Temporal and Spatial Evaluation of Stormwater Engineering Standards Reveals Risks and Priorities Across the United States

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Abstract

Stormwater infrastructure in the United States is designed using governmental precipitation frequency documents and informed by State Departments of Transportation (DOT) guidelines that balance risks and costs. However, both governmental precipitation documents and State DOT guidelines are updated infrequently, which enhances risks in areas where precipitation patterns have changed over time. This study reviewed State DOT design manuals from the 48 contiguous US states and the District of Columbia and found wide variation in design return period standards recommended for similar roadways and infrastructure types. Precipitation differences between successive US precipitation documents for 43 states over the period of 1961–2000 were found to be statistically significant in more than 90% of the study area. These differences indicate that stormwater infrastructure installed prior to the latest update of precipitation frequency documents could be under-designed for present and future climate conditions. Comparing State DOT design storm values for each roadway and infrastructure type, an index for each climate region was developed to assess the relative stringency of each state's requirements. Using these index values, the observed change in precipitation frequency estimates, and each state's design manual publication date, this research identified the states that need to prioritize revision of their stormwater standards to maintain the originally intended design performance over time. Eight out of 43 states were found to have the highest priority for immediately revising their stormwater standards. In addition, these states should assess whether existing infrastructure requires additional adaptive capacity to manage observed precipitation increases. The priority increased for all states under both the RCP 4.5 and RCP 8.5 emissions scenarios for 2050. While local assessments comparing infrastructure costs of increasing the stringency of standards versus the expected costs of future damages under climate change remain necessary, a no-regret action is revising stormwater standards to incorporate observed precipitation increases.

1 Introduction

Analyses of long-term precipitation records show evidence that daily precipitation patterns in many regions have changed in the past few decades. In most of the contiguous area of the United States (U.S.), an increase in the frequency and intensity of extreme rainfall has been observed over the twentieth and early twenty-first centuries (Karl and Knight 1998, Karl *et al* 1995, Groisman *et al* 2001, 2005, DeGaetano 2009, Kunkel

et al 2012, Wu 2015). Although internal climate variability partially explain increasing trends in daily heavy precipitation observed within short periods, long-term changes in the frequency and intensity of extreme events are also attributed to increasing levels of anthropogenic greenhouse gas emissions (Hoerling *et al* 2016, Kim *et al* 2016, Easterling *et al* 2016, Lehmann *et al* 2015). It is projected that these changes in some regions will be further intensified by climate change, with the magnitude of increases dependent on total greenhouse gas emissions levels (Wilby and Wigley 2002, Wuebbles *et al* 2013). In 2017, Hurricane Harvey delivered 32.47 inches (82.47 cm) of total rainfall in Houston Texas, breaking the largest 3-day precipitation record in a major U.S. city. Other cities in the region received 48-hr rainfall totals exceeding 40 inches (101.6 cm) (NOAA National Centers for Environmental Information 2017, National Weather Service 2017). An assessment on Harvey's extreme rainfall showed that this event had approximately a 1% annual chance of occurring over 1981-2000, but will increase to an 18% annual probability of occurring over 2091-2100 under Intergovernmental Panel on Climate Change (IPCC) AR5 representative concentration pathway 8.5 (Emanuel 2017). For the engineering community and other stakeholders, changing precipitation patterns represent a complex challenge because design standards for both existing and new stormwater infrastructure are based on analyses of historical precipitation records that are likely not representative of future climate conditions (Gibbs 2012). Drainage infrastructure designed to existing standards can be stressed beyond capacity if exposed to higher rainfall conditions, especially if there have been changes in urban landscape, and/or if the soil is saturated preceding extreme rainfall. Failure to convey precipitation runoff from roadways sometimes leads to deadly flash floods, infrastructure failures, or roadway closures (Shepard 2016, IPCC 2012, National Weather Service 2017) resulting in significant socioeconomic consequences, especially in densely populated areas. Stakeholders need robust resilience plans that enhance the performance of existing and new infrastructure that will continue to be used over the coming decades (IPCC 2014). Yet how both existing local infrastructure performance has degraded, and future performance is affected due to increasing precipitation is not well quantified.

In the U.S., stormwater infrastructure design specifications are provided in national standards, such as (Brown *et al* 2013, AASHTO 2014, ASCE 2017) as well as State and local Departments of Transportation (DOT) design manuals. These standards provide guidance to engineers to size stormwater infrastructure to achieve acceptable performance levels, commonly represented by a design storm. The design storm is specified as the expected average time interval between the occurrence of two precipitation events of the same magnitude (often referred to as design return period), the reciprocal of which represents an annual probability of exceedance. By design, a system's capacity is equal to the rainfall from the storm described by the design return period over a specified time interval. Consequently, selecting a specific design return period assumes a level of failure risk for a single structure. Increasing the design return period increases the level of protection against extreme events and requires larger pipes to convey the excess runoff in conventional "gray infrastructure", since higher return period storms produce more rainfall. Increasing the pipe size is likely to increase the total drainage system cost because of material, equipment, and labor costs, and while these cost increases might be small relative to overall project costs, these tradeoffs and associated transaction costs need to be valued and balanced by stakeholders. Under changing climate conditions, designing infrastructure with solely historical information can result in expensive and frequent damages to assets in areas where stormwater systems fail (Arnbjerg-Nielsen *et al* 2013). Pipe enlargement, if combined with other strategies such as green infrastructure, might be cost-effective while meeting acceptable service levels over the life of the infrastructure (Manocha and Babovic 2018). Given the long service life (between 50 to 100 years) of stormwater infrastructure, uncertainties also exist regarding future land use and travel volumes in the urban environment. Hence, the choice of a design return period is not limited to the standard, but required to reflect a balance between construction costs and expected damage costs from flooding, depending on the conditions where the project will be developed (Mailhot and Duchesne 2010, Zhou *et al* 2012, Wenzel Harry G. 2013, Wark *et al* 2015).

