CENTER FOR WATERSHED PROTECTION
National Watershed Research Network

ACCOUNTING FOR CLIMATE CHANGE IN POST-CONSTRUCTION STORMWATER STANDARDS

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Executive Summary

Stormwater management systems have historically been designed based on the assumption that climate is stable. The unprecedented rate of change in global climate patterns therefore has important implications for stormwater managers; yet, incorporating climate information into stormwater management has been a challenge for many communities.

The objective of this study was to review the existing state post-construction stormwater standards to provide a clearer understanding of the current stormwater management approaches to climate resiliency. To achieve this objective, the Center for Watershed Protection (CWP) first reviewed the technical literature to identify: 1) vulnerabilities posed by climate change to effective stormwater management and 2) best stormwater design practices to manage these vulnerabilities. Next, CWP evaluated state-published stormwater standards with respect to each state's specific stormwater vulnerabilities and the degree to which stormwater-related climate adaptations have been incorporated into standards.

The review identified four major climate impacts most relevant to stormwater best management practice (BMP) function (Figure ES-1) and rated the extent to which each impact is expected in each U.S. region. By overlaying these projected climate impacts with the projected increase in developed land over the next 25 years, CWP then categorized each state based on its overall **vulnerability** to stormwater-related climate impacts.

The review also identified a typology of stormwater adaptations to the major climate impacts, organized around seven categories: 1) design storm data & BMP sizing, 2) BMP selection and siting, 3) BMP storage, 4) conveyance & pre-treatment, 5) material selection, 6) maintenance, and 7) landscaping & plant selection. Based on the typology of stormwater adaptations, CWP developed a questionnaire and scoring sheet to evaluate the extent to which existing state stormwater standards incorporate these adaptations and, in particular, if the standards have been modified to address the climate impacts most important in that state's region. The questionnaire also evaluated the extent to which the standards are up to date and based on the best available science and practices.

CWP used the resulting scores to characterize the overall **readiness** of each state to adapt their stormwater standards to expected climate impacts. Figure ES-2 shows each state's combined vulnerability and readiness ranking.

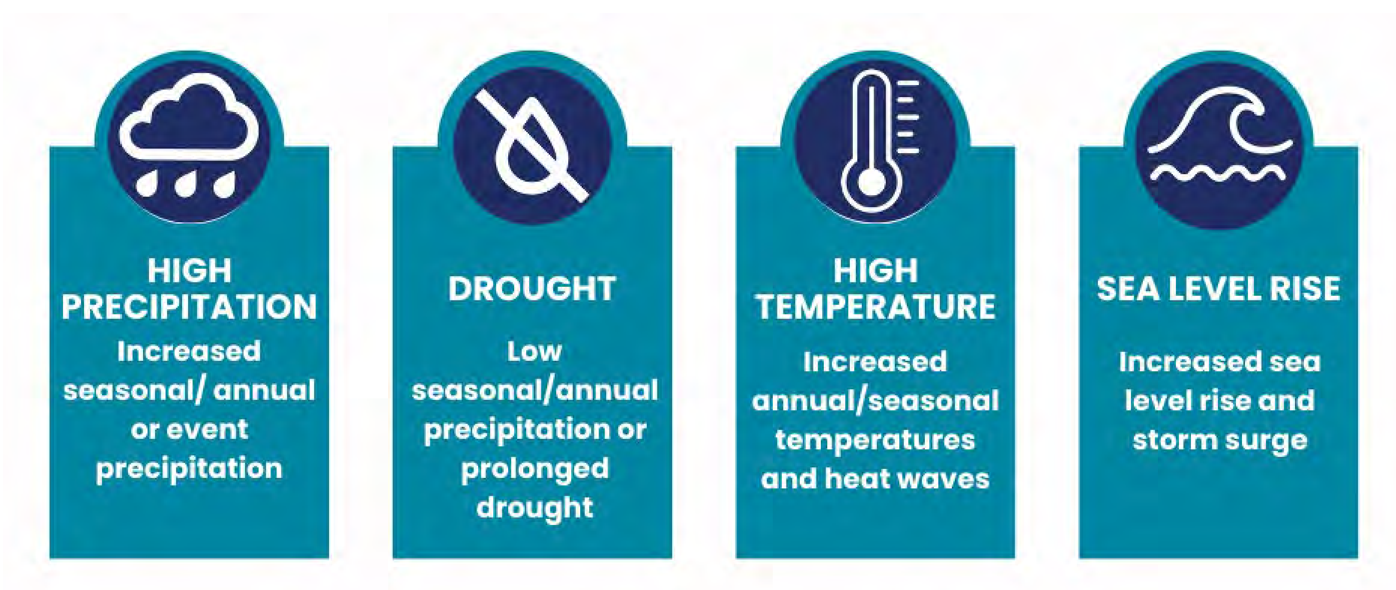

Figure ES-1. Major Stormwater-Related Climate Impacts

Finally, CWP compared state vulnerabilities to readiness and identified recommendations for states to close the gaps. This paper includes state-specific recommendations for improvements to post-construction stormwater standards. Local or regional agencies who wish to evaluate their own stormwater standards can do so using a similar process as this study and the Climate Assessment Tool for Stormwater Standards provided with the report.

This study focused on improving resilience to stormwater-related climate impacts through changes to stormwater standards at the state level. This paper serves as a resource for state and municipal stormwater managers to look up their projected levels of climate vulnerability and readiness and access actionable recommendations for adapting stormwater standards to climate change. It also provides a snapshot of each state's vulnerability and readiness relative to other states to highlight where action is urgently needed.

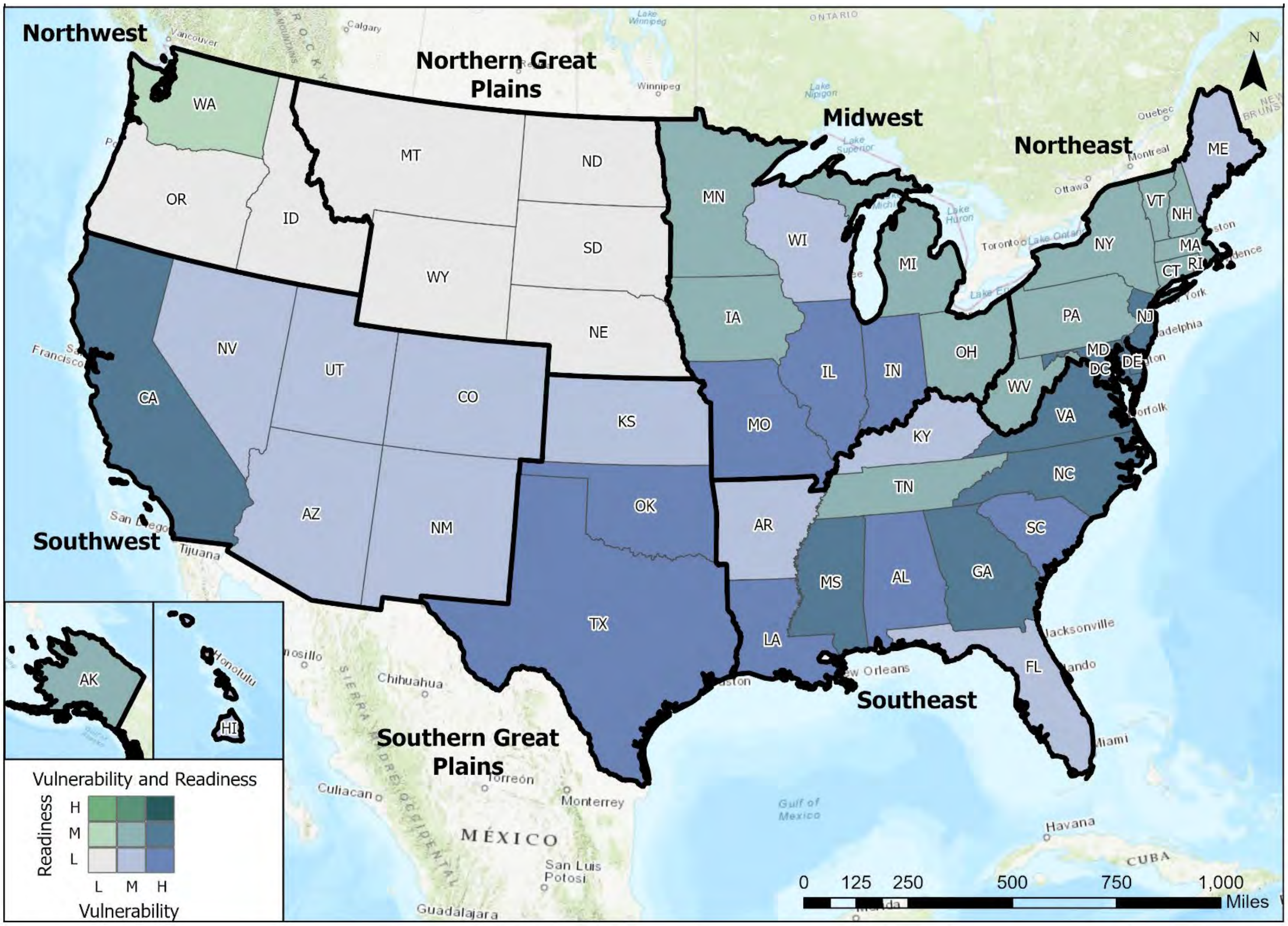

Figure ES-2. State Vulnerability and Readiness Categorization

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Introduction

Traditional stormwater design has assumed that, while rainfall depths and water levels may vary from year to year, overall weather patterns remain constant over time. However, the earth's surface temperature has increased faster since 1970 than in any other 50-year period over at least the last 2000 years, largely due to increased levels of atmospheric carbon dioxide produced by fossil fuel use.[i] This unprecedented rate of change in global climate patterns, referred to as "climate change," is important because our infrastructure—including but certainly not limited to stormwater management systems—is built upon the assumption that the climate is stable.

The expected changes in precipitation patterns, such as more frequent and intense storms, more extreme flooding, more frequent, protracted drought, or sea level rise resulting from climate change have implications for how stormwater runoff is managed across the U.S. The amount of climate change information available to stormwater managers is growing rapidly but much of it remains in the peer-reviewed literature or in quantitative databases that are often difficult for non-experts to access and apply. There is also uncertainty about the extent to which climate will change, and when. As a result, incorporating climate information into stormwater management is a challenge for many communities.

Engineering and design guidance on managing the quantity and quality of stormwater runoff from development sites varies across the country. In many areas, these rules are established by post-construction stormwater standards and best management practice (BMP) design manuals developed by states under the National Pollutant Discharge Elimination System (NPDES) municipal separate storm sewer system (MS4) program. A growing number of studies identifying proposed design changes and other adaptations are being completed for specific communities or regions, but it is not clear if or how the results of these studies could be enacted in stormwater standards. These studies have not been evaluated on a national scale through the lens of changes to stormwater standards.

A logical first step to adapting stormwater management for climate change is to evaluate the ability of state stormwater management standards to address future climate change conditions. While larger municipalities with individual MS4 permits may be more likely than states to have evaluated the potential impact of climate change and be leading the way on adaptations, the smaller communities typically defer to the state requirements as they may not have the resources to commission climate change-related studies. Therefore, focusing on the state-level standards has the potential to impact a larger footprint and help communities with more limited resources explore options for improved resiliency.

The objective of this study was to review the existing state-level standards governing post-construction stormwater management (quantity and quality) to provide a clearer understanding of the current approaches to climate resiliency. The Center for Watershed Protection (CWP) first reviewed the technical literature to identify: 1) vulnerabilities posed by climate change to effective stormwater management and 2) best stormwater design practices to manage these vulnerabilities. Next, CWP evaluated state-published stormwater standards with respect to each state's specific stormwater vulnerabilities and the degree to which stormwater-related climate adaptations have been incorporated into standards. Finally, vulnerabilities were compared to readiness and recommendations to close the identified gaps provided. The key questions this white paper addresses are:

1. **What are the potential vulnerabilities posed by climate change to effective stormwater BMP performance in different regions of the country?**
2. **To what extent are states incorporating stormwater-related climate adaptations into stormwater design standards?**
3. **How can stormwater standards be modified to increase resilience?**

This white paper summarizes the methods and findings of this research and is written for state and municipal stormwater managers and regulators. It serves as a resource for state and municipal stormwater managers to look up their projected levels of climate vulnerability and readiness and provide actionable recommendations for adapting stormwater standards to climate change. It also provides a snapshot of each state's vulnerability and readiness relative to other states to highlight where action is urgently needed.

