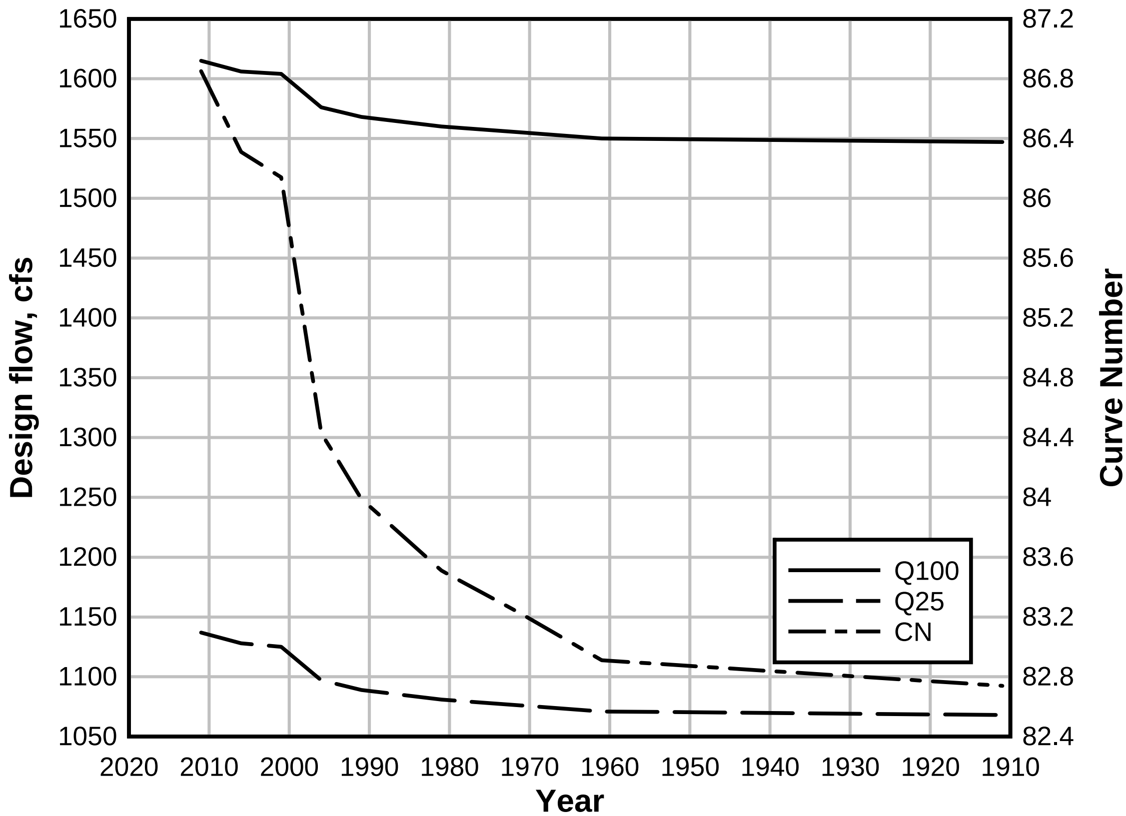

Figure 16. Curve Number and AEP flows versus year

What then was the source of the peak flow discrepancy? A further examination of the regression equation method as outlined in the 1985 manual shows that the bridge was assumed to be in regression Region 1 when in fact it is in Region 2, although the location is quite close to the demarcation line between the two regions (see Figure 17). As shown in Table 9, the difference in peak flow between the two regions is significant, despite spatial separation of only a few miles. Ideally, because the project was located close to the dividing line between regions, the engineer should have calculated values for both regions and chosen the more conservative value.