While some engineering documents (e.g. (Brown *et al* 2013)) provide guidelines for the selection of design return periods, other documents provide precipitation depths or intensities of expected extreme precipitation for a given duration and return period. Intensity-duration-frequency (IDF) curves are the most common method to represent the characteristics of extreme rainfall events and are widely used in stormwater infrastructure design (Testik and Gebremichael 2013, McCuen 2016). In the U.S., federal weather agencies have collected precipitation data and compiled these estimates in standardized governmental precipitation frequency documents. Table 1 shows the publication date and use period for each precipitation document over time. Among the published documents, the Technical Paper 40 (TP40), published in 1961, had extensive use in engineering design in the U.S. (Hershfield 1961, Testik and Gebremichael 2013). In the 1990s, concerns about TP40 being potentially obsolete led to the publication of Atlas 14 by the National Oceanic and Atmospheric Administration (NOAA) (Testik and Gebremichael 2013). Data for six states (Oregon, Washington, Idaho, Wyoming, Montana, and Texas) have not yet been included in Atlas 14 update (NOAA 2018). Because of an increase (lengthening or newly available) of precipitation records and new statistical approaches used in Atlas 14, shifting from TP40 to Atlas 14 resulted in a change in the precipitation estimates for certain return periods and durations in some areas of the U.S. Another important feature missing in all precipitation documents prior to Atlas 14, is the quantification of uncertainty. Atlas 14 is the only official rainfall information that provides 90% confidence intervals along with their precipitation depth estimations (Bonnin *et al* 2006, 2011, Perica *et al* 2013a, 2013b, 2014). Because of the change in precipitation estimates (either positive or negative) by replacing TP40 by Atlas 14 in some areas, stormwater systems designed prior to the update of precipitation frequency estimates could be under- or over-designed to handle present conditions described by Atlas 14. For example, a structure designed using a 25-year depth from TP40 may be inadequate to handle increases in rainfall extremes that were observed in the later Atlas 14 data period. In addition, subsequent increases as result of climate change will further degrade the performance of under-designed structures (Guo 2006, Mailhot and Duchesne 2010, Janssen *et al* 2014, Cook *et al* 2017).

Table 1. Published standard precipitation-frequency documents used for engineering design in the U.S.

Document	Publisher	Release date	Active use period	Features and shortcomings	Reference
Rainfall intensity-frequency data	U.S. Department of Agriculture	1935	1935 - 1953	• First extensive study of extreme rainfall • Length of precipitation records analyzed was short	(Yarnell 1935)
Technical Papers 24, 25, 28 and 29	Weather Bureau	1953, 1954, 1955, 1958, 1960	1953 - 1960	• Extended analysis, proving importance of record length	(Weather Bureau 1953, 1954) (Weather Bureau 1955, 1956, 1957, 1958a, 1958b, 1959, 1960)
Technical Paper 40 (TP40)	Weather Bureau	1961	1961-2006	• Nationwide analysis • Inaccurate estimations for storms shorter than 1hr and in the western U.S.	(Hershfield 1961)

Atlas 2 and NWS HYDRO-35	National Oceanic and Atmospheric Administration	1973, 1977	1973 - present	• Addressed specific flaws of TP40 • Still used in engineering design in the northwestern U.S.	(Miller *et al* 1973a, 1973b, 1973c, 1973d, Frederick *et al* 1977)
Atlas 14	National Oceanic and Atmospheric Administration	Various depending on volume	2004 - present	• Includes the analysis of longer precipitation records • Application of statistical techniques allowed for calculation of confidence intervals in their rainfall depth estimations • Evidences and projections of a non-stationary climate threats the validity of estimations	(Bonnin *et al* 2006, 2011, Perica *et al* 2013a, 2013b, 2014).

Even with the uncertainty in timing and magnitude of future rainfall patterns (Milly *et al* 2008, IPCC 2012, Easterling *et al* 2017) as well as changes in climate variability (Barros and Evans 1997, Barros *et al* 2017), several studies have recognized that these changes must be accounted for and have estimated possible impacts of climate change on urban stormwater infrastructure design and performance in future climate conditions (Willems *et al* 2012, Mailhot and Duchesne 2010, Semadeni-Davies *et al* 2008, Arisz and Burrell 2006, Cook *et al* 2017).

In this paper, we present a novel and complementary approach to inform resilience assessments of stormwater infrastructure design and assign a level of priority for State DOTs to revise their design standards by characterizing the spatial and temporal variability of minimum design standards for stormwater infrastructure. By analyzing the spatially averaged difference between TP40 and Atlas 14, we show that the acceptable infrastructure failure probabilities (or failure risk) have not remained constant from 1961 to the latest Atlas 14 documents released beginning in 2004. This can inform stakeholders about changes in installed stormwater infrastructure performance and likelihood of failure, as well as the risks of specific design choices new infrastructure. While a risk assessment for a specific local infrastructure asset includes understanding exposure, vulnerability and hazard, we envision our results can serve as an initial screening tool to inform priorities. We classify each state into one of four different priority classes to revise their design standards using the spatially averaged TP40 and Atlas 14 differences, comparing a state's standards with other states in the same climatic region, and noting the DOT design manual publication date. We also evaluate the projected priority for each state in both higher emissions and lower emissions future scenarios using precipitation change projections from the U.S. National Climate Assessment (Easterling *et al* 2017).

2 Methods

2.1 Stormwater infrastructure design standards in the U.S.

This study extracted the minimum design return period standards recommended by each state from the design manuals of the 48 contiguous states and the District of Columbia (D.C.) (See table S.1 in the Supplemental Information for the complete description of state design return periods and references). Design return periods are usually specified by type of drainage structure, highway classification, traffic volume, or combinations of these variables. In order to enable comparisons between State DOT guidelines, we made several assumptions to classify each standard. Classifications and general and per state assumptions are described further in Section S.1, and S.2. Additionally, we noted which governmental standardized precipitation document was used during the manual's development. Figure 2 shows a timeline

across regions of Atlas 14 release dates, as well as the State DOT design manual publication date for the states within a climate region.