Methods

This project began with a review of two chief sources of data on projected climate impacts to identify those most relevant to stormwater BMP function and assign a rating of High, Moderate, or Low to each U.S. region or state for those impacts. CWP also reviewed available data and tools for projecting urban growth in the U.S. and used this information to assign a rating of High, Moderate, or Low to each state that reflects the relative projected increased in developed land over the next 25 years. By overlaying the projected climate impacts and developed land increase, CWP categorized each state's vulnerability to stormwater-related climate impacts as High, Medium, or Low.

Next, CWP reviewed the technical literature with a primary focus on national or regional synthesis papers that present strategies for adapting stormwater management to climate change. From this review, a menu of stormwater adaptations was compiled for each major climate impact. CWP then evaluated state-published post-construction stormwater standards to assign scores that reflect the degree to which these standards are up to date and based on the best available science as well as the extent to which stormwater-related climate adaptations have been incorporated into standards with respect to each state's specific stormwater-related climate vulnerabilities. The scores were used to categorize the overall readiness of each state to adapt their stormwater standards to expected climate impacts. Categorization of results into vulnerability and readiness was a qualitative exercise that rated states relative to each other.

Finally, state vulnerabilities were compared to readiness and recommendations to close the gaps were identified. This included state-specific recommendations for improvements to stormwater standards as well as more general guidance for both states and regional or local agencies on using the results of this study to increase resilience. A full description of this study's methods is available in Appendix A.

Potential Vulnerability to Stormwater Impacts of Climate Change by Region

Observed and projected changes to climate conditions vary by region. While the impacts of these climate changes can be wide-reaching, affecting habitat, coastal systems, and communities, this report focuses more narrowly on effects of climate change that: 1) directly impact the function of stormwater BMPs or 2) can be directly or indirectly mitigated by changes to stormwater BMP design (Figure 1).

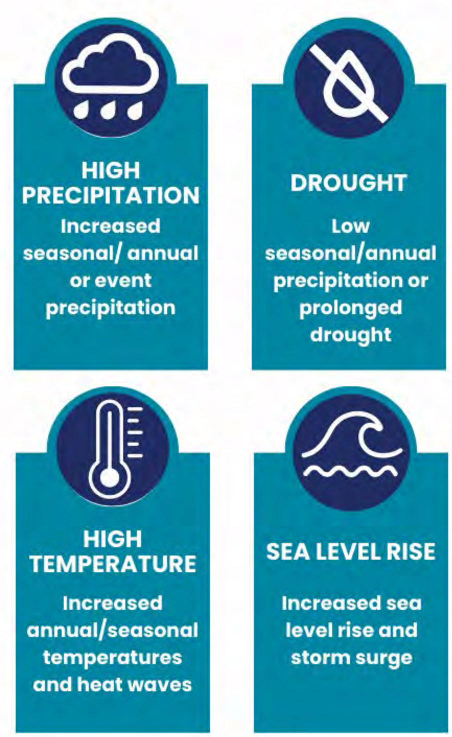
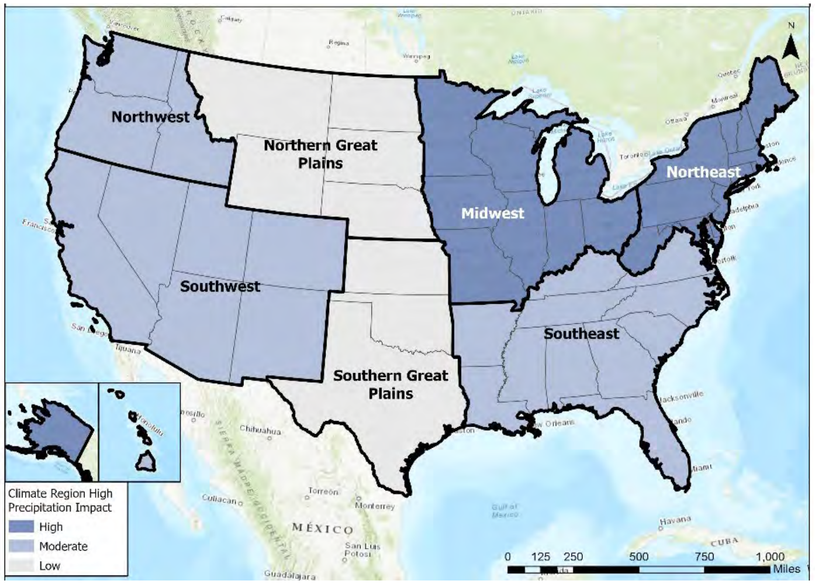


Figure 1. Major Stormwater-Related Climate Impacts

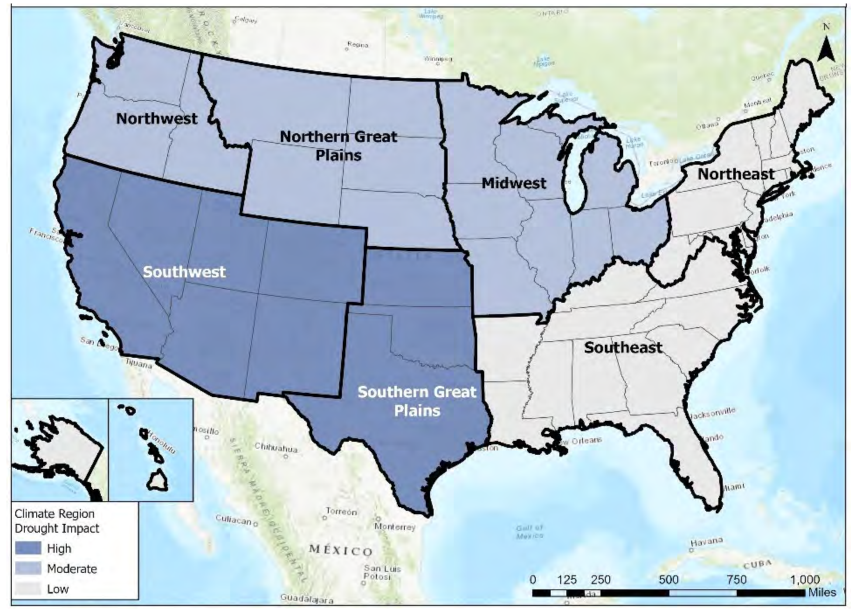
Table 1 summarizes how these climate change impacts are relevant to stormwater management. The information in Table 1 draws primarily on climate indicators from two sources: the Fourth National Climate Assessment[ii] and the EPA's Climate Change Indicators in the United States website. These climate-related stormwater impacts were mapped to the U.S. climate regions used in the National Climate Assessment (or, in the case of sea level rise, in each state) and assigned a value of High, Moderate, or Low based on interpretation of the data described in Appendix A. Figure 2 (A-D) illustrates the extent to which these major climate impacts are occurring or are expected within each U.S. region and state.

TABLE 1. STORMWATER-RELATED CLIMATE IMPACTS

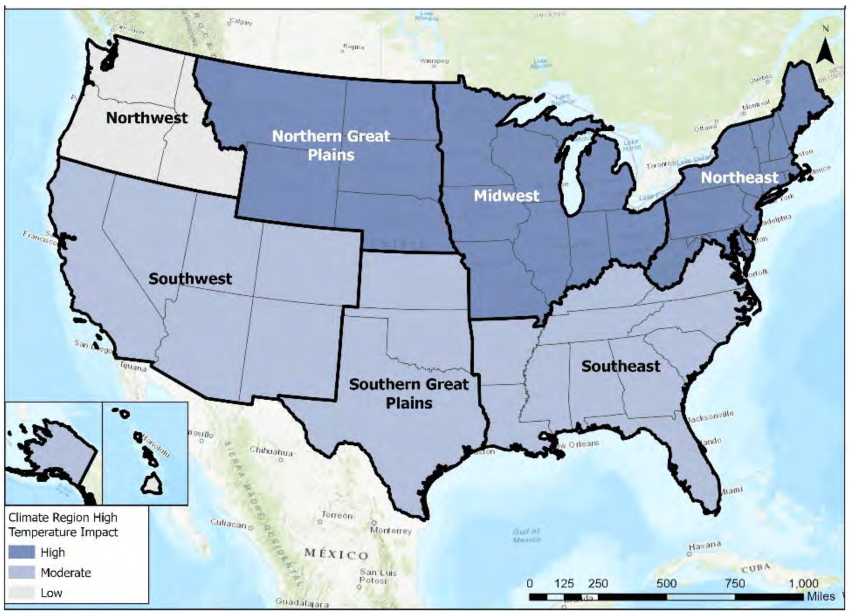
CLIMATE IMPACT	SPECIFIC EFFECTS ON STORMWATER MANAGEMENT
HIGH PRECIPITATION	• Increase in size and frequency of extreme storms fundamentally affects stormwater infrastructure design • Prolonged/more frequent rainfall leads to wetter soils affecting infiltration rates • Plant stress/mortality due to inundation in areas not previously considered wet • Increased river and localized flooding • Increased erosion due to high flows and flooding • Associated increased sediment and other pollutant loads
DROUGHT	• Affects performance of BMPs that incorporate vegetation due to plant stress/mortality • Stormwater BMPs can be used to harvest stormwater for re-use in times of drought • Prolonged drought affects soil structure in surface soils, resulting in soil compaction and decreased permeability • The combination of decreased plant cover and compromised soil structure in the drainage area results in increased sedimentation during periods of rainfall • Decreased precipitation affects in-stream flows and stream ecology
HIGH TEMPERATURE	• Plant species that thrive in a given region may shift as temperatures increase • Increased evapotranspiration and soil temperature can contribute to soil compaction and decreased permeability affecting BMP soil media's ability to store water between storm events • Higher temperatures present human health risks, and stormwater solutions that incorporate trees and other vegetation, or use lighter-colored materials present opportunities to mitigate these impacts • Increased temperatures may affect the longevity of some BMP components such as permeable pavement sealants • As temperatures increase, less of the annual precipitation occurs as snowfall • Downstream resources shift away from cold-water species as temperatures increase
SEA LEVEL RISE	• Partially or fully submerged outfalls lead to inundation of the storm sewer network, creating prolonged tailwater conditions • Sea level rise can increase groundwater elevation, limiting use of certain BMPs • Saltwater intrusion has detrimental impacts to BMP vegetation and soil media • Flood events may result in periodic inundation by salt water • Sea level rise leads to an expansion of the floodplain over time.



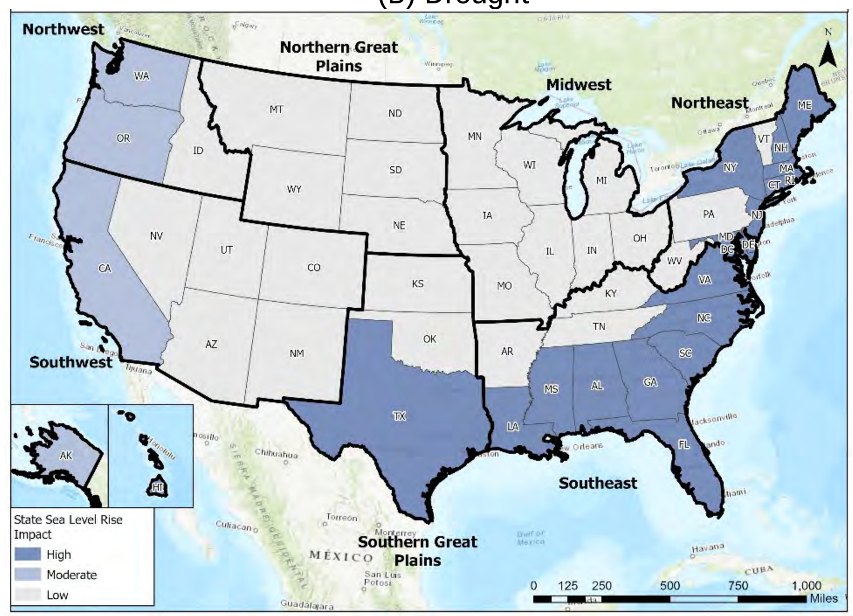
(A) High Precipitation



(B) Drought



(C) High Temperature



(D) Sea Level Rise

Figure 2. Projected Climate Change Impacts of (A) High Precipitation, (B) Drought, (C) High Temperature, and (D) Sea Level Rise for the U.S. by Region (A-C) and State (D)

These expected climate impacts are of considerable concern in locations where significant urban growth is anticipated. The loss of natural vegetation, soil disturbance, changes to hydrology, and addition of impervious surfaces associated with land development are well-known to cause erosion, flooding, water pollution, degradation of aquatic habitat, and a host of other impacts[iii,iv,v] that will be exacerbated by the effects of increased precipitation. Similarly, in regions where drought is the main concern, population growth and the associated increase in water demand will intensify the problem. Arid regions face unique challenges without simple solutions due to competing demands for water use; for example, water conservation efforts have many benefits but can have unintended impacts on habitats that have become dependent on urban runoff.