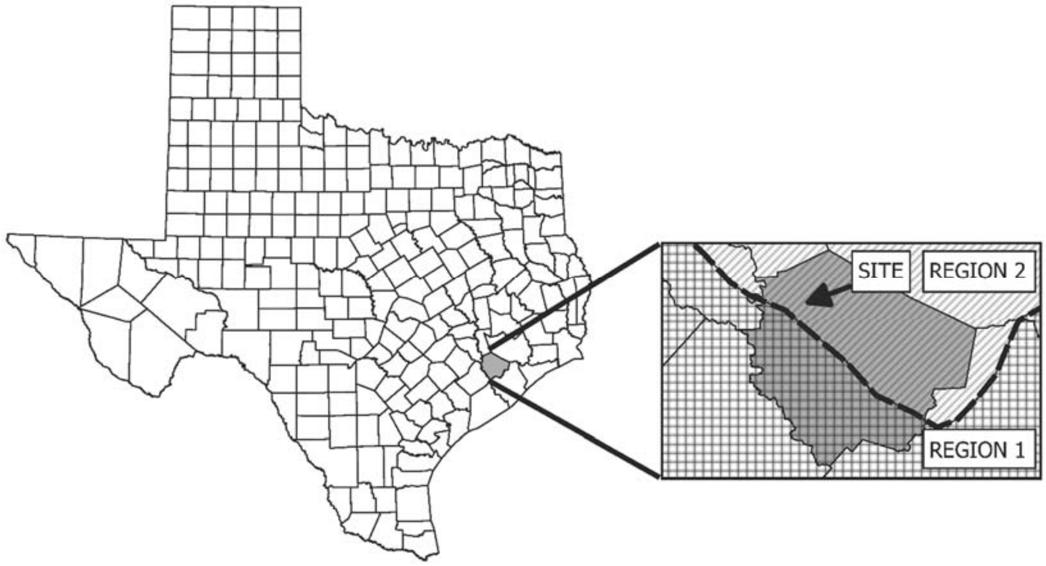

Figure 17. Fort Bend regression regions circa 1985 (Basemap via TNRIS 2012)

Was this incorrect choice of regression parameters then intentional or merely an oversight? Elms (1999) refers to three basic threats to safety that contribute to engineering failure: ignorance, meaning what the engineer should have known but didn't; uncertainty, meaning randomness inherent in design and modeling; and complexity, meaning the difficulty of representing natural processes mathematically. Ignorance can be further divided into the ignorance of the engineer and the ignorance of the profession. In this case, it is likely that the source was complexity, assuming Elms' theory is appropriate; the mapped theoretical parameter values change sharply along a demarcation line but do not actually behave this way in nature. However, it is debatable whether the design of the bridge was actually a threat to safety. This could have been a case of a "kludge", to borrow a term from computer troubleshooting, in this instance referring to the act of making something work despite its lack of ideal characteristics for the situation.

Table 9. Designed versus correct flows, 1985 regional regression equations

Storm Event	Region 1	Region 2
25 year	522 CFS	1207 CFS
100 year	701 CFS	1676 CFS

4.4 Ethical considerations, risks, and tradeoffs

Calculation manipulation in order to meet budgetary or regulatory requirements is unquestionably unethical (ASCE 2006); however, reflecting on the outcome of the project can reveal some potential for insight into the current state of the practice. The engineer was perhaps making an undocumented decision about the potential risk of the project's failure versus the actual cost to construct a bridge that would meet all regulatory requirements. A decision of this nature in this context reflects much of how engineering decisions are made by experience or educated estimation (Elms and Brown 2013). The engineer almost certainly did not do a full risk versus cost calculation for such a small project, but likely had enough professional experience to make an educated estimate of the outcome.

A larger bridge would have resulted in added cost to the original project. The cross-sectional flow area under the original bridge was 225 square feet, adequate to pass the incorrectly-sized design storms. In order to pass the correct values, the bridge would have required a cross-sectional flow area of 465 square feet, and to pass modern land use condition values, 475 square feet. The original span length of the bridge was 45 feet, and without raising the elevation of the road deck, the actual span would have had to have been 75 feet long. Because the original bridge was supported by slab beams, which can be used for spans up to 50 feet, a longer bridge would have required a different type of support structure. One common configuration for longer bridges of this type is known locally as the “Texas shape” I-beam bridge. Additionally, the channel would require widening at that point in order to avoid raising the bridge deck.

The original bridge design drawings contained quantity takeoffs with TxDOT standard specification categories, so a cost estimate of the bridge project was possible with modern values. Furthermore, TxDOT publishes line-item bridge square foot costs, intended for preliminary project estimates. Unit cost values are not available for 1996, but modern day values are available yearly dating back to 2009 (TxDOT 2014b). By comparing the two bridge designs and taking a weighted average of the costs for both DOT in-system and out of system bridges, the bridge as it should have been built would have cost 125% of the original slab beam bridge, including additional channel excavation (see Table 10). Note that this value is only for the actual bridge line item itself and does not include foundations, pavement, accessories, channel improvements, mobilization, environmental controls, and construction contingencies.

Table 10. Line item cost estimate

Item	Cost
Original bridge	$ 84,672.70
Correct bridge	$ 110,746.75
Correct bridge + channel excavation	$ 112,870.19
% increase	25%

Anonymous Bridge was demolished and replaced with a wider 3-lane bridge with full road shoulders in 2014, and at the same time the stream channel was widened and armored with concrete, imparting to the 1996 bridge, and therefore also the design life of the bridge, a finite 18-year lifespan. The design life was likely not calculated in 1996 but is in keeping with the general character of development in suburban East Texas. Was the reduction in cost defensible, considering the eventual 18-year life span of the bridge and the low-volume residential nature of the road? Elms (1999) makes the case that structures in rural areas could possibly tolerate lower design requirements than those in higher traffic areas. When applying the typical binomial risk formula, as originally built the bridge had a 92% chance of experiencing an overtopping event in its 18 year lifespan, whereas if constructed correctly, it would have been 17%. Based on climatological records and news reports, two events in that watershed greater than the 100-year storm were confirmed by both precipitation data and news reports, one confirmed by precipitation but not by news reports, and one confirmed by news reports and not by precipitation data (Ward 2005, Fort Bend Star 2012, Ravat 2012, NCDC 2014). Therefore it follows that the bridge likely saw at least two possible overtopping events in its life span; however, neither of them caused any permanent damage, catastrophic or otherwise.