2.1.2 Variability of stormwater engineering standards

We characterized the variability of the minimum design return periods across states using both classifications defined in Section S.1. For each infrastructure element and highway classification, the coefficient of variation was calculated for all states. We determined the variability of the design standards within NOAA climate regions by developing a normalized regional index from 0 to 1, which compares state DOT standards within the same region. The regional index is defined in Section S.3. Higher index numbers characterize states within a climate region with higher design return periods relative to neighboring states in the same climate region.

2.2 Changes in precipitation frequency estimates

For each 24-hour duration minimum design return period, we estimated the percentage change between the previous (TP40) and current (Atlas 14) precipitation frequency document. When published, Atlas 14 included a comparison with TP40 only for the 100-year return period. However, return periods such as 10-, 25- and 50-year are frequently selected as design standards by State DOTs which motivates further comparison. Using QGIS software (QGIS Development Team 2017), we first digitized TP40 contour maps into vector shapefiles. Subsequently, contour lines for each map were interpolated using an inverse distance weighting algorithm to generate a point-estimate raster map. We retrieved Atlas 14 raster data from the Hydrometeorological Design Studies Center website (NOAA 2017). Finally, the percent change between TP40 and Atlas 14 was computed by subtracting the generated TP40 raster maps from the Atlas 2 or Atlas 14 raster maps and dividing by the corresponding TP40 value. To further illustrate local variation and to reduce potential bias derived from directly interpolating TP40 contour lines, the results were spatially averaged by county.

2.3 Identification of states where standards likely require revision

Figure 1 shows the process used to classify states within each priority class. The first level of the flow diagram contains three bins, each with different thresholds for the observed percent change in precipitation. All thresholds are positive, considering only percent increases (i.e. the precipitation depth for a given return period is greater in Atlas 14 than in TP40) because we are only concerned about potential under-design conditions that can lead to flood events. The highest threshold (10%) was selected based on (Niemczynowicz 1989) who found if the precipitation depth of a selected design return period increased by 10% or higher, the system was likely to suffer from stress or even failure during precipitation events defined by such return periods. The second level is a binary decision that is based on whether the latest state DOT design publication date is more recent than the latest precipitation frequency document, meaning that the standards provided in this design publication refer to the most updated precipitation estimates. The third level takes the midpoint of the regional index, defined in section 2.1.2 and section S.3, and divides states into groups above and below the midpoint. Since the regional index can vary between 0 and 1, states with regional index values greater than or equal 0.5 implies they have higher return periods than at least half of the states within the same climate region. Infrastructure in states in the top group are considered to have an added climate factor of safety, or the capacity to cope with increases in precipitation depth for a wider range of return periods, than those states with lower standards. For example, a system with an expected service life of 80 years and designed for a 100-year design return period is potentially able to cope with increases in precipitation depths for the 20, 40, 60 and 80-year return periods (Mailhot and Duchesne 2010). On the other hand, a lower minimum standard will be less resilient to changes in precipitation depth. In the absence

of additional information that would allow us to favor weighting the index, each criterion was assigned equal weight. Individual stakeholders could assign weights based on their preferences using our method.

Based on these three criteria, four different priority classes were identified ranging from lowest (1) to highest (4) priority. Recognizing that the percent change in the precipitation depth estimates defined by Atlas 14 and TP40 is based on historical records, we extended the analysis to identify the priority for each state under future climate change. To illustrate how priority levels would change under these future conditions, we classify priority levels using our method and the reported regional percent increases from the National Climate Assessment, assuming the projected increases in return periods above 25 years would be at least as high as projected by the National Climate Assessment for the 20-year return period (Easterling *et al* 2017). If, for example, the percent increase is higher for the 50- and 100-year future events than that of the 20-year, our use of the National Climate Assessment projections would underestimate the future priority. To assign a priority under future climate conditions, the flow diagram remained the same except for the second level which for each state design manual, always corresponded to a negative answer since there is no standardized assessment of local future climate conditions yet.