In low-lying coastal regions, flat topography, tidal influence, and saltwater intrusion present major challenges with adequately managing stormwater runoff, while sea level rise combined with urban expansion will increase risks for people, property, and infrastructure[vi]. To better assess the overall vulnerability of each state to stormwater-related climate impacts, CWP compiled data on expected urban growth to provide another lens through which to view the projected climate impacts.

Figure 3 shows the projected change in the percentage of developed land in each state from 2020-2050. With the exception of Alaska and Hawaii, these data are derived from the EPA's Integrated Climate and Land Use Scenario tool, which is based on population projections and migration using social, economic, demographic, and climate factors. Appendix A provides a description of how this map was generated.

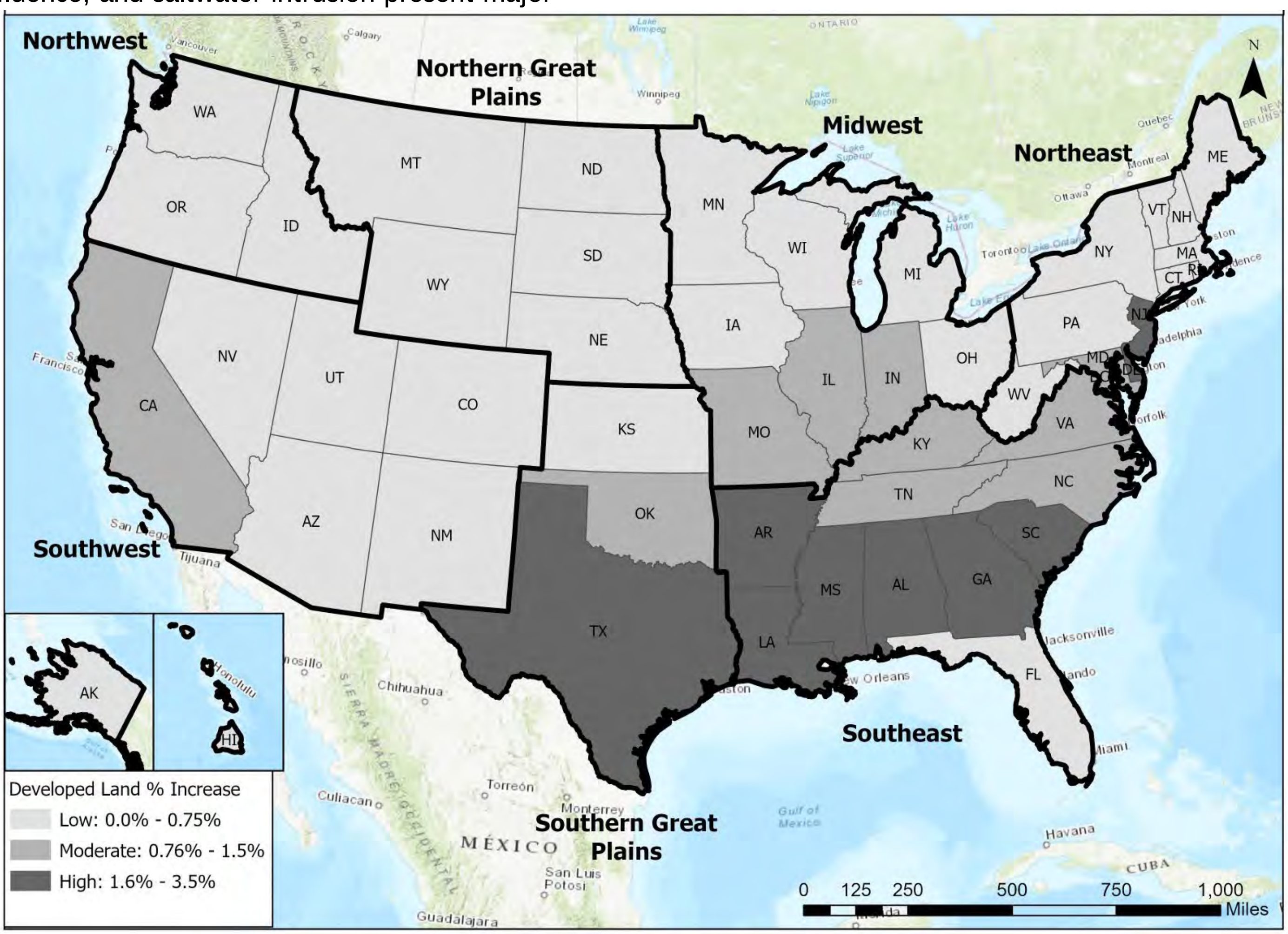


Figure 3. Projected Increase in Developed Land in the U.S. by State, 2020-2050

Using the above information on projected climate impacts and urban growth, CWP categorized each state based on its overall **vulnerability** to stormwater-related climate impacts. The categorization is as follows:

1. **High Vulnerability:** Includes states with High expected impacts for High Precipitation, Drought, or Sea Level Rise[1], AND Moderate or High projected increase in developed land.
2. **Medium Vulnerability:** Includes states with High expected climate impacts (precipitation or sea level rise only) AND Low projected increase in developed land as well as states with Low to Moderate expected climate impacts (precipitation or sea level rise only) AND Moderate to High projected increase in developed land.
3. **Low Vulnerability:** Includes states with Moderate or Low expected climate impacts (precipitation or sea level rise only) AND Low projected increase in developed land.

Figure 4 presents the results of the vulnerability categorization for each state.

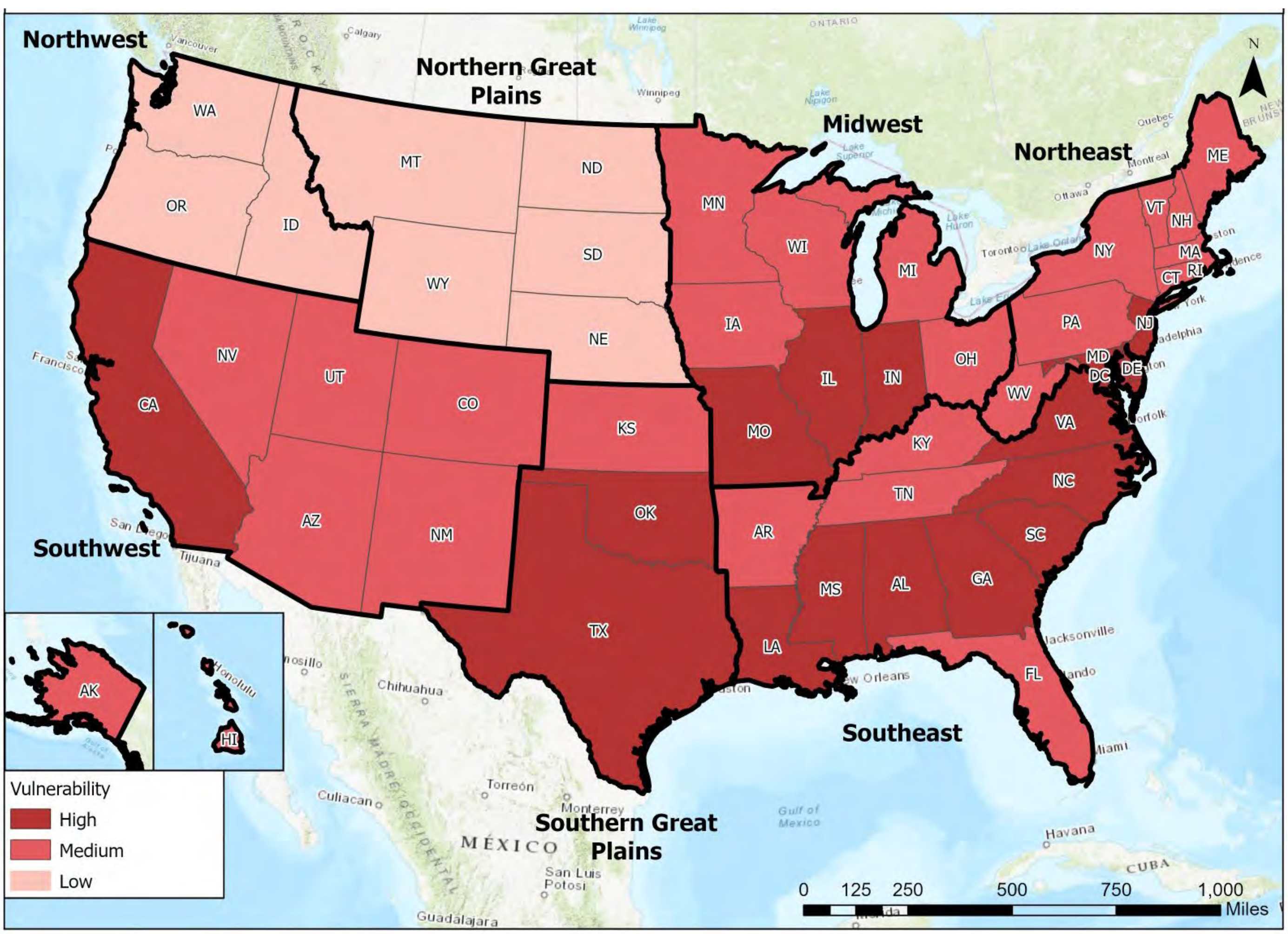


Figure 4. State Vulnerability to Stormwater-Related Climate Impacts

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[1] High Temperature was not included as a factor in the vulnerability categorization because it is indirectly related to stormwater management.

Menu of Stormwater Adaptations to Address Climate Impacts

CWP compiled and reviewed 30 recent articles and reports—primarily synthesis papers—identifying proposed stormwater BMP adaptations to manage the expected climate impacts. The major categories of stormwater BMPs for which these adaptations are relevant include detention/retention, infiltration, filtering, open channels, rainwater harvesting/water reuse, and site design. Figure 5 illustrates a typology of adaptation options identified through this literature review, while Tables 2-5 present a detailed matrix of adaptations for each major climate impact. Appendix A provides more detail on the literature review.