Design codes are ideally intended to prescribe minimum requirements necessary to protect human health and safety. Codes can be further classified along a spectrum ranging between explicit design requirements and implicit design goals. This “encoded” combination of requirements requires decoding, which individual engineers will decode according to personal idiosyncrasy, the particulars of the project, and the intent of the code (Bulleit and Adams 2011). Striking a balance between implicit and explicit design needs can be complex, but in the case of hydrologic return period design, this project appears to indicate that a more implicit scheme is warranted (Björnsson 2015).

4.5 Conclusions

The purpose of this portion of the research was to examine real-world engineering decision making processes, using the case study of an unusual situation in hydrologic engineering design in the form of a low-volume bridge in a residential area. The bridge was undersized (intentionally or not), but it did not fail; this could have ramifications for hydrologic infrastructure design theory. Perhaps design based on professional judgment and cost/benefit factors as well as maximum possible consequences of failure is more theoretically sound than design based on an arbitrary annual exceedance frequency.

We will never know the true motives behind the engineers' actions when designing this bridge, but there have been calls for the addition of more engineering judgment rather than pure calculated numbers in hydrologic and engineering design (Miller et al. 2000, Elms and Brown 2013). Perhaps modern engineers enjoy the benefit of hindsight, but when envisioning alternate scenarios it is difficult to conceive of any situation that could result in catastrophic damage for this neighborhood. It is therefore concluded that this particular bridge project was an example of engineering judgment done correctly rather than malicious or ignorant calculation fudging.

5. DESIGNING FOR HYDROLOGIC NONSTATIONARITY

5.1 Introduction

American infrastructure has long been known to be deteriorating due to decreased investment, deferred maintenance, increased use, and increased anticipated design life (ASCE 2013). While it is tempting to cast the situation in a negative light, some authors suggest that it instead be seen as an opportunity to integrate sustainable solutions at every point in the design and planning process (Binney 2010). Recent efforts have focused on making infrastructure more sustainable and integrating the concept of sustainability into ethical engineering practice (ASCE 2006). Sustainability in a civil engineering design context refers to infrastructure that has fewer negative environmental impacts to the surrounding ecosystem and is socially responsible and cost effective.

The existing system of infrastructure and design codes can at times be a hindrance to deployment of sustainable infrastructure. Modern utility infrastructure is characterized by its end-of-pipe configuration and general lack of flexibility which can hinder efforts to retrofit or modify it (van Timmeren et al. 2004). Olenik (1999) described what he termed the “misuse” of hydrologic modeling wherein too much faith is placed in model results and causes a false sense of security against possible flooding. The author contrasted the state of legally mandated stormwater micromanagement with watershed level integrated management and concluded that design by legislative fiat is less than ideal. Kloster et al. (2002) stressed that sustainable design should be tailored to the unique circumstances and that no “one size fits all” approach will be effective.

5.1.1 Risk assessment under nonstationarity

Incorporating hydrologic nonstationarity into engineering design introduces the question of how to accurately evaluate risk of infrastructure failure under such circumstances. One working theory is that engineering design variables should have larger confidence intervals and should anticipate a greater range of possible events. Barros and Evans (1997) stressed that the actual real or perceived sources of nonstationarity are irrelevant from a perspective of infrastructure design and indicated that combined structural and nonstructural adaptations would likely fare best under unanticipated conditions. Brown (2010) conjectured that all systems will fail and indicated that engineers should anticipate this in their designs. Dawdy and Lettenmaier (1987) suggested that engineers should investigate the use of probable maximum events and paleohydrology in determining the possible magnitude of extreme hydrologic events. Research by Stedinger and Griffis (2008) has focused on the flood frequency computation techniques in Bulletin 17B and recommended several changes to existing procedures for better treatment of extreme events. Existing hydrologic modeling techniques such as the NRCS rainfall-runoff method often lack a procedure for creating confidence intervals, but can be modified to create simulated confidence interval estimates by using additional input parameters under a broader set of possible conditions (Voigt 2001).

Some researchers have hypothesized that additional prediction value may be created by integrating forecasts from climate models into existing precipitation models. Hydrologic modeling conducted with precipitation predictions from climate models showed that engineering design variables would be exceeded under future predictions; actual exceedance magnitudes were difficult to ascertain (Forsee and Ahmad 2011). Similarly, Moglen and Rios Vidal (2014) combined climate model predictions with the commonly used engineering precipitation estimation documents TP-40 and NOAA Atlas 14 to try to predict future precipitation conditions. This analysis showed that return-period precipitation may increase in the future. Karl and Katz (2012) suggested using a metric to represent the increased probability of extreme events, termed the Climate Extremes Index value, for future weather and climate prediction. Hunt and Watkiss (2011) pointed out that not only should climate variables be considered, but the relative vulnerability of the receiving community should be included as a source of uncertainty in planning and design.