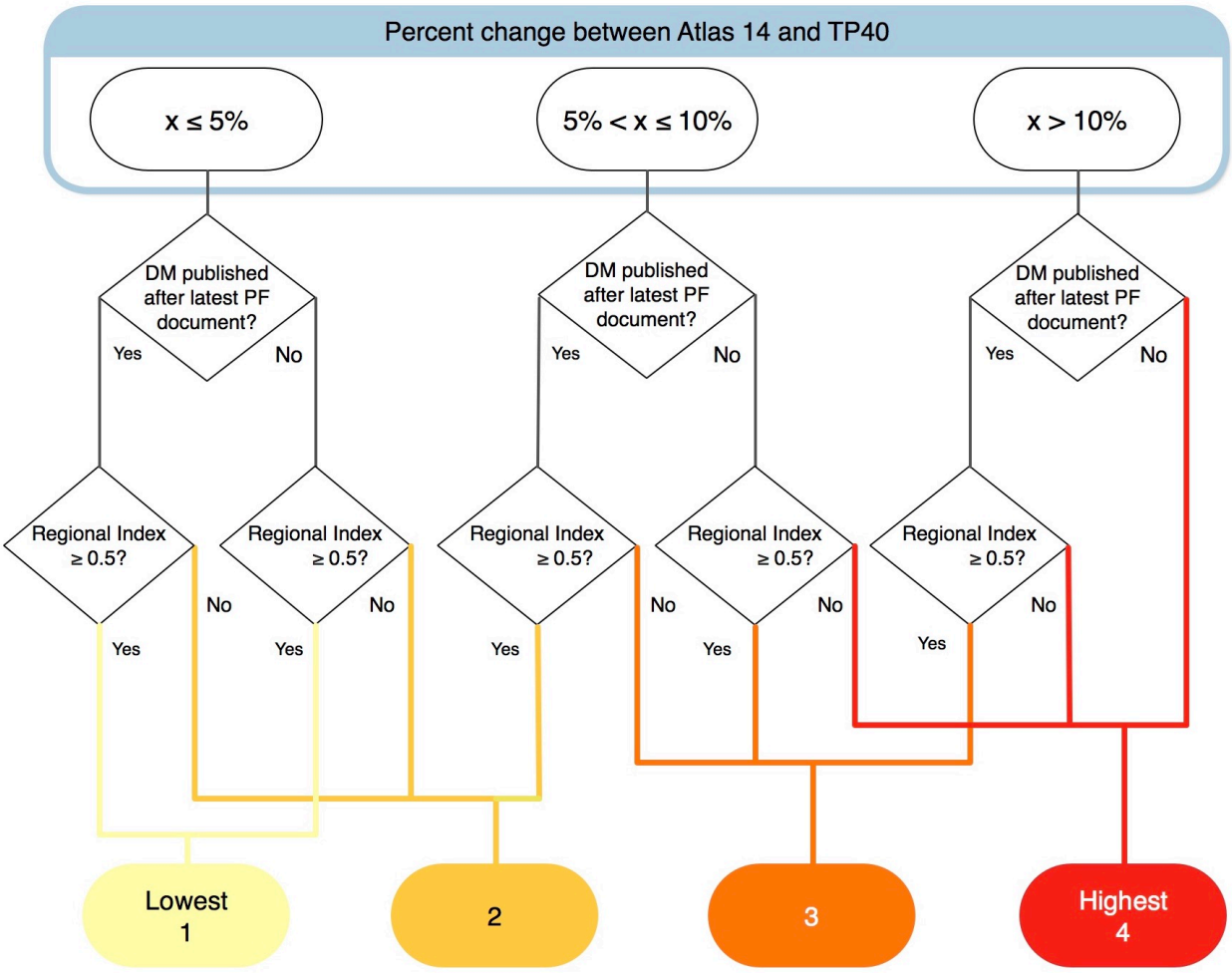

Figure 1. Categories defined for recommended priority (1-lowest, 4-highest) to revise design manual's (DM) standards based on observed change in the precipitation depth associated to each standard, DM publication date relative to the latest official precipitation frequency (PF) document and the state's regional index.

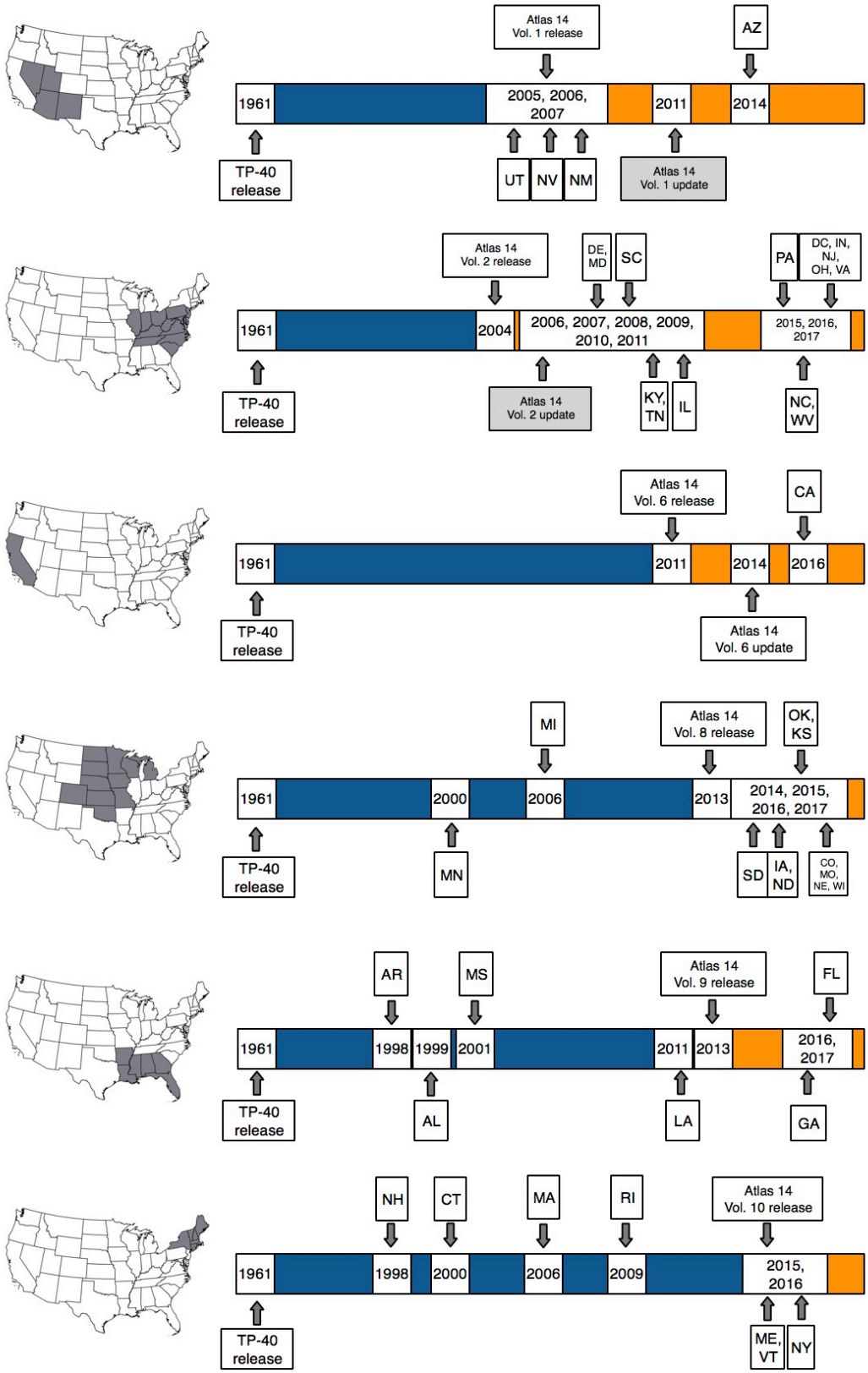

Figure 2. Governmental precipitation frequency (PF) documents (TP40 and Atlas 14) release date by region and State DOT design manuals release date by state (as of October 2017).