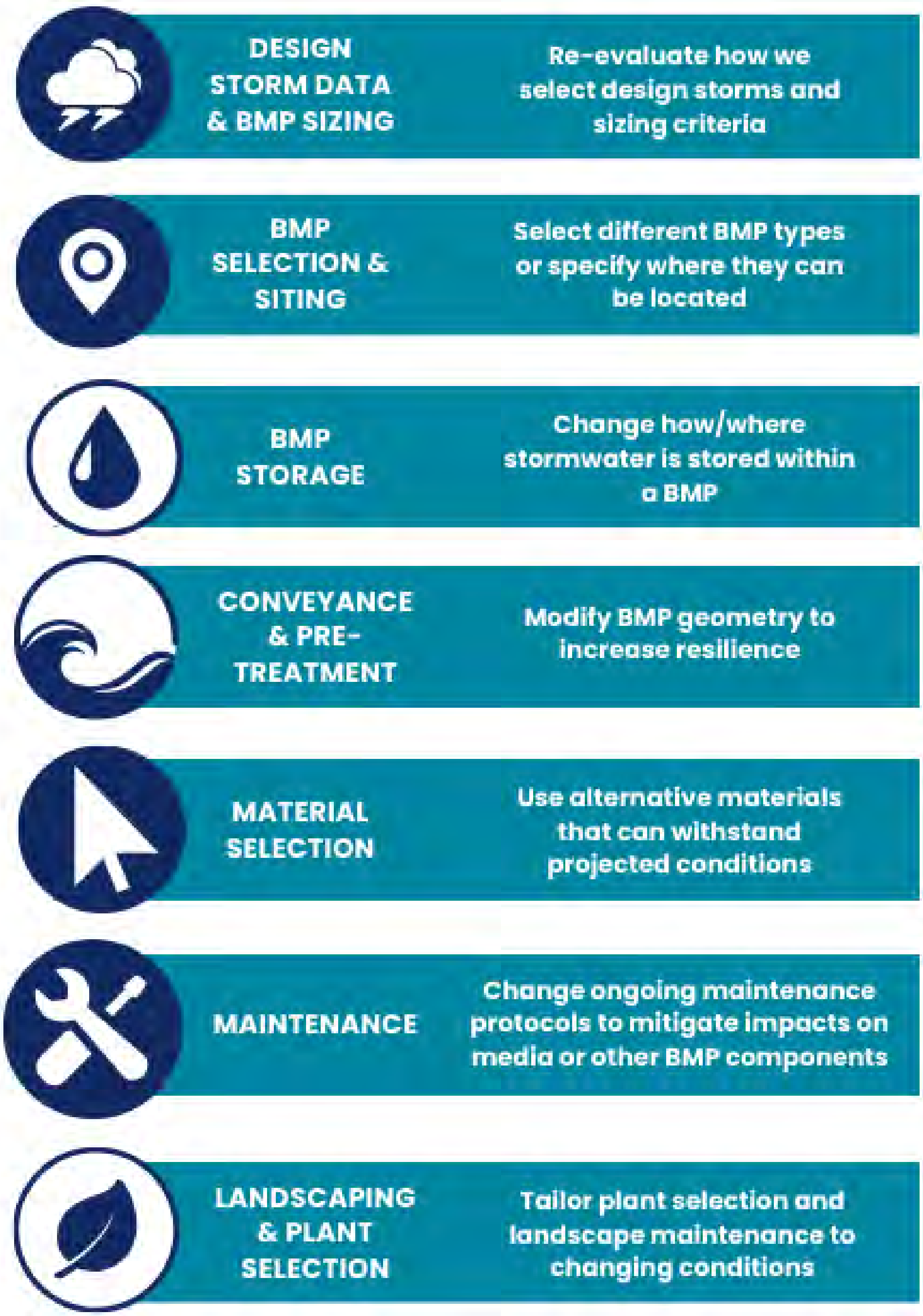

Figure 5. Typology of Stormwater Adaptations to Climate Change

TABLE 2. STORMWATER BMP ADAPTATIONS FOR HIGH PRECIPITATION	
ADAPTATION TYPE	**POSSIBLE ADAPTATION(S)**
DESIGN STORM DATA & BMP SIZING	• Use climate projections to select quantity and quality storm events/ volumes. • Overcontrol quantity storms (e.g., reduce peak by 20% or match to a smaller pre-developed storm). • Incorporate continuous modeling to set capture targets for quantity control. • Incorporate downstream channel protection and runoff reduction standards. • Set water quality sizing standards based on short-duration storm events (e.g., the 5-year, 1-hour storm). • Incorporate modeling to determine required BMP volumes for water quality or runoff reduction, incorporating climate-projected changes. • Consider downstream hydrology when establishing water quality and quantity targets (e.g., water quality or flooding potential).
BMP SELECTION & SITING	• Incentivize or encourage the use of Green Infrastructure. • Promote natural areas and tree conservation. • Provide a right-of-way or buffer for large storm events during large or extreme storms. • Consider expanding floodplains when recommending site design practices and BMP locations.
BMP STORAGE	• Provide storage in ponding above filtering systems to accommodate high intensity storm events. • Encourage the use of continuous monitoring and adaptive control systems (e.g. "Smart BMPs") to maximize storage capacity and control outflows. • Include designs that include sub-surface flood storage in ultra-urban environments or small sites.
STORMWATER CONVEYANCE & PRE-TREATMENT	• Design conveyance structures such as inlets and flow-diversion measures to convey a flashy water quality or retention storm event. • Be conservative in design of conveyance measures by using an upgraded or climate-informed conveyance storm. • Provide supplemental freeboard to accommodate flashy storms. • Provide detention in pre-treatment or at practice inlets.
MATERIAL SELECTION	• Incorporate filter media enhancements that promote long-term permeability, such as biochar.
MAINTENANCE	• Provide detailed maintenance guidance that includes maintenance inspection checklists. • Provide guidance on how to adapt maintenance measures to more frequent erosive events or BMP bypass. • Provide guidance on how to modify the BMP design or type to accommodate changing climate conditions.
LANDSCAPING & PLANT SELECTION	• Identify plants that are tolerant of frequent inundation and saturated soils/anaerobic conditions.

TABLE 3. STORMWATER BMP ADAPTATIONS FOR DROUGHT	
ADAPTATION TYPE	**POSSIBLE ADAPTATION(S)**
DESIGN STORM DATA & BMP SIZING	• Consider downstream hydrology and ecology when establishing water quality targets (i.e., require enhanced runoff reduction or water quality treatment to protect temperature-sensitive species such as trout). • Establish a specific requirement for rainwater harvesting
BMP SELECTION & SITING	• Limit or prohibit BMPs with a permanent pool of water such as wet ponds and stormwater wetlands.
BMP STORAGE	• Encourage the use of smart BMP technologies.
STORMWATER CONVEYANCE & PRE-TREATMENT	• Provide and encourage the use of an “upturned elbow” design for filters. This feature forces water to reman longer in the bottom of the cell, creating a saturated internal water storage zone which promotes runoff reduction, enhances exfiltration, provides water to plants during dry conditions, and creates anerobic conditions to increase nitrogen removal through denitrification.[vii]
MATERIAL SELECTION	• Incorporate filter media enhancements that promote water retention between storms, such as biochar or moisture-retaining polymers
MAINTENANCE	• Provide detailed maintenance guidance, informed by observed changes rather than scheduled maintenance activities. • Provide guidance on how to adapt maintenance measures to increased erosion in the drainage area. • Provide guidance on how to modify the BMP design or type to accommodate changing climate conditions. • Conduct an analysis to determine if a water source is needed to establish and maintain BMPs.
LANDSCAPING & PLANT SELECTION	• Identify plants that are tolerant to prolonged-drought conditions and fire resistance.

TABLE 4. STORMWATER BMP ADAPTATIONS FOR HIGH TEMPERATURE	
ADAPTATION TYPE	**POSSIBLE ADAPTATION(S)**
DESIGN STORM DATA & BMP SIZING	• Consider downstream hydrology and ecology when establishing water quality targets (i.e., require enhanced runoff reduction or water quality treatment to protect temperature-sensitive species such as trout).
BMP SELECTION & SITING	• Incentivize or encourage the use of Green Infrastructure. • Promote natural areas and tree conservation.
MATERIAL SELECTION	• Incorporate filter media enhancements that promote water retention between storms, such as biochar or moisture-retaining polymers. • Select materials that are resistant to higher temperatures. • Select materials that are reflective (i.e., using lighter colors)
MAINTENANCE	• Provide detailed maintenance guidance, informed by observed changes rather than scheduled maintenance activities. • Provide guidance on how to adapt maintenance measures to changing vegetation. • Provide guidance on how to modify the BMP design or type to accommodate changing climate conditions.
LANDSCAPING & PLANT SELECTION	• Identify plants that are tolerant to high temperatures and are fire-resistant. • Include plants that provide shade/cooling. • Include plants and encourage use of “bumping up” to a warmer hardiness zone.

TABLE 5. STORMWATER BMP ADAPTATIONS FOR SEA LEVEL RISE	
ADAPTATION TYPE	**POSSIBLE ADAPTATION(S)**
DESIGN STORM DATA & BMP SIZING	• Establish different sizing standards for runoff quantity in coastal versus non-coastal regions of a state.
BMP SELECTION & SITING	• Incentivize or encourage the use of Green Infrastructure. • Promote natural areas and tree conservation. • Consider expanding floodplains, rising groundwater, and rising sea level when recommending site design practices and BMP locations. • Incorporate a reserve area outside of infiltration BMPs to accommodate future sea level rise and potential BMP conversion.
STORMWATER CONVEYANCE & PRE-TREATMENT	• Provide and encourage the use of an "upturned elbow" design for filters. • Elevate outfall inverts to projected high tide. • Use check valves to prevent backups in outlet pipes. • Incorporate features such as an elbow joint at outlets to allow discharge at a higher elevation in the future. • Oversize pipes or open channels to account for lost storage from rising sea levels.
MATERIAL SELECTION	• Select corrosion-resistant materials.
MAINTENANCE	• Provide detailed maintenance guidance, informed by observed changes rather than scheduled maintenance activities. • Provide guidance on how to adapt maintenance measures to changing sea levels. • Provide guidance on how to modify the BMP design or type to accommodate changing conditions.
LANDSCAPING & PLANT SELECTION	• Identify plants that are tolerant of frequent inundation, saturated soils/anaerobic conditions, and salt.

Status of State Post-Construction Stormwater Standards

Based on the typology of stormwater adaptation options, CWP developed a questionnaire and scoring sheet intended to evaluate the extent to which existing state post-construction stormwater standards for managing runoff quantity and quality incorporate these adaptations and, in particular, if the standards have been modified to address the climate impacts most important in that state's region. Appendix B provides the questionnaire and scoring system which includes 55 questions organized around the categories in Table 6.

TABLE 6. CATEGORIES OF QUESTIONS FOR STORMWATER STANDARDS REVIEW

CATEGORY	DESCRIPTION
MODERN STORMWATER MANUAL	This category of questions evaluates the extent to which the standards are consistent with modern stormwater management principles, irrespective of climate change. Examples include promoting use of Green Infrastructure and Low Impact Development, inclusion of BMP design specifications, and incorporating storm event data by reference so that the most recent data can be used without updating the standards.
HIGH PRECIPITATION	This category of questions evaluates the extent to which the standards have been adapted to address increasing precipitation, including increased frequency of extreme storms, increased storm intensity or "flashiness," and increased annual or seasonal precipitation. Example adaptations include selection of appropriate storm events, and design modifications to safely convey and treat flashier storm events and reduce erosive velocities throughout the BMP and project site.
DROUGHT	This category of questions evaluates the extent to which the standards have been adapted to address reduced precipitation such as drought conditions. Examples include selection of BMPs that are suitable for drier conditions as well as methods that result in greater water conservation.
HIGH TEMPERATURE	This category of questions evaluates the extent to which the standards have been adapted to address increased temperatures. Example adaptations include selection of BMPs, materials, and plant communities that can withstand high temperatures and incentivizing the incorporation of elements that reduce air temperatures, such as vegetation and light-colored materials.
SEA LEVEL RISE	This category of questions evaluates the extent to which the standards have been adapted to sea level rise. Examples include use of salt tolerant plants and modifiable outlet pipes, planning for future BMP conversion, and incorporating a reserve or future expansion area to provide additional buffer from the coast.

Using the questionnaire and scoring sheet, CWP completed the review for all 50 states and the District of Columbia using publicly-available stormwater standards. Depending on each state's regulatory source for the standard, this involved review of a statewide regulation, MS4 permit, the Construction General Permit, stormwater BMP manual, and/or other non-regulatory document. The documents reviewed are listed in Appendix A.

While designed to be repeatable, the review is somewhat subjective, so CWP reviewers coordinated closely during the review process for consistency. The review was completed in late 2023 and does not reflect any changes that were underway or made after that time period. Key findings of this review are presented below while Appendix C provides an overview of the results for each state.

MODERN STORMWATER MANUAL

An important part of CWP's work has included helping states adopt the most up-to-date stormwater regulations and design criteria based on the best available science. During the review, CWP found that many states lack some key elements of a "modern" manual. Table 7 provides a list of these elements and Figure 6 presents the state scores (with ten being the best possible score) for the Modern Manual component of the stormwater standards review.