Some authors suggested that watershed engineering should use a systems approach rather than focusing on smaller points of interest (Cai et al. 2013). Integrated Water Resource Management is one such approach, which offers engineers the platform from which to optimize many goals including flood control and design goals (Halbe et al. 2013). The concept of risk becomes a single point in a larger system of tradeoffs and opportunities. Infrastructure inventories such as bridge management systems have gained traction as well, which allow for a big-picture view of a design's performance (Minchin et al. 2006). A resilience indicator is a measure of overall how well a system can respond to an extreme event (Milman and Short 2008), which can be incorporated into infrastructure project evaluation procedures. In summary, engineering design stands to benefit from less event-specific modeling and more systems-level knowledge and engineering judgment (Bulleit et al. 2014).

A discussion of risk would be complete without an analysis of the costs and benefits of different infrastructure solutions. Bayesian and stochastic risk and financial loss estimation methods have become common in recent decades (Bogárdi and Szidarovszky 1974, Toneatti 1996, Al-Futaisi and Stedinger 1999), as have economic project justification studies that incorporate both structural and nonstructural factors (Wurbs 1983). Brody et al. (2013) calculated the potential dollar amounts of flood damages both inside and outside of the official statutory flood plain, and found damage locations akin to spatial hot spots. The authors recommended a dynamic spatial gradient of flood risk. Stewart and Deng (2014) used a risk-based decision support system and recommended that building codes adopt a strategy of larger hazard modeling with use of the official IPCC climate change scenarios and incorporate risk/loss functions. Gersonius et al. (2010) contrasted the economic impact of systems constructed with initial robustness and systems created to employ adaptive resilience and suggested that adaptation costs be accounted separately from regular operations and maintenance costs (Gersonius et al. 2013). Tilley and Brown (2006) suggested the use of a metric called "emergy" as a means of numerically comparing human economic activity with ecosystem services. Similarly, Londono Cadavid and Ando (2013) suggested applying human behavioral economic theories to urban stormwater impacts in an effort to account for societal values with respect to the environment.

5.1.2 Alternative design techniques

Engineering design must adapt to foreseeable future circumstances, especially when considering civil infrastructure that is typified by long design lives. If return period based hydrologic design is no longer adequate to account for possible future circumstances, the industry must consider new possible ways of designing infrastructure.

In today's society, talk of personal downsizing, small-footprint living, and quintessential simplicity have become commonplace; perhaps this concept can extend to hydrologic design. Appropriate technology is a concept often used in disaster relief or humanitarian work, which involves designing the minimal technological solution that can meet the project needs and be easily maintained using local labor and materials. Appropriate technology can be seen as a design philosophy rather than a technique (Akubue 2000).

Ecological engineering and biomimicry are concepts that have gained much traction in recent decades (Matlock and Morgan 2011). Some have explored the concept of flexible structures that resemble plants (Lienhard et al. 2010), and others have explored the integration of animal habitat with structural bridge components (Yu 2014). Another ecological engineering technique involves natural watershed management. In this case, rivers are assumed to self-regulate to some extent. Burns et al. (2012) discussed the flaws of conventional stormwater management by use of comparative modeling and stressed that a natural flow regime is usually superior but not always appropriate. Entities in the state of Maine recommended natural bottom streams for purposes of facilitating fish habitat and migration, but the design technique still uses return-period sizing methods (Maine Audubon 2015). An example of successful ecosystem services in hydrologic engineering is the Vermont floodplain initiative. The state of Vermont experienced significant flooding in 2011 as a consequence of Hurricane Irene. This event accelerated the state's drive to implement reformed floodplain regulations. The state recommends river corridor management and meander belt buffers rather than traditional stream bank buffers (Kline and Cahoon 2010).

More extreme future events may be adapted to by increasing the factor of safety or overall size of civil infrastructure. Karl and Katz (2012) suggested that as the probability of extreme events increases, infrastructure should be designed such that these extreme events are not thought of as extremely rare. Downscaling of existing climate prediction models is a frequent suggestion when discussing design factors of safety (Timbal et al. 2011). Additionally, when critiquing design codes to anticipate effects of future climate change, it is important to differentiate between the effects of changes to climatological averages and changes event intensity ranges (Johns and Fedeski 2001). Altered climate averages can contribute to base deterioration; effects of extreme events may become more catastrophic.

Infrastructure that can be adapted to future conditions is another promising approach. Some have called this 'dynamic' design, as in the "plan that is effective in meeting multiple plausible futures" (Galloway 2011). Incremental adaptation is one possible design method (Gersonius et al. 2010), as is adaptive watershed management (Sendzimir et al. 2008). Modular designs are a possible implementation of this concept, which are characterized by standardized units for rapid assembly and flexible configurations. Modular bridges have been proposed for extreme situations such as military or disaster response installations (Bannon et al. 2009).