3 Results

3.1 Variability of stormwater design return period standards

Minimum design return periods for each infrastructure type were found to vary considerably across State DOTs (See Figures S.5–S.16). The difference is substantial in some cases, for example drainage inlets or storm drain systems show high a coefficient of variation, whereas culvert standards are more homogenous across State DOTs (see Figure S.6). This variation implies a different minimum tolerance to failure across State DOTs. The difference could ultimately be associated with the expected damages of failure and infrastructure design and cost differences across states. State DOT officials have different reasons and tradeoffs for determining minimum design return periods. For example, the Arizona DOT states "the goal in highway drainage design is to minimize off-project impacts while maintaining an acceptable frequency of protection for the highway at near optimal construction as well as maintenance cost." (Arizona, 2012). Funding priorities is another potential justification for the difference across the United States. Meyer (2008) provides an example where federally-aided highway projects must meet federal guidance requirements, and acknowledges that many transportation agencies have developed their own design manuals to provide their engineers with guidance (Meyer 2008). The design return periods by drainage structure and roadway functional class varied in most cases more than 50% across the United States. While most states share similar guidelines, there are some states that design for very low design return periods (2 and 3 years) and some for relatively high return periods (50 and 100 years) for the same type of highway and stormwater infrastructure (see Figure S.7-S.16 for U.S. maps for each highway class and drainage infrastructure type).

States within the same climate region were also found to have very different minimum standards. Using the regional index, we identified those states who have higher or lower return periods as design standards compared to other in the same climate region have a higher regional index. Figure 3 shows the regional index of each state by climate region. In the South climate region, Texas has set the lowest minimum return periods for their infrastructure design in comparison with its neighboring states, Arkansas, Mississippi, Oklahoma, Louisiana and Kansas. Louisiana and Arkansas have similar levels of protection, higher than Texas but lower than Oklahoma. Kansas and Mississippi have the greatest level of protection in comparison with the other states in the South climate region.

3.2 Changes of precipitation depth estimates in official precipitation frequency documents

Figure 4 shows the percent change in precipitation depth estimates for the 25-year return period 24-hour duration storms, from the estimates provided in TP40 compared those from Atlas 14. Zones in red correspond to a 25-year return period with a smaller precipitation depth estimation in Atlas 14 than in TP40, meaning that the 25-year return period precipitation depth estimate decreased from the past to the present estimate. Likewise, zones in blue correspond to a greater precipitation estimate, meaning that precipitation depths increased from TP40 to Atlas 14 estimate. The differences found for the 100-year return period were consistent with the previous comparison between TP40 and Atlas 14 made for the 100-year return period in Atlas 14. Larger changes were observed in higher return periods (i.e. 100-, 50- and 25-year) than for smaller return periods (2-, 5-, 10-year). Estimating large return periods with higher accuracy require long precipitation records. Therefore, the larger differences observed in higher return periods can be partially attributed to the considerable lengthening of precipitation records analyzed in Atlas 14 compared to TP40.

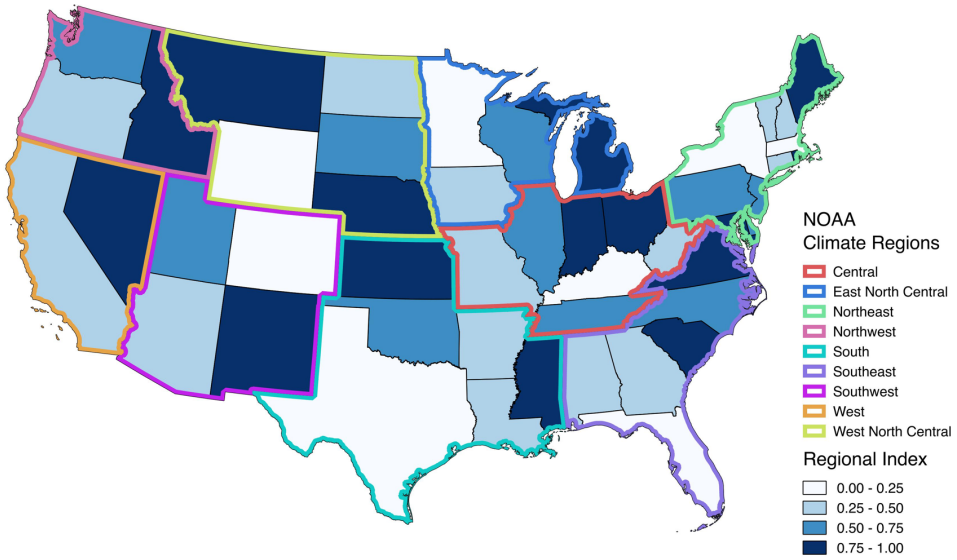

Figure 3. Comparison between state DOT stormwater standards within a NOAA climate region. Highest category represents states that have higher standards (and thus, are more prepared for rare storm events) compared to the other states within the same climate region. Lowest category (0 to 0.25) describes states that have the lowest guidelines in the region.