TABLE 7. ELEMENTS OF A "MODERN" STORMWATER MANUAL	
• Updated relatively recently (< 5 years) • Underlying stormwater regulation applies to most development occurring within a state • Provides list of acceptable BMPs to meet water quality standards • Provides guidance for designing and selecting BMPs, or references resources that provide this guidance • Requires the use of Green Infrastructure BMPs • Uses recent data to characterize design storms • Encourages developers to consider site design features that minimize impervious cover, expand natural vegetation, and protect critical natural areas • Requires pretreatment and safe conveyance to stormwater BMPs	• Identifies specific stormwater quantity, quality, and runoff reduction design volumes or goals • Water quality criteria are at least equivalent to retaining the 90th percentile storm event • Requirements vary based on hydrology or water quality of downstream resources • Includes numeric specifications for storage within BMPs and for components such as filter media • Includes a landscaping list that identifies where specific plants are the most appropriate within BMP design • Requires ongoing maintenance and includes a checklist or other mechanism to adapt BMPs as they age

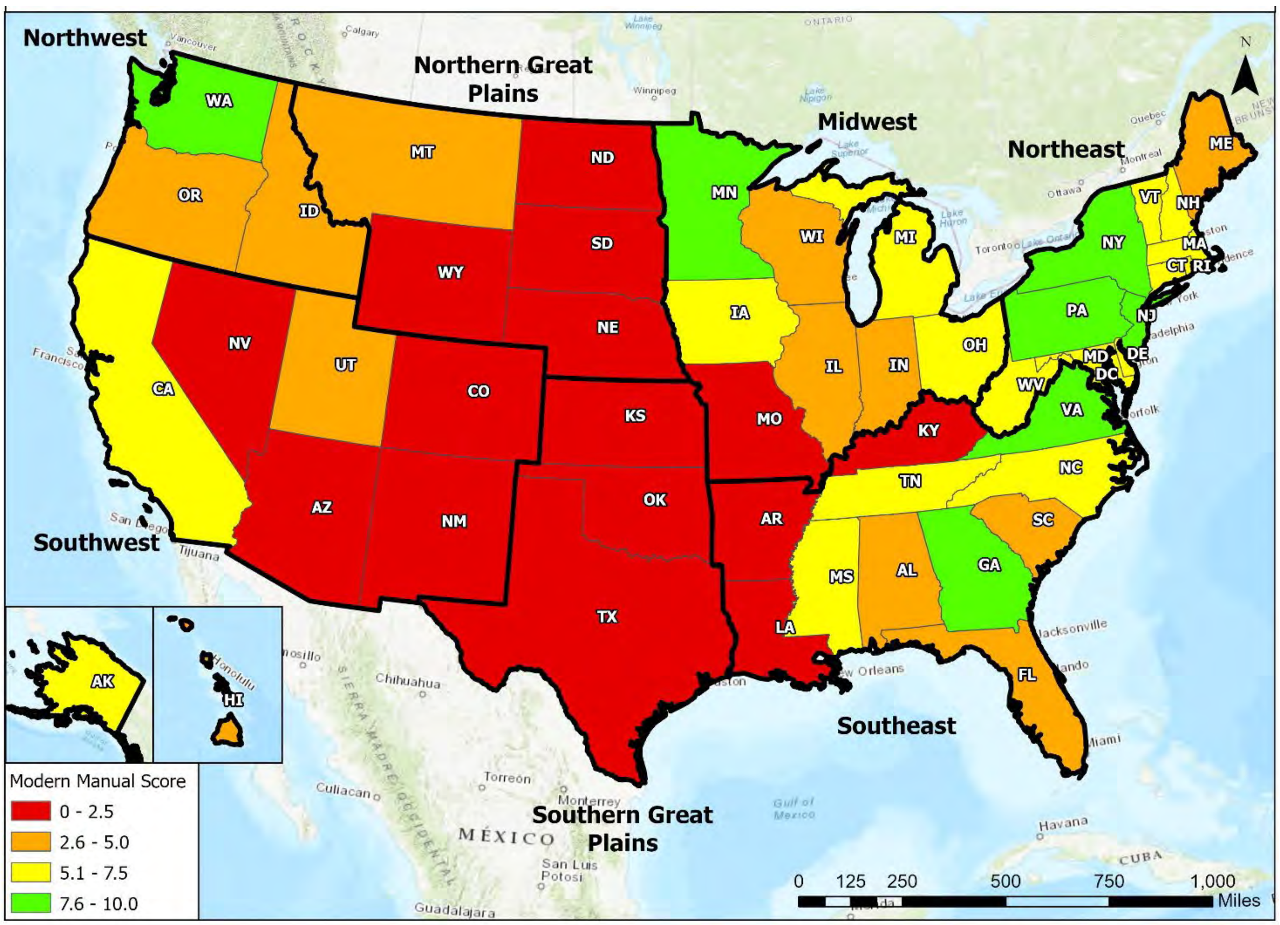

Figure 6. Status of "Modern Manual" Elements in Stormwater Standards

CWP's review found that most states apply their post-construction stormwater standards within regulated MS4s. Only 17 states apply their standards statewide, providing protection to additional water resources from development impacts. The review also found that 17 states do not maintain a stormwater BMP manual (or set of regional manuals) to guide post-construction stormwater design in the state. Of the states that do publish manuals, only 16 have been updated in the past five years (although updates are in progress in several states) and therefore do not include many of the elements listed in Table 7 which are considered by CWP to be baseline elements of effective stormwater management. As an example, Table 8 compares and contrasts the content of BMP specifications for bioretention from a recently updated manual versus one that is over 15 years old. While most stormwater manuals do include BMP specifications, sufficient detail is needed so the specifications are easy for designers to understand and consistently apply. North Carolina and the District of Columbia are two examples of BMP specifications that fit this description.

Over half of states promote or require the use of Low Impact Development Environmental Site Design to minimize runoff and watershed impacts. The goal of Low Impact Development (also referred to as Environmental Site Design or Better Site Design) is to emulate the natural hydrology as much as possible by preserving natural areas, reducing impervious cover, and treating stormwater close to its source. Use of these principles minimizes runoff from development sites, which can result in lower costs for stormwater management. A handful of states, such as Maryland and Connecticut, require MS4s to review and update their codes and ordinances to remove barriers to the use of Low Impact Development as a condition of the stormwater permit.

Almost half of states promote or require the use of Green Infrastructure BMPs to store, infiltrate, or evapotranspire stormwater. By keeping stormwater on site, these practices effectively treat and reduce runoff, significantly improving protection for downstream waterbodies. Most of these same states also include numeric runoff reduction requirements in their stormwater standards.

TABLE 8. COMPARISON OF BIORETENTION SPECIFICATIONS FOR TWO STATE MANUALS

Element	Manual 1	Manual 2
Year Updated	2020	2007
Summary	35 pages long; includes 5 design variants and 2 design configurations	9 pages long; no design variants
Definition	Included	Included
Standard Details	Included	Included but is outdated
Feasibility Criteria	Included	Included
Conveyance Criteria	Included	Not included
Pretreatment Criteria	Included	Very minimal
Design Criteria	Included; provides very detailed filter media criteria and recommended material specifications	Included but minimal detail
Landscaping Criteria	Included	Very minimal; does not include species lists
Construction Sequence	Included	Not included
Maintenance Criteria	Included	Included
Stormwater Compliance Calculations	Included	Not included

High Precipitation

Figure 7 presents the state scores (with ten being the best possible score) for the High Precipitation component of the stormwater standards review. The map illustrates the extent to which the state standards have been adapted to address increasing precipitation, relative to the expected impact of High Precipitation in each region.

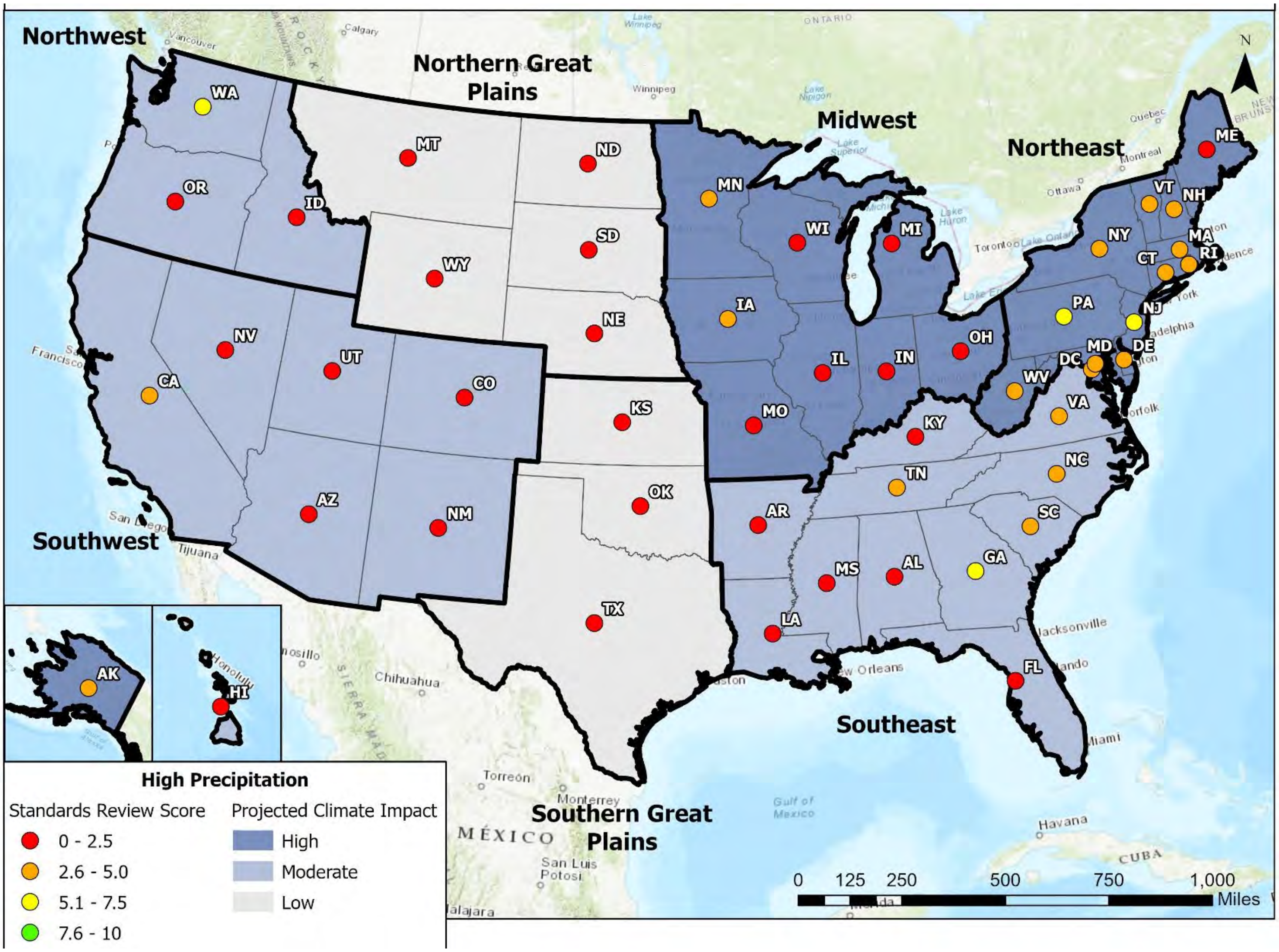

Figure 7. State Adaptation of Stormwater Standards for High Precipitation

Example Adaptation: Climate-Ready Storms in New Jersey

New Jersey's standards are among the very few in the U.S. to specifically incorporate projected storms for water quantity control and to identify a high intensity, short-duration storm for water quality treatment. Both features, combined with the conservative design goals for water quantity control, help to address two primary concerns of climate change: 1) the increased depth of large, infrequent storm events (i.e., water quantity storms) and 2) the increased frequency of short-duration, high-intensity storms (i.e., water quality storms). Table 9 highlights some details of New Jersey's standards.

TABLE 9. WATER QUALITY AND QUANTITY CONTROL IN NEW JERSEY		
Element	**Water Quality Storm**	**Water Quantity Storms**
Storm Depth/ Frequency	1.5 inches	2-, 10- and 100-year, 24-hour storms for both current and projected conditions
Storm Source/ Characteristics	2-hour storm duration Peak intensity of 3.2 inches/hour	Initial storm depths from NOAA Precipitation Frequency Data Server (NOAA Atlas 14) County-specific adjustment factors are applied to account for climate change
Management Goals	Size stormwater BMPs and conveyances to accommodate this storm	For both projected and current storms: a) Manage stormwater so that discharges over the entire runoff hydrograph are lower than those for the pre-developed condition, or b) Match peak discharges for all storms and conduct a downstream analysis for current and watershed build-out conditions to ensure that no downstream damage occurs, or c) Reduce peak discharges for the 2-, 10- and 100-year events by 50%, 25% and 20%, respectively
What Makes the Standard Climate-Ready?	Addresses high-intensity, short-duration, small storm events projected to occur more frequently	Includes forecasted storms Requires designers to go beyond matching post-developed to pre-developed peak discharges, providing a factor of safety to address climate changes

Example Adaptation: Conservative Bioretention Sizing in North Carolina

Bioretention is one of the most common Green Infrastructure practices, incorporating a soil media filter bed, with area for stormwater ponding. The North Carolina standards are unique in that the entire water quality volume must be stored above the filter media, while also limiting the ponding depth to 12 inches (Figure 8). By contrast, other state manuals do not set a minimum for storage volume in ponding, and/or require only a portion of the design storm to be stored in ponding, with the remainder stored in the pores of the filter media. This more traditional bioretention sizing is less conservative, as it assumes that runoff fills up the filter media almost immediately as the storm occurs, and the entire storage volume of the bioretention area will be utilized over the course of a storm event.