Flood-tolerant design (or disaster-tolerant design in general) is recommended by FEMA and involves the reasonable anticipation of flooding and design such that events will not cause a total loss (Bass and Koumoudis 2012). A structure designed to withstand an extreme event is less likely to need repair or replacement (Coulbourne 2010). Existing infrastructure can survive unprecedented flood events with proper modifications (Barták and Slížková 2010), which contributes to a community's ability to resist and recover from major disasters (Geis 2000).

Another design technique involves the concept of matching the design life of the item to the design life of the design, when assuming changing design variables (Lemer 1996). This design was out of the scope of this research because the actual design life of civil infrastructure can be very difficult to predict. Some infrastructure may be demolished relatively early in its anticipated design life due to functional obsolescence or failure, and many infrastructure solutions may be made to perform long after their anticipated replacement date due to funding shortages.

5.1.3 Sustainability evaluation metrics

Traditional design techniques are convenient to evaluate quantitatively, in part because of the straightforward calculation methods, and in part because most engineers have working familiarity with how to conduct and review the calculations. It is worthwhile to determine whether designs can be adequately evaluated using metrics other than cost, size, design life, and traditional quantitative characteristics. For example, Colorni et al. (2000) presented four main factors to be used when evaluating infrastructure design alternatives: functional utility, environmental compatibility, territorial compatibility, and social acceptability. This methodology is best for the preliminary planning phase.

Evaluating infrastructure sustainability remains a challenge to traditional design practice (Ahern et al. 2014). Bass et al. (1998) outlined what they call the “ecosystem approach” to human activity evaluation, which is based on thermodynamics and energy flow. Baetz and Korol (1995) formulated a list of seven criteria for how to evaluate engineering alternatives for their relative sustainability: integration, simplicity, inputs/outputs, functionality, adaptability, diversity, and carrying capacity. Using stormwater drainage infrastructure as an example, Upadhyaya et al. (2014) studied several methods of integrating traditional project assessment metrics with values related to sustainability. Sustainability metrics studied included ranking systems, sustainability indicators, measures of metabolism and environmental footprint, and performance assessments.

In this portion of the research, several and traditional non-traditional design techniques were assessed under qualitative and quantitative evaluation structures. Three example watersheds of differing characteristics were used to rank the performance of the techniques under different design circumstances. A system for numerically evaluating design effectiveness was applied, as was a qualitative ranking system for determining intangible traits and incorporating engineering judgment. Finally, a few better performing design techniques were recommended based on the findings.

5.2 Methods

Engineering designs must be evaluated quantitatively for design performance and cost effectiveness. An ad hoc evaluation technique was created using available data and simple optimization methods. For this research, three example watersheds were used to test new design theories. The watersheds were selected based on their diverse geographic features, availability of surveyed stream cross section data, and availability of watershed models or information available to construct calibrated models.

Watershed #1: The Rabbs Bayou watershed is a suburban and developing stream within the lower Brazos Valley in Southeast Texas. This stream is characterized by a visible channel but indistinct flood plain as it is in the historical path of the Brazos River. A hydrologic model was developed as part of previous research by the author.

Watershed #2: Bull Creek Tributary is in a suburban and developing area outside of Austin, Texas and is characterized by deep channels with steep sides. This watershed was analyzed for a local floodplain governing authority and calibrated hydrologic/hydraulic models are publicly available.

Watershed #3: Sweetwater Creek is located outside of Atlanta and is likewise suburban and developing. It has distinct channels and floodplains but due to extensive development in the past 30 years appears to be undergoing shifting control as the stream naturally regains equilibrium.

Drawing on the nature of the case studies and a review of the existing literature, seven possible configurations for stream crossings were examined. These techniques do not represent an exhaustive list of all possible design methods but function as a survey of engineering design methodology on the whole.

1. All watersheds had many existing stream crossing in place. These existing bridges were assumed to be modern typical return-period design in accordance with state regulatory guidelines in place at the time of construction. In truth, the existing stream crossings exhibited many design scopes depending upon road importance and numerous local factors. Some older bridges were no longer performing to the standard at which they were designed; in those cases the existing bridge design was not revised upward.
2. The design case of floodable bridges assumes existing return-period design as with the existing bridges and enhances the failure-tolerant attributes by inclusion of submersible bridge characteristics such as cast in place guard rails, structural measures, and additional channel armoring to reduce scour. This design assumes that the bridge will eventually flood and allows for it without destruction of the bridge.
3. Borrowing from the concept of appropriate technology, the design case of a ford assumes that not every road will need a large or complex bridge design, and indeed, this type of design is relatively common on many roads in the southwestern US including Texas, which use low-water crossings across ephemeral streams. These crossings become impassable whenever flow is above six inches depth and follow the natural stream bottom with some kind of armored pavement.