For the 25-year return period, some regions experienced considerable changes in precipitation depth estimations between TP40 (released in 1961) and Atlas 14 (released from 2006 to 2013). For example, the average precipitation depth corresponding to the 25-year return period in Michigan is at least 25% percent greater than the precipitation depth estimated in TP40 for the same return period. Alternatively, in West Virginia the precipitation depth is at least smaller by 25% between TP40 and Atlas 14. This means that infrastructure currently in place that was designed before the publication of Atlas 14 could be undersized (such as in Michigan) or oversized (such as in West Virginia).We also compared the precipitation depths from TP40 to the upper and lower bound estimates from Atlas 14 and noted, as shown in Figure 4, that a design for the 25-year return period in the Appalachian Mountains under TP40 estimates would be likely oversized even if designed for the upper bound estimate from Atlas 14.

The differences between TP40 and Atlas 14 values were tested for significance at the 95% level using two different tests, the two-tailed paired t-test and the Kolmogorov-Smirnov (K-S) test. To generate the samples to be tested, we first generated 50 random points within the state of Rhode Island (smallest state in the U.S.) and scaled the number of points to sample within each state by its area relative to the area of Rhode Island. For each point, we extracted the TP40 and Atlas 40 (pixel value from respective raster maps) value corresponding to the point location. We divided the study area using a hexagonal mesh (approximately 1-degree by 1-degree maximal diameter (approximately same area as Rhode Island), following (Karl and Knight 1998)) covering the study area. We chose a hexagon grid instead of a rectangular grid because a hexagon mesh is advantageous for the dividing a study area into smaller areas while ensuring the sampling results are representative of all regions (Birch *et al* 2007). For each return period and hexagon shape, we analyzed the evidence to reject the null hypothesis (in the case of the two sample K-S test that both samples are drawn from the same distribution, and in the case of the paired t-test that the mean difference between the paired observations is zero). We repeated the process 10 times using different sample points to assess the robustness of the results.

For the 25-year return period, the difference between TP40 and Atlas 14 was statistically significant at the 0.05 level using the paired t-test in 91% to 93% of the study area, and 89% to 92% of the area using the two sample K-S test. For the same return period, a positive statistically significant difference ($\mu_{Atlas14}$ −

$\mu_{TP40} > 0$) using the paired T-test was found in 69.9% to 72.1% of the study area at the 0.05 significance level while negative statistically significant difference was found in 5.7% to 10.3% of the study area. At the state level, 14 states (out of 43) exhibited positive statistically significant difference in more than 50% of the state area. Table S.6 and Table S7 shows a summary of the maximum and minimum statistically significant percentage area of the 10 replications for the paired T-test and the two sample K-S test while Table S.8 shows the percentage area with statistically significant positive difference ($\mu_{Atlas14} - \mu_{TP40} > 0$) by state. Sampling regions (hexagons) with statistically significant positive difference are shown in Figures S.26 through S.31.