By requiring that the entire water quality volume is stored above the filter bed, the North Carolina standard provides resiliency to two potential impacts of climate change. First, it ensures that the entire water quality volume will be captured and treated, even during very intense storms that are anticipated with climate change. Second, it provides greater ability to capture and treat back-to-back storms (e.g., on consecutive days) that may occur more frequently with climate change.

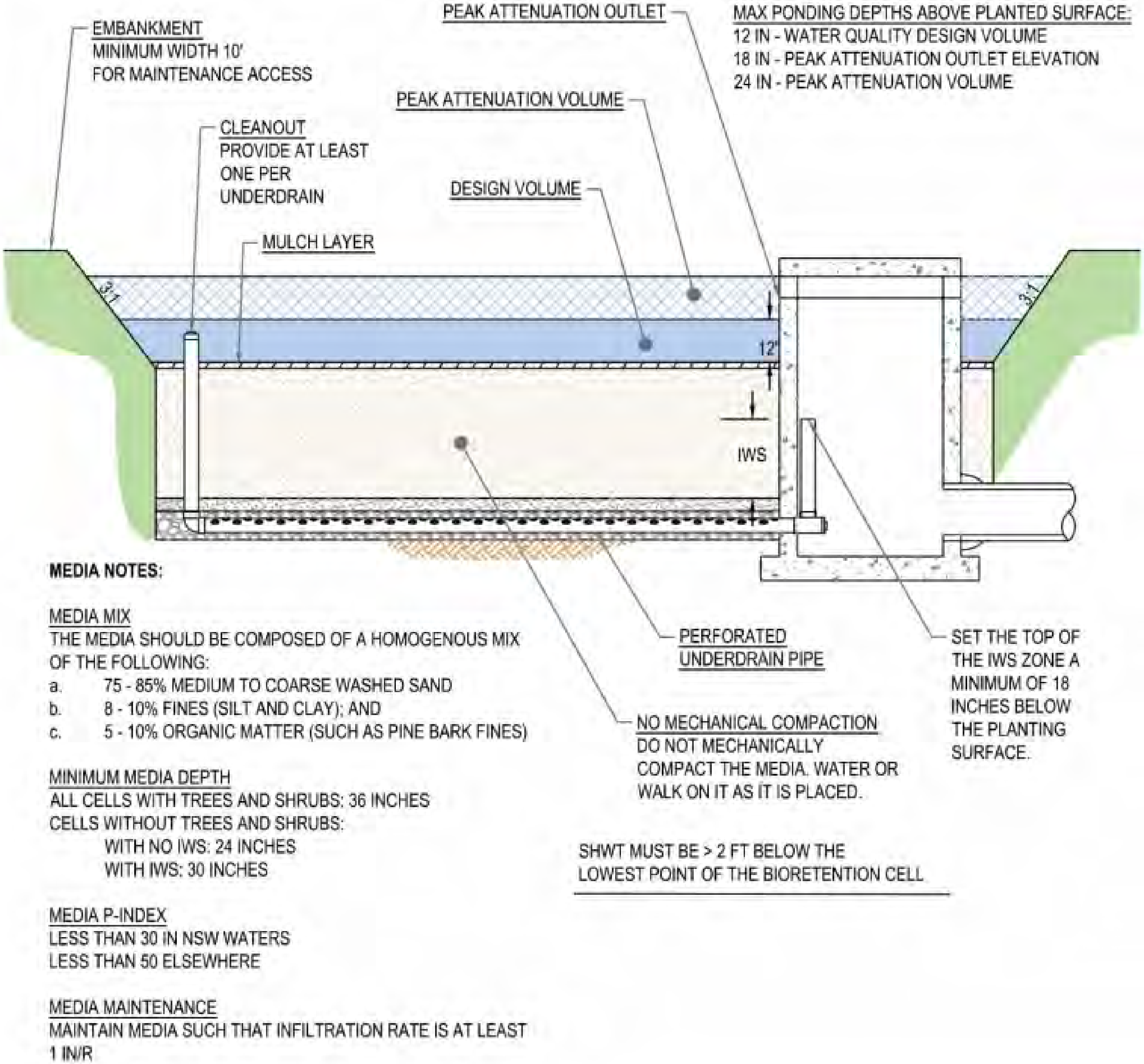

Figure 8. Bioretention Cross-Section from the North Carolina Stormwater Design Manual

Drought

Figure 9 presents the state scores (with ten being the best possible score) for the Drought component of the stormwater standards review. The map illustrates the extent to which the state standards have been adapted to address reduced precipitation, relative to the expected impact of Drought in each region.

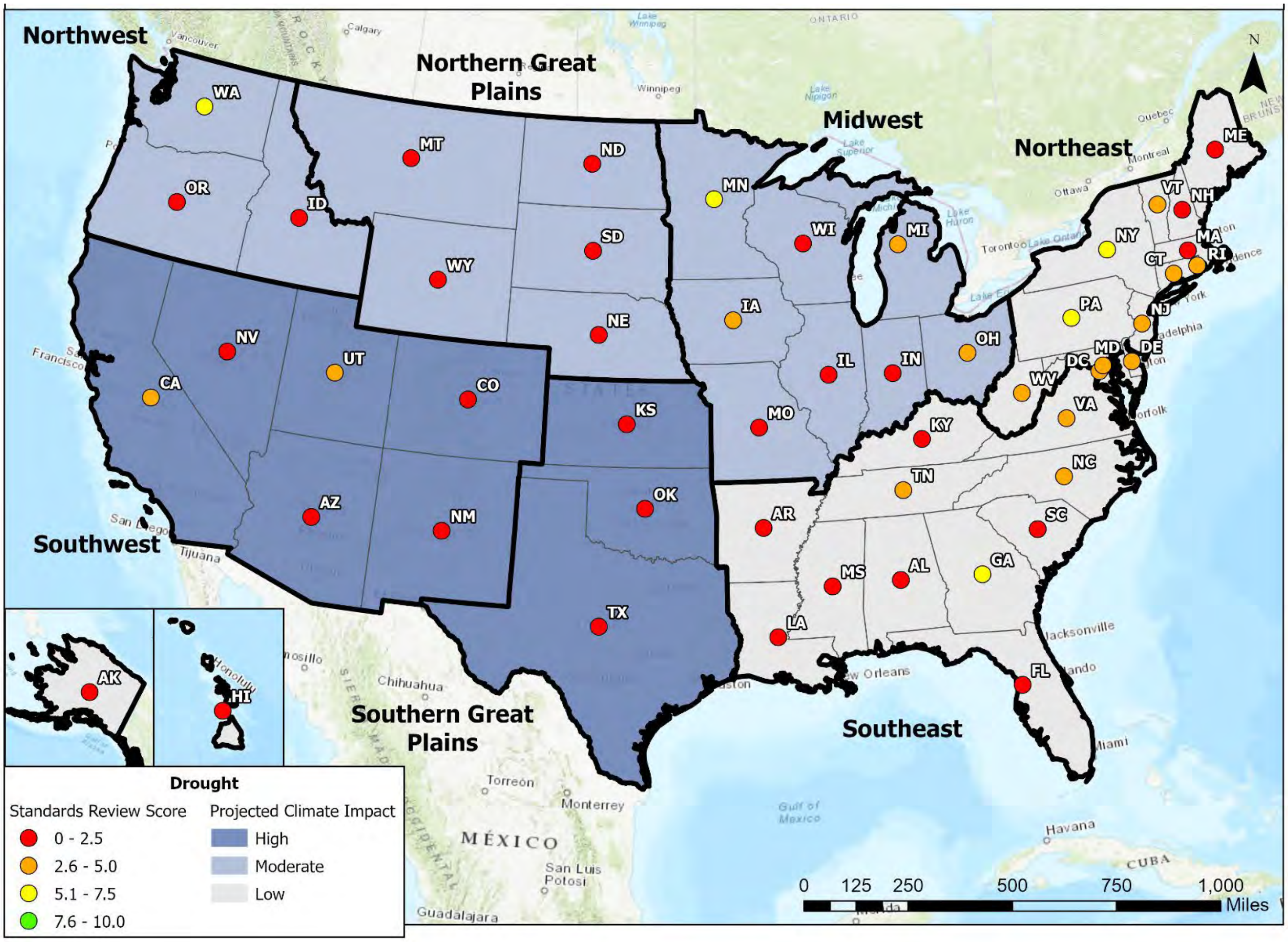

Figure 9. State Adaptation of Stormwater Standards for Drought

High Temperature

Figure 10 presents the state scores (with ten being the best possible score) for the High Temperature component of the stormwater standards review.

The map illustrates the extent to which the state standards have been adapted to address increasing temperatures, relative to the expected impact of High Temperature in each region.

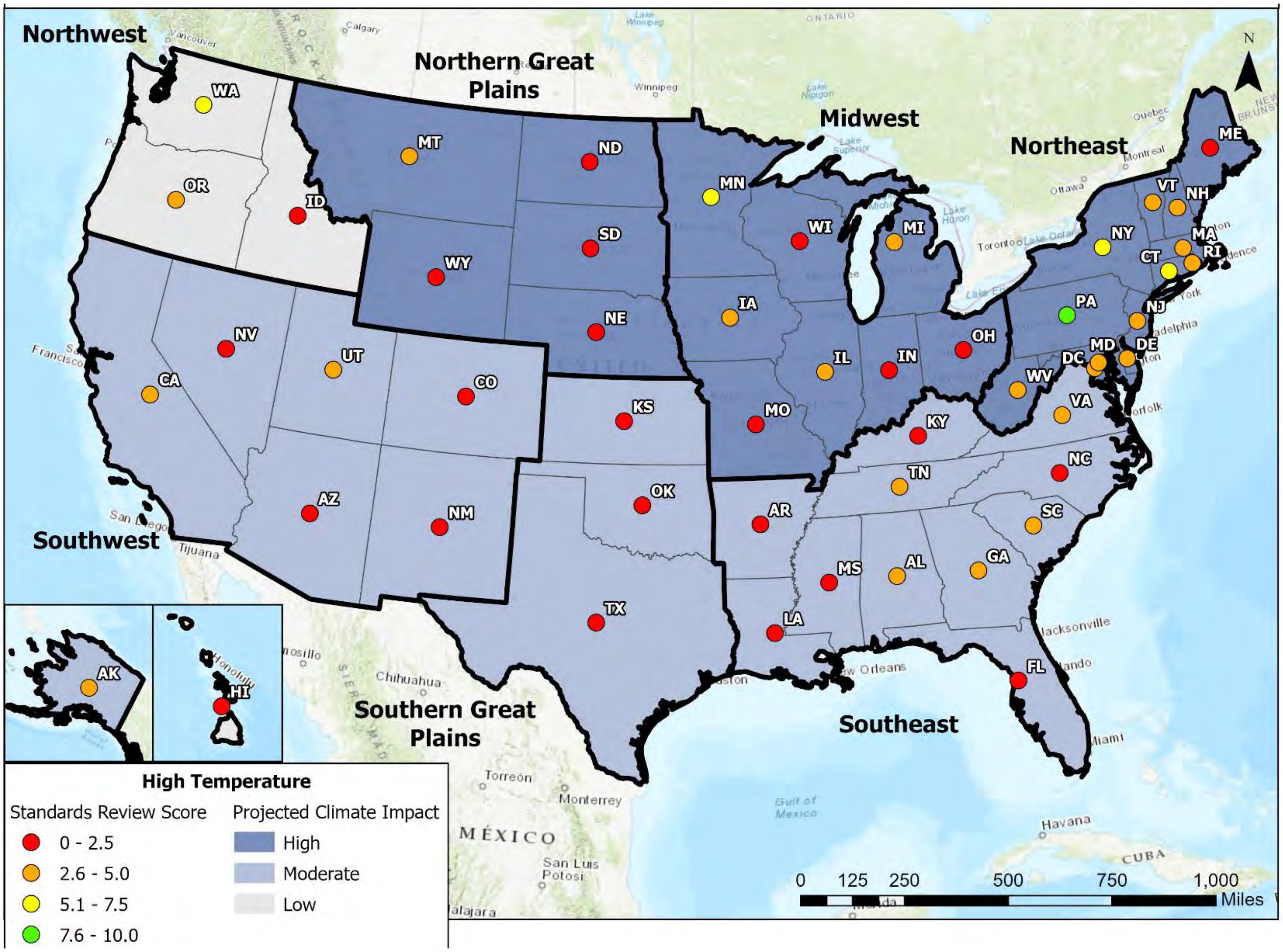

Figure 10. State Adaptation of Stormwater Standards for High Temperature

Sea Level Rise

Figure 11 presents the state scores (with ten being the best possible score) for the Sea Level Rise component of the stormwater standards review.