4. Box culverts commonly used in stream crossing design and can be manufactured with a removable upper portion. The modular culvert design style is a bridge that can be expanded or contracted as needed to accommodate future stream flows. This design will be sized according to existing state regulatory standards (whether return-period based or not) and can be resized in the future as necessary.
5. Drawing on the concept of ecosystem services, the channel avoidance bridge is designed such that the bridge deck will not impede any portion of the natural bank-full stream channel, with the possible exception of pylons or support structures. The river is allowed to behave naturally without negative consequences to the infrastructure.
6. The floodplain avoidance bridge is likewise modeled on the concept of ecosystem services but takes it a step further by including not only non-impedance of the stream channel but non-impedance of the basic riverine floodplain, pylons excepted. In this case, the river is allowed to flood occasionally without overtopping the crossing.
7. The PMP bridge is designed to pass the flow resulting from the Probable Maximum Precipitation as currently estimated by the National Weather Service (Schreiner and Riedel 1978). Despite the somewhat dated publications and stationary nature of the PMP (Stratz and Hossain 2014), it remains as the largest available precipitation estimate in many locations within the United States. This

precipitation event is assumed to represent the worst-ever conditions that a bridge may ever face.

5.2.1 Quantitative analysis

The performance of the design techniques was evaluated by an optimization algorithm which used three numerical measures of bridge performance, an example of which is shown in Table 11. First, accurate cost estimates are essential to optimization evaluation of infrastructure options. State Departments of Transportation often provide bridge square-foot cost estimates intended for line-items within larger project estimates. For this project, the sizes of the bridges were estimated by using a rating curve and determining the location of the bridge needed to pass certain flows or to achieve a certain elevation goal. Culverts were sized to either the existing bridge's design flow or to current state design standards on the assumption that designers would use the traditional sizing method with a future option for enlargement if necessary. These estimated sized bridges were then combined with line-item bridge square foot cost tables for an estimate of the total dollar cost for the entire bridge.

Second, infrastructure options need some estimate of risk of failure, in this case given as the probability of overtopping. Rather than returning to a regional return period for probabilistic estimation, instead each proposed bridge was examined in-situ and assigned a value of how many times it would flood per year if it were currently installed. Daily precipitation gauges from within each test watershed with sufficiently long (> 50 years) time series were available. Using a calculated relationship between precipitation and flow obtained from hydrologic modeling, the precipitation events were translated into flow events, which were then ranked. The number of times the bridge would flood per year was calculated as the number of times stream flows actually exceeded the bridge design flows, converted to units of events per year.

The third numerical performance criterion represents a measure of how well the bridge performs under normal traffic circumstances. The quality of traffic flow is assessed in the Level of Service metric, a qualitative letter-grade given to road segments under normal operating conditions. The LOS metric contains many input parameters and empirical tables; one such consideration is the quality of the vertical alignment. Sharp upgrades and downgrades impede traffic, as trucks and other vehicles must slow to a crawl to traverse the impediment. A good-quality alignment is one without much sudden grade change. The quality of alignment was taken as the average of the absolute values of the downgrade and upgrade as it would appear to a vehicle approaching the bridge. Longer, higher bridges have flatter alignments and lower slope values and thus are easier for traffic to pass unobstructed.

After calculating each value for the proposed bridge design, each bridge in each situation was fit to a three-dimensional triangular surface with one point of the triangle located at the point of each of the three performance criterion axis (see Figure 18). The area of the triangle was calculated, and the minimum area was selected as the best infrastructure option.

Table 11. Example numerical performance evaluation

Solution	Quality of alignment	Times flooded / year	Cost
Appropriate technology	0.01970	7.492537313	$32,000.00
PMP bridge	0.00802	0	$2,254,464.00
Modular culvert	0.01292	0.074626866	$40,942.00
Channel avoidant	0.01117	0.029850746	$119,768.00
Floodplain avoidant	0.01013	0	$746,791.00
Current size	0.01127	0.074626866	$84,672.00
Current size floodable	0.01127	0.074626866	$75,978.00