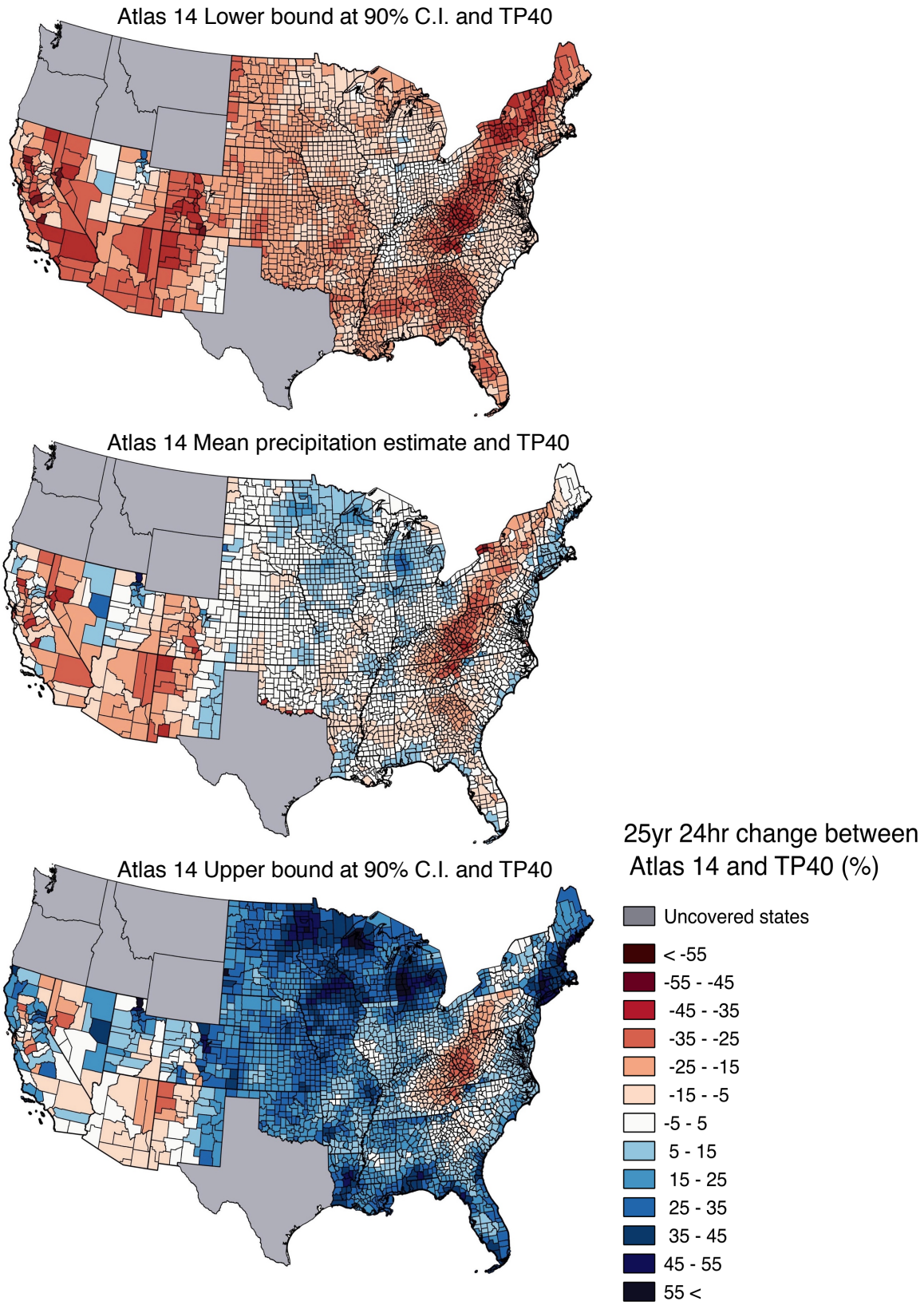

Figure 4. 25-year return period, 24h duration spatially averaged percent change (by county) between NOAA Atlas 14 and TP40 [(NOAA Atlas 14 - TP40)/TP40] for the 24h duration, 25-year return period. Northwestern states and Texas are excluded from this figure because they are not covered by Atlas 14.

3.3 Who should revise stormwater standards?

Using the method described in Figure 1 and repeating for each return period used as a design standard, states were classified into four categories to prioritize an update of their stormwater design manuals, 1 being the lowest and 4 the highest priority, as shown in Figure 5. States assigned the highest priority to update their design manuals experienced a 10% or greater increase in precipitation between Atlas 14 and TP40, published their current design manual prior to the release of the latest precipitation document, and were estimated to be in the lower half of their regional index for design return period standards. Depending on the average percent increase from Atlas 14 to TP40 for a given return period, a different number of states with high priority were found. Under higher return periods, many states in the Northeast and upper Midwest were found to be in high priority categories. These states should update their design standards to ensure new drainage infrastructure performs under current and future precipitation levels. In addition, these states should assess whether existing infrastructure requires additional measures such as green infrastructure to serve as adaptive capacity to manage precipitation increases between TP40 and Atlas 14 or further changes due to climate change.

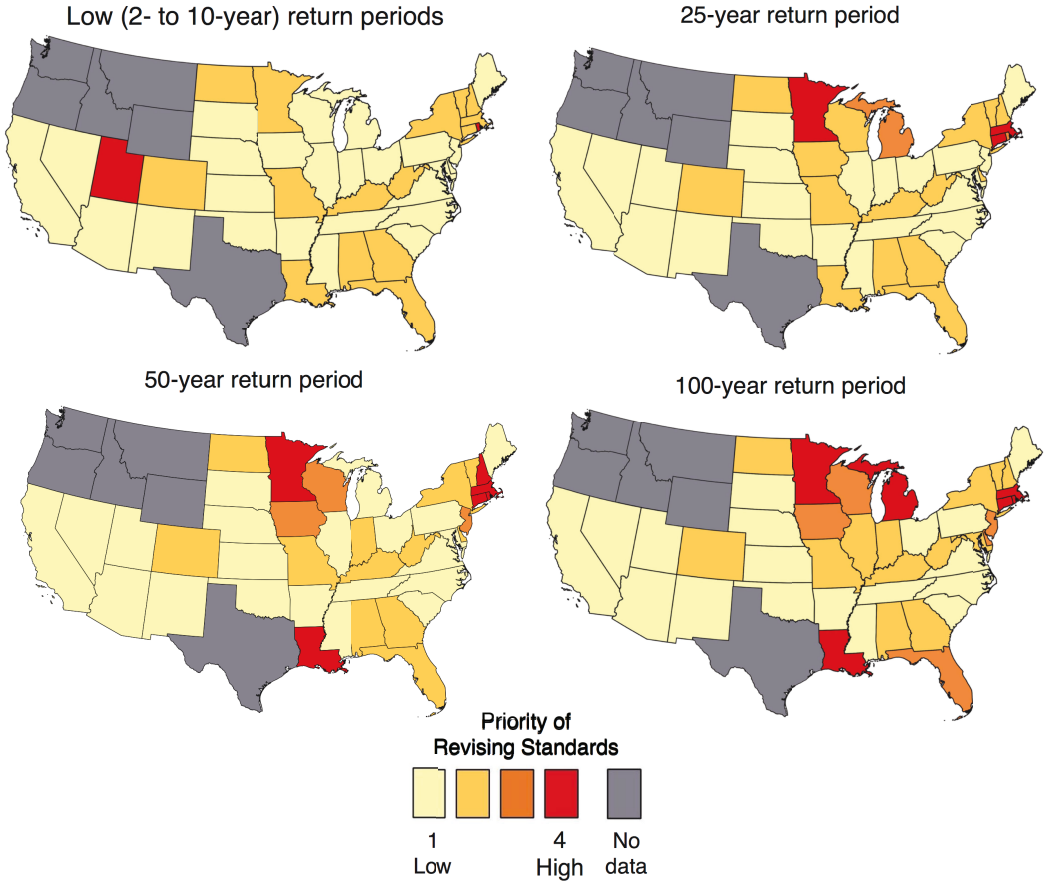

Figure 5. Priority (1-lowest, 4-highest) for each state to revise stormwater infrastructure standards according to the changes in low return periods (2- to 10-year) and 25-, 50-, and 100-year return periods. As of January 2018, states in gray remain uncovered by Atlas 14 and thus were not included in the analysis. Priority of revising standards is highest in 8 states for at least one return period.

The National Climate Assessment projected a range of 21st-century regional percent increases in daily

precipitation depths for the 20-year return period for RCP 4.5 and RCP 8.5, relative to the period of 1986-2005 (Easterling *et al* 2017). For 2050, the National Climate Assessment projects greater than a 10% increase in all regions under RCP 8.5, and greater than an 8% increase in all regions under RCP 4.5. Because the National Climate Assessments projects an increase for all states, the priority class to revise stormwater standards for future climate change would increase across all states. Figure 6 shows the priority to revise standards for each state under projected climate conditions. We recommend that states in the top two priority classes (3 and 4) should assess areas to increase preparedness of stormwater infrastructure to projected changes in precipitation patterns. This implies that much of the infrastructure built under minimum standards specified as of today will be stressed beyond their design capacity in 2050 and will likely not provide the minimum level of protection implied by the original design standard.