The map illustrates the extent to which the state standards have been adapted to address sea level rise, relative to the expected impact of Sea Level Rise in each state.

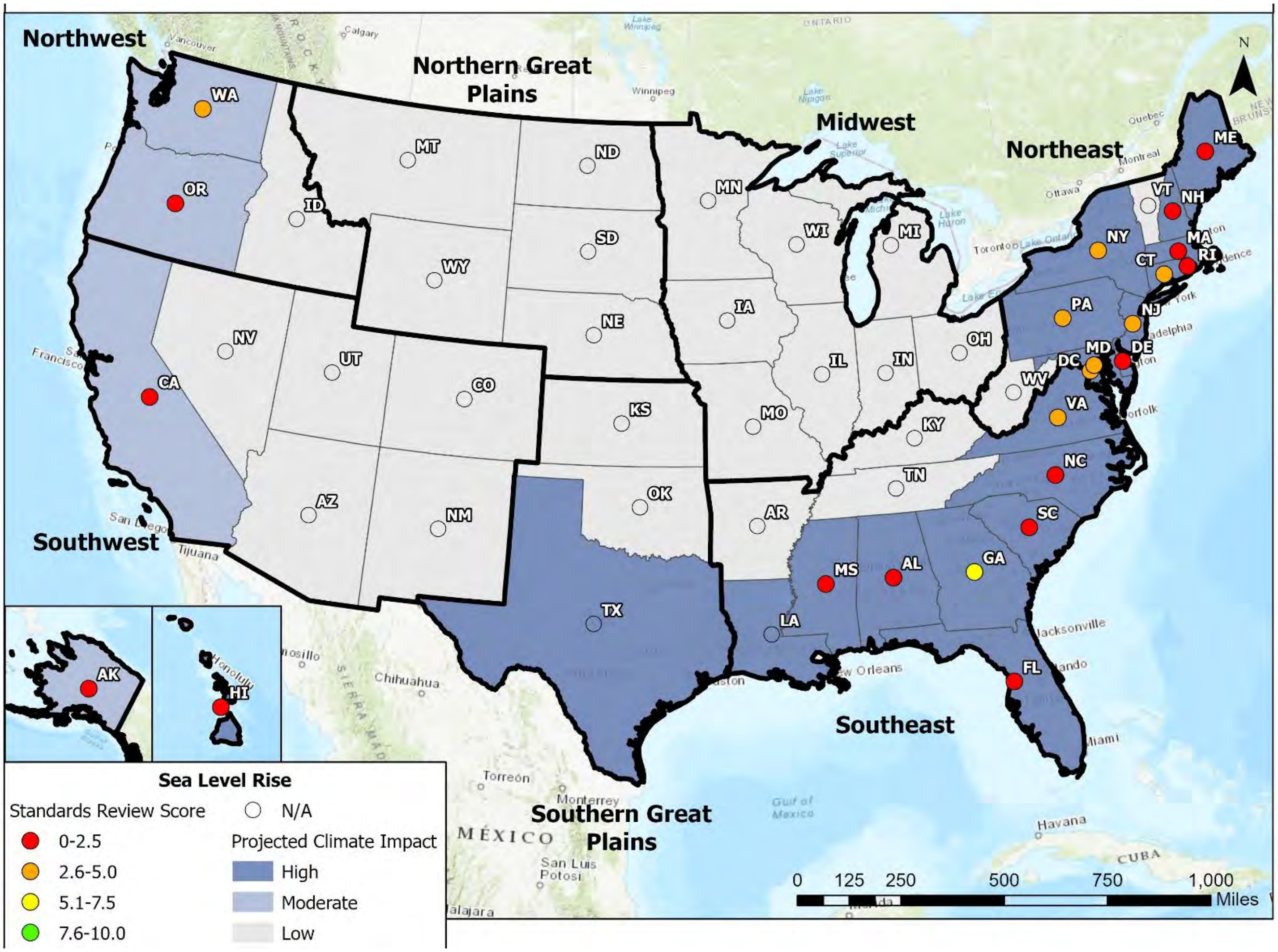

Figure 11. State Adaptation of Stormwater Standards for Sea Level Rise

Example Adaptation: Designing for Sea Level Rise in Georgia

Georgia's stormwater manual, which had the highest score in the Sea Level Rise category, includes a section that acknowledges the importance of considering future climate conditions in stormwater design. With respect to Sea Level Rise, the manual states that coastal communities are uniquely vulnerable to the effects of tidal flooding and sea level rise, citing inundation in low-lying areas caused by submerged outfalls, and corrosion in pipes as possible impacts. Solutions to these issues, which are only minimally addressed in the manual, include 1) raising the elevation of at-risk structures and proposed outfalls above the expected water level, and 2) using gates and pumps to prevent backups through the stormwater system at low-lying outfalls. Georgia's manual refers to NOAA's Adapting to Climate Change: A Planning Guide for State Coastal Managers[viii] for recommended strategies to regularly evaluate the system and build resilience to anticipated future conditions.

State Readiness

To characterize the overall **readiness** of each state to adapt their stormwater standards to expected climate impacts, CWP categorized them based on the following factors:

1. **High Readiness:** Includes states with scores > 7.5 for Modern Manual and all relevant climate indicators.[2]
2. **Medium Readiness:** Includes states with Modern Manual scores between 5.1 and 7.5 as well as states with Modern Manual scores > 7.5 but ≤ 7.5 for one or more relevant climate indicator.
3. **Low Readiness:** Includes all states with Modern Manual scores ≤ 5.

Figure 12 shows the results of this categorization. While no states had High Readiness, Georgia and Pennsylvania came closest to a High ranking because their standards included most of the elements of a Modern Manual as well as specific references to climate change. However, both states lacked the incorporation of projected future storm data and techniques to enhance conveyance, pretreatment, and storage capacity for water quality or runoff reduction to increase BMP resilience. States with low Modern Manual scores tended to also have low scores on all relevant climate indicators.

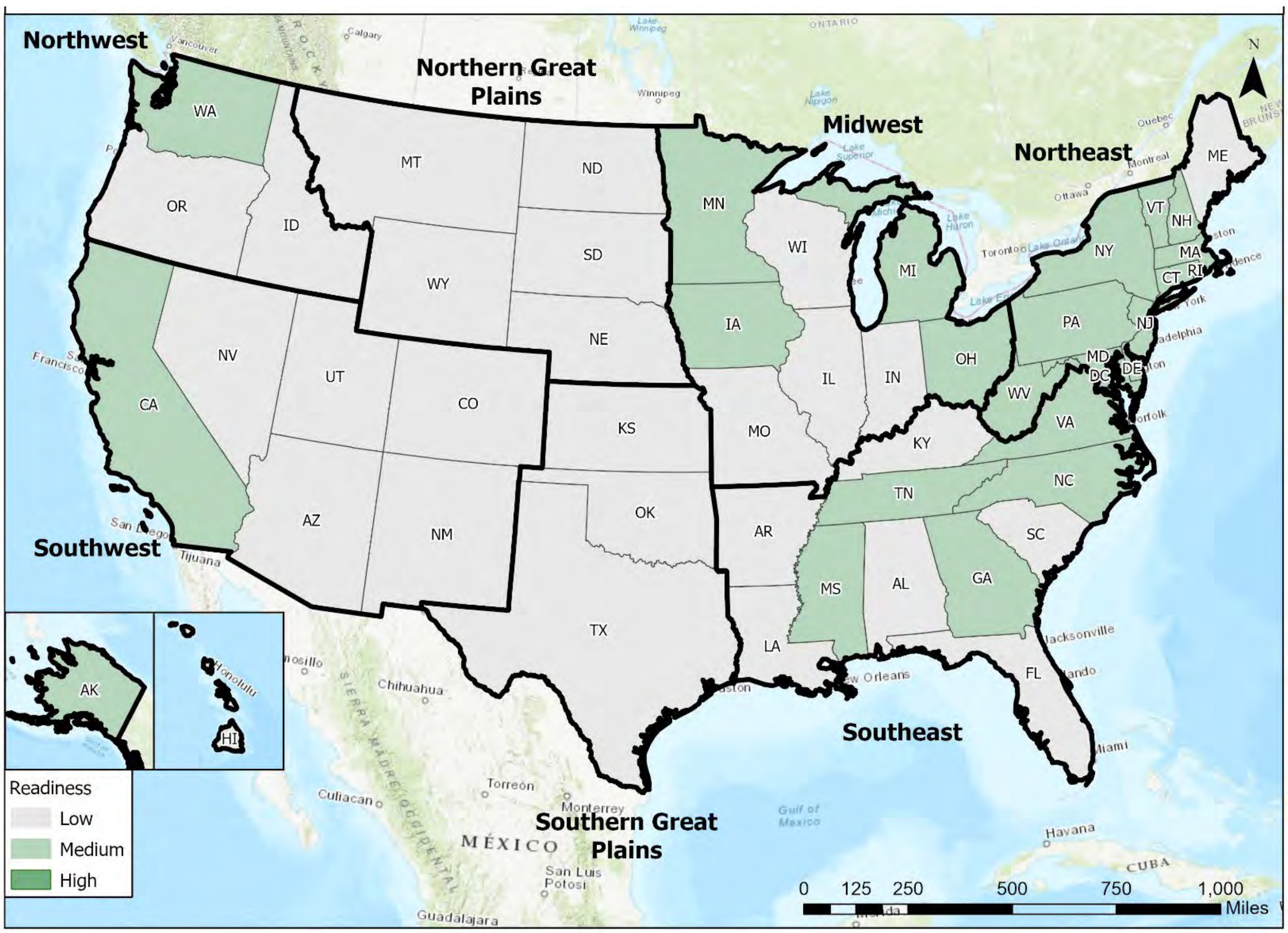

Figure 12. State Readiness to Adapt Stormwater Standards to Climate Change

[2] Relevant climate indicators include those with High or Moderate expected impact for that state.

Recommendations to Increase Resilience

Each state's **vulnerability** to climate impacts and **readiness** to adapt stormwater standards determine the potential impact that making (or not making) revisions can have on heading off future stormwater problems. The level of effort needed to update the standards should be weighed against the potential impact. For example, in states where urban growth is limited to one or two cities that have their own stormwater standards, making changes at the state level may not be as useful, and the focus should be on strengthening municipal post-construction stormwater standards. Figure 13 shows each state's combined vulnerability and readiness ranking, while Figure 14 summarizes approaches for different levels of readiness and vulnerability. The remainder of this section provides additional detail on how state and local stormwater agencies can use the results of this study.