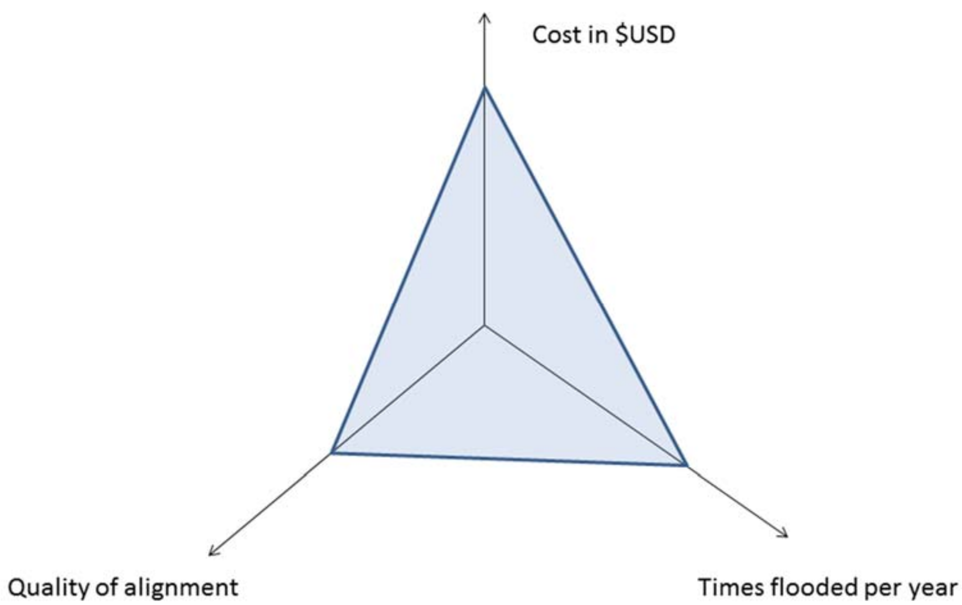

Figure 18. Triangular optimization surface

5.2.2 Qualitative analysis

Purely quantitative assessment can at times miss the bigger picture when it comes to human interaction with the environment, and designing bridges is no exception. Engineers must take into account not only the bridge users but also the bridge designers, construction firms, and infrastructure management experts. To incorporate intangible and opinion-based metrics into design consideration, a qualitative ranking system was devised to compare each bridge solution against the others. Eight metrics were devised as shown in Table 12, and each bridge was assigned a rank of 1 through 7 to represent if it were better or worse in a certain category. Lower scores were considered better, and the solution with the lowest overall score was considered optimal.

Table 12. Qualitative assessment metrics

Design metric
Able to be clearly written into a specification or code, to protect both the designer and the user from malpractice
Clear and user-friendly design guidelines
Requires skill and judgment in engineering design
Not burdensome to calculate, using engineering bachelor's degree level mathematics and common publicly available data
Able to accommodate current estimated design flows and possible increased, decreased, or re-estimated future flows
Cost-effective in engineering design process
Defensibly cost-effective in construction
Encompasses multi-modal safety for all types of users including cars, trucks, transit, bicyclists, and pedestrians

One major consideration in attempting to overhaul engineering design theory is what role existing engineering judgment should play and to what extent it is appropriate to incorporate into written design codes. Much has been written about the need for a more holistic approach to engineering design and less prescriptive building codes

(Bulleit and Adams 2011, Björnsson 2015). In order to assess the current state of engineering judgment with respect to return-period based design, a survey will be distributed to practicing civil engineers. The survey will (a) assess the current level of understanding of what return-period design represents; (b) gauge current opinion of the effectiveness of return-period design; and (c) allow the engineers to rank the seven previously selected bridge designs using the qualitative analysis ranking system. Survey results will be tallied with a simple averaging analysis without regression. Correlations will be assessed, as will population characteristics of the responding engineers.

5.3 Results

5.3.1 Quantitative analysis

Based on the quantitative performance analysis, depending upon the unique situation of the case study, more than one of the analyzed solutions appeared to have the best qualities. For a typical suburban stream, it appeared that the channel avoidance bridges and modular culverts had relatively similar results. These solutions represented the best combination of attributes for stream crossings in these locations. For very deep channels with steep side slopes, the current practice is such that bridges are designed to span the top of the gorge, thus creating a bridge that will likely never be overtopped but enable a flat alignment for traffic to pass unimpeded. In these cases, the floodplain avoidant bridges or existing condition bridges achieved the best optimal score despite their relatively higher cost.

As previously stated, Sweetwater Creek was in the process of undergoing shifting control, wherein the stream channel was adjusting itself to rapidly changing flow amounts across the spectrum of precipitation events. In this case, the modular culverts achieved the optimal score. This could be because the channel reaches bank full conditions much more often than in a stable stream, which causes additional stream overtopping than normally expected.

5.3.2 Qualitative analysis

Based on the authors' completion of the qualitative assessment scoring system, channel avoidant bridges had the lowest overall score. Results of the engineering survey and other engineers' opinions with respect to the bridge ranking system will be provided upon approval by the Institutional Review Board.

5.3.3 Recommendations

Based on the results of the qualitative and quantitative assessments, the authors recommend channel avoidant bridges, due to their overall superior performance and increasing acceptance in the industry. The secondary recommendation is modular culverts, due to the fact engineers are sometimes reluctant to certify existing infrastructure due to unknown remaining strength and design life. Additionally, although concrete box culverts can have a long lifespan, there is debate about their relative sustainability with regard to the habitat value of natural stream channels. In some cases, a floodplain avoidant bridge may be the preferred solution if the stream channel is very steep.