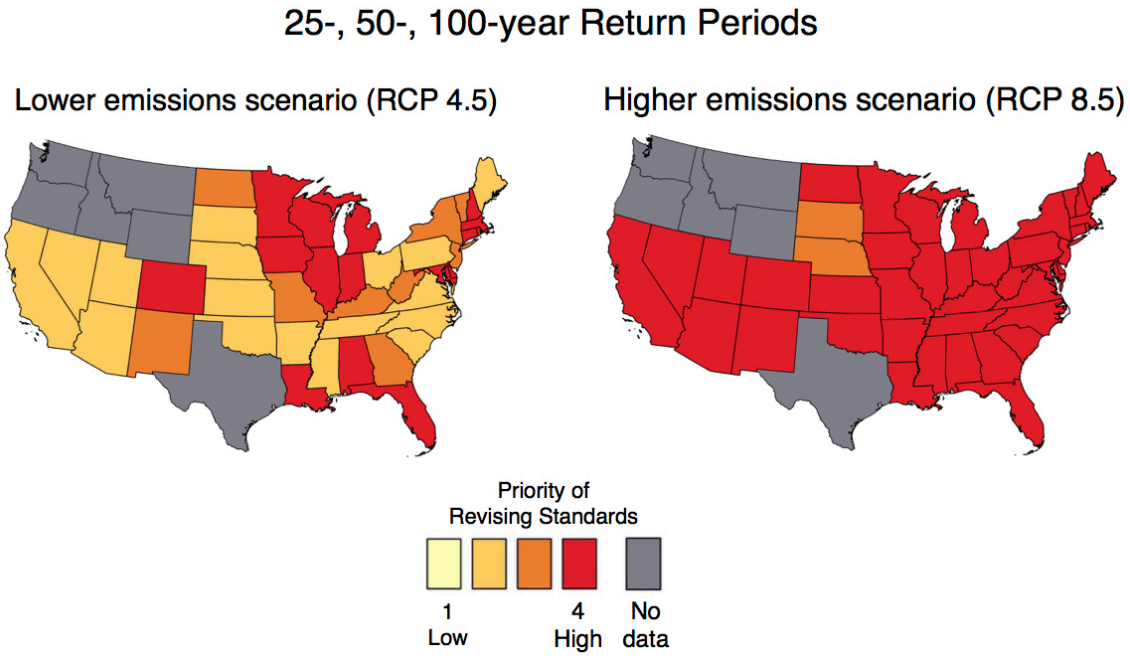

Figure 6. Priority (1-lowest, 4-highest) under projected climate conditions defined as per the percent increase in the 20-year 24-hour duration rainfall event by 2050 for each state to revise stormwater infrastructure for the 25-, 50- and 100-year return period standards under RCPs 4.5 and 8.5. As of January 2018, states in gray remain uncovered by Atlas 14 and thus were not included in the analysis.

5 Conclusions

We identified changes in precipitation depth estimates between older and more recent standardized precipitation frequency documents used for infrastructure design in the U.S., characterized the spatial variability of stormwater design standards across the U.S., and identified which states need to prioritize a revision of their State DOT stormwater standards in order to increase stormwater resilience to observed and projected impacts from climate change. Eight states were found to have the highest priority (for revising stormwater standards for a single or more return period. As future percent increases for the 20-year return period precipitation is projected to be between 8% and 10% under a lower emissions scenario, and greater or equal than 10% across the entire U.S. for a high emissions scenario by 2050 (Easterling *et al* 2017), the number of states classified in higher priority levels increases. Furthermore, these changes are expected to accelerate in the late-century, with a projected percent increase greater or equal to 10% across all the U.S. under a lower emissions scenario, and greater or equal to 16%, reaching 22% increase for the northeastern U.S. under a high emissions scenario. While there is uncertainty in these estimates, prudent infrastructure

planning for long-lived assets requires planning for resilience under uncertainty. Given that the infrastructure expected level of service is deteriorated when the percent change in a return period exceeds 10% (Niemczynowicz 1989), under the conditions projected by future scenarios, infrastructure constructed using existing and historical standards will likely not cope with such changes, especially in those states we identified to have high priority under present conditions.

Updating stormwater standards to account for current and potential future precipitation increases represents a governance challenge for states—existing stakeholders are likely to value lower initial costs of less stringent standards versus reducing life cycle costs and risks for future stakeholders. We recommend regularly revising standards and explicitly considering the potential climate change impacts that infrastructure might experience throughout its lifetime as additional precipitation observations and ranges of climate projections are generated. At the same time, the U.S. Federal government should consider encouraging the systematic, periodic review and updating of stormwater standards across states. These policy mechanisms could be in the form of resilience grants, incentives, minimum requirements for federal funding, or by supporting localized analyses to encourage a more synchronized approach across climate regions. The advantages of such an approach include alignment of local incentives to increasing life cycle regional resilience, while the disadvantages include potential higher capital costs and challenges of choosing threshold values from a range of climate projections.

Many areas follow similar stormwater infrastructure design practices as U.S. states, for example in Australia (AUS-SPEC 2013). Other areas such as the Government of Hong Kong (2018), the United Kingdom (2016) and New York City in the U.S (2017) recommend increasing rainfall values by specified percentages to account for future climate change. While local economic and risk assessments comparing costs of increasing the design return period versus the expected costs of future damages related to local exposure and vulnerabilities to infrastructure system failure under climate change remain necessary, a no-regret solution is the revision of stormwater engineering standards to incorporate observed precipitation increases. Having frequently updated precipitation information and design standards, coupled with an understanding of the range of future increases, will enable stakeholders to enhance the resilience of stormwater infrastructure for a changing climate.

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