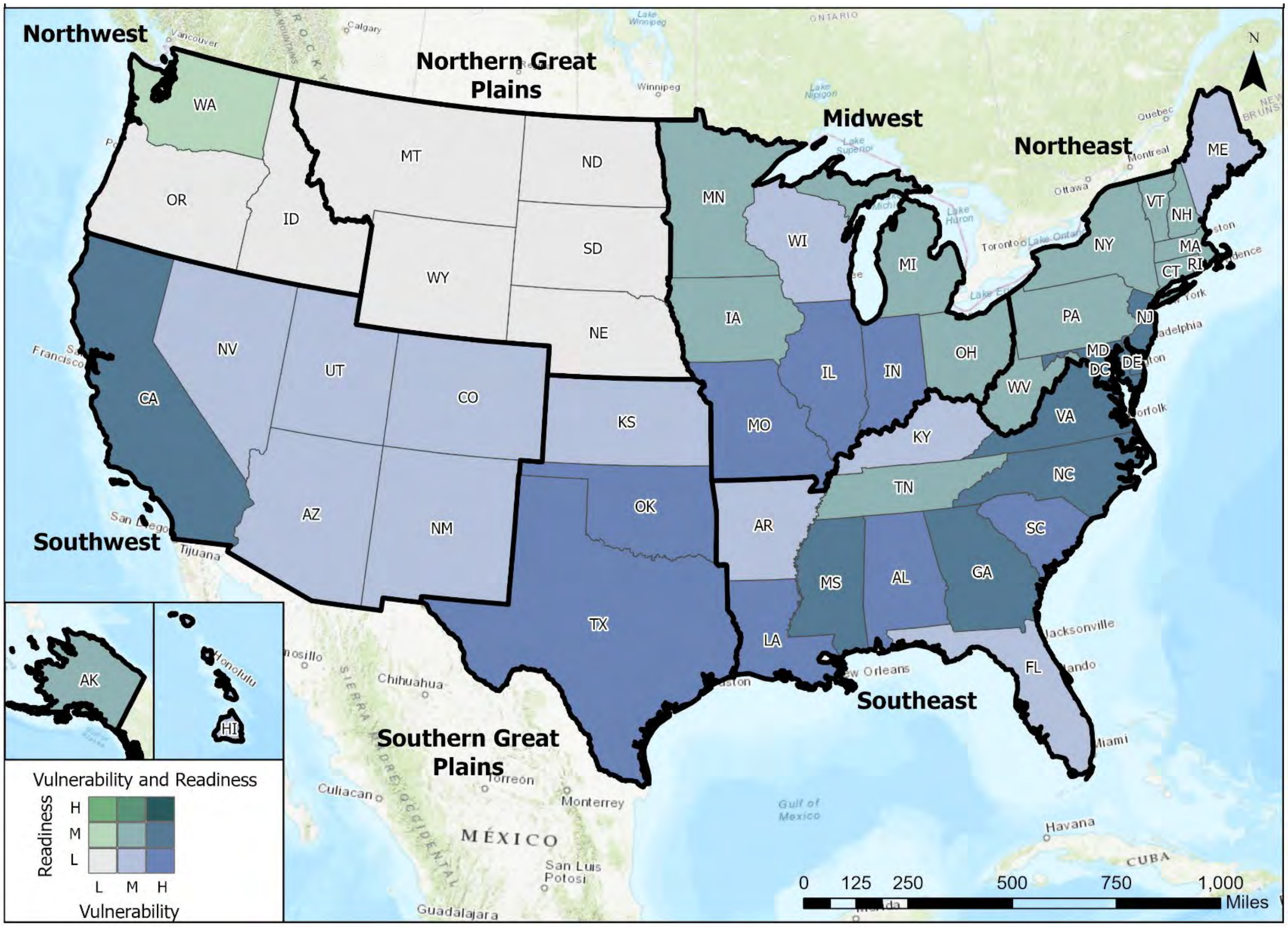

Figure 13. State Vulnerability and Readiness Categorization

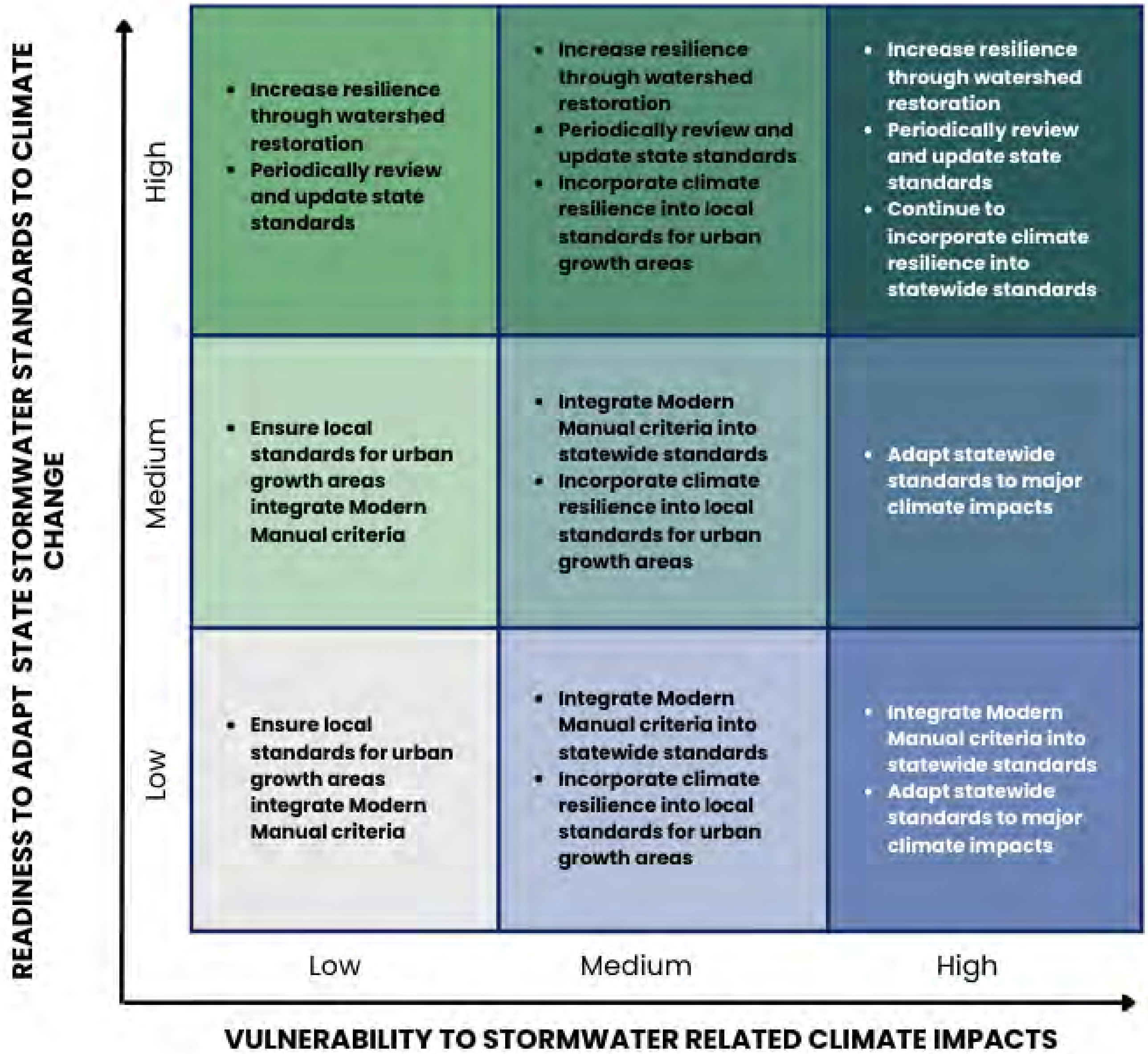

Figure 14. Overall Recommendations

How to Use this Review at the State Level

The potential impact of adapting state post-construction stormwater standards to account for climate change varies from state to state, depending on the number of municipalities that refer to these standards, the applicability of the standards (e.g., statewide vs only within MS4 areas), and how much new urban growth is expected. This study evaluated state-level standards with the idea that improvements can potentially impact a large footprint including the many smaller communities who likely defer to state stormwater standards.

As shown in Figure 14, overall recommendations at the state level vary with vulnerability and readiness. **States with Low readiness** typically have no stormwater manual at all, their standards do not meet Modern Manual criteria, and/or regulations do not apply to most of the development occurring within the state. Recommendations for these states vary depending on the state's vulnerability. Where vulnerability is Low, expected development is likely to be concentrated around specific metropolitan regions. For these states, ensuring that new development within these urban growth areas is governed by strong Modern Manual standards is a priority. Where vulnerability is High, statewide stormwater standards offer the greatest opportunity to address climate and development-related stormwater impacts. In these states, revising statewide standards to address Modern Manual criteria is a high priority, followed by adapting the standards to address the major climate impacts expected in the region. Recommended approaches for states with Medium vulnerability include a combination of those suggested for Low and High vulnerability states.

Most **states with Medium readiness** have strong stormwater standards, but are limited in addressing future climate issues. Where vulnerability is High, the focus should be on improving statewide standards to include climate adaptation strategies. Table 10 provides a list of good resources for more detail on specific climate adaptations. States with Low or Medium vulnerability can follow similar approaches to those recommended for Low readiness states.

Although several states had very strong stormwater standards, none met the criteria of **High readiness**. States in this category would have strong statewide standards that also address climate concerns. It is anticipated that states currently in the Medium readiness category could move into the High readiness category by revising their existing standards to address climate change. Once at the High readiness level,
States should develop a plan to periodically revisit climate and stormwater science to keep their standards up to date. In particular, states with Low vulnerability should reassess vulnerability to climate impacts in the future, as new and more accurate regional climate projections become available. States in the High readiness category can focus more effort on improving the resilience of existing developed areas through watershed restoration, to include flood control projects, floodplain management, stormwater retrofits, infrastructure upgrades, habitat restoration, and improvements to monitoring and public warning systems.

Table 10. Resources for Stormwater-Related Climate Adaptation

Resources
Climate Impacts to Restoration Practices (Butcher et al. 2020)
Vulnerability Analysis and Resilient Design Considerations for Stormwater Best Management Practices (Chesapeake Stormwater Network, 2021)
Climate Resilience Resources Guide: Part 1 (Geosyntec Consultants, 2022)
A Synthesis of Climate Change Impacts on Stormwater Management Systems: Designing for Resiliency and Future Challenges (Hathaway et al. 2023)
Linking Stormwater and Climate Change: Retooling for Adaptation (Hirschman et al. 2011).
Vulnerability Analysis and Resilient Design Considerations for Stormwater Best Management Practices (Chesapeake Stormwater Network, 2021)
A Review of Climate Change Effects on Practices for Mitigating Water Quality Impacts (Johnson et al. 2022)
Evaluating the impact of climate change on future bioretention performance across the contiguous United States (Weathers et al. 2023)
Assessment of Climate Change Impacts on Stormwater BMPs and Recommended BMP Design Considerations in Coastal Communities (Horsley Witten Group, Inc., 2015)

Where the above recommendations point toward the need for improvements to stormwater standards at the state level, two products of this study provide a starting point for states to begin working on updates. Appendix C provides individual state profile sheets summarizing the key features of each state's stormwater standards, vulnerability to climate impacts, and readiness to adapt stormwater standards. Each profile sheet provides specific priority recommendations for each state to increase their ability to address stormwater-related climate impacts. Appendix D provides a complete non-prioritized list of recommendations for each state. Detailed results of the review can be requested from this study's authors.

How to Use this Review at the Local Level

Local or regional agencies can use the results of this study along with local data on expected urban growth to determine the extent to which new or improved stormwater standards may be needed for a particular city or metropolitan area. For example, in states with Low or Medium readiness and low expected urban growth across the state, there may be pockets of high expected development around urban centers that are not reflected in the statewide urban growth projection map shown in Figure 3. In these locations, adopting new local standards that incorporate Modern Manual criteria and address climate impacts may be the most effective way to improve the resilience of new developments within those states.

Recognizing that smaller municipalities may face financial or technical challenges, the formation of regional partnerships or other multi-municipal collaborations can be an effective way to increase expertise, secure grant funds, and gain political support for improved stormwater standards. A good example of this scenario is the Kansas City metropolitan region. While overall, Missouri and Kansas are primarily rural with only low to moderate expected growth, the metropolitan region is growing significantly. The Mid-America Regional Council or MARC maintains a Manual of BMPs for Stormwater Quality and is currently undergoing a process to update regional stormwater standards that involves 22 participating local governments. In this situation, having strong regional standards to guide development where most of the growth is happening is a more effective approach to improving stormwater management than updating the state manuals.

The results of this review do not reflect the extent to which city, county, and regional government agencies that maintain their own stormwater standards have adapted these requirements to address climate change. In fact, states with low or moderate readiness scores may be home to cities with very advanced stormwater programs, such as New York City and Boston, who are leading the way on climate adaptation.

Local or regional agencies who wish to evaluate their own stormwater standards can do so using a similar process as this study. We recommend these agencies use local or regional projections of expected urban growth along with the climate impact maps in Figure 2 to assess future vulnerability. The Climate Assessment Tool for Stormwater Standards (CATSS)—a modified version of the review tool used for this project—can then be completed to evaluate how well the community's stormwater standards contains modern manual elements and addresses potential climate impacts. The CATSS provides specific recommendations for improvements based on the results.

This study focused solely on improving resilience to stormwater-related climate impacts through changes to stormwater standards at the state level. At both the state and local levels, strengthening stormwater management for new developments is just one of many strategies needed to improve community resilience to climate impacts. Other approaches such as mapping vulnerable stormwater infrastructure, retrofitting and upgrading stormwater systems, improving resilience through redevelopment, and watershed-based stormwater planning, are also needed.

This paper provides a starting point for state and municipal stormwater regulators and managers at different stages of climate readiness to better account for climate change in post-construction stormwater standards. Future work on this topic by CWP's National Watershed Research Network will drill down to the local level to identify innovative approaches being used by municipalities to increase the resilience of existing developed areas to stormwater-related climate impacts.

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[3] Appendix A contains a full list of references included in the literature review portion of this project.