To create a channel avoidant bridge on a stream with shifting control, the engineer must anticipate the channel characteristics when the stream re-stabilizes. Urbanization produces a relatively well-known response in stream channel morphology

(Bledsoe 2002, Hawley et al. 2013), and stream behavior can be predicted by geomorphological study of its geological and geographic characteristics (Rosgen 1994). In these cases, additional fluvial geomorphological study may be warranted.

5.4 Conclusion

Designing under new circumstances is difficult and requires engineers to harness creativity and learn from past failures. This requires new design inputs and new ways of evaluating designs and infrastructure performance. Drawing on available design theory, the authors devised seven types of bridges and created qualitative and quantitative evaluation techniques in an effort to evaluate these seven types of bridges along several dimensions of project appropriateness and sustainability. The results of this evaluation showed that designs based on the concept of ecosystem services performed best, and modular designs performed adequately as well. These solutions help engineers provide the best possible design expertise in the modern era.

6. CONCLUSION

This dissertation analyzed the role of hydrologic nonstationarity on the engineering design storm and in light of the research findings proposed alternative design techniques that are likely to perform well under possible future conditions. These conclusions provide engineers and designers with the tools to use in the process of adaptation.

In order to examine the effects of nonstationarity on the engineering design storm, a nonparametric statistical test was applied to the annual maxima time series of numerous rain gauges. This test showed that an estimate of the 1% exceedance design storm, using the best available data and techniques, is often no better than an estimate achieved by random shuffling of the annual maxima time series. Furthermore, while tropical storms are often perceived as rare and severe events, research showed that they were not unduly influential when computing rain gauge exceedances. Spatial trending of rain gauge time series behavior was not detected. These findings called into question whether the typical exceedance-based engineering design storm and atlas configuration is the best available knowledge for the design industry.

This research analyzed the impacts of land cover and geomorphological alterations on design flows. Research on the sole contribution of urbanization showed that the physical design life of a piece of infrastructure may be much longer than the design life of the design, as it were, due to rapid changes in stream flows from development. A further analysis of the combined effects of precipitation, land use change, and topographic subsidence on inundated area of a stream showed that land use change was in fact the least influential source of nonstationarity, and that the greatest impact was due to the alteration of the anticipated precipitation. Given the ability of urban planners to effect major changes in land use and lesser changes in topographic subsidence, it is worthwhile to note that both of these impacts to stream flows were overshadowed by the effect of precipitation which is entirely out of the control of regulatory entities.

Less obvious as potential sources of nonstationarity are the individual decisions of practicing engineers. A case study of an (intentionally or unintentionally) undersized bridge showed that a design may be successful without following existing design codes to the letter; this is not a defense of slovenly calculations, but rather an opportunity to reexamine the concepts of risk, consequences of failure, cost-effectiveness, and professional judgment. The bridge was designed to half its required design flow but performed without failure through a normal design life. Furthermore, the decisions of design engineers can introduce new sources of nonstationarity into infrastructure and must be accounted for when proposing new design techniques.

The existing body of engineering literature contains the seeds of the new design theories required to lift the industry into the modern age. Drawing on previous available research and philosophical ideas, this research formulated several possible techniques for adaptation to changing conditions. The techniques were evaluated quantitatively using numerical performance measures and an optimization algorithm; additionally, the techniques were evaluated qualitatively using a ranking system and will be further evaluated within the sphere of professional judgment using surveys. These evaluations showed that modular designs and designs based on the concepts of ecosystem services performed most reliably.

This research contributes to current issues in engineering practice in several ways. Engineering design is largely driven by state and local laws and codes, which are often slow to adopt change. This project offers evidence for new design theory to help revise codes and standards of design. These ideas enable engineers to practice with more integrity, as there would be fewer opportunities for “fudging” in order to meet antiquated or inadequate codes. The public should retain a more realistic idea of the true performance of infrastructure; rather than expecting structures to never fail, the populace should be aware of the conditions for failure and be better prepared. More cost-effective design will improve project finances in the short term, while in the long term, society can stop bearing the cost of taxpayer subsidized ineffective designs.

This dissertation opens up several avenues for future research. The concept of hydraulic design under shifting control is yet to be thoroughly researched and might provide additional insight into which designs truly stand the test of time under changing hydrologic regimes. An unexplored source of hydrologic nonstationarity is that contributed by stormwater management systems – i.e. runoff detention and retention systems. A large segment of the practice of hydrology and hydraulics involves the design of such systems intended to reduce downstream impact of large development projects. Design codes for these systems can vary widely in their requirements, and are prone to frequent change and revision at the local governmental level, leading to a very piecemeal system of detention and storage confined to individual properties. Such a system contributes to variability in streamflow; the exact significance of such a contribution in comparison to other sources of nonstationarity is unknown.

Engineering design codes tend to be quantitative in nature, and although qualitative and judgment based codes do exist, they are not in wide distribution. How such codes would impact the practice is undetermined. Exploration of these concepts will improve the practice of civil engineering and facilitate the engineer's primary responsibility to hold paramount the health, safety, and welfare of the public.

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