PACIFIC INSTITUTE

Untapped Potential: An Assessment of Urban Stormwater Runoff Potential in the United States

ADVANCING WATER RESILIENCE THROUGH EFFICIENCY AND REUSE

FEBRUARY 2024

IN PARTNERSHIP WITH 2NDNATURE

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SUGGESTED CITATION

Berhanu, Bruk, Morgan Shimabuku, Shannon Spurlock, Jessica Dery, Heather Cooley, Catherine Riihimaki, Nicole Beck, and Gary Conley. 2024. "Untapped Potential: An Assessment of Urban Stormwater Runoff Potential in the United States" Oakland, Calif.: Pacific Institute.

ABOUT THE PACIFIC INSTITUTE

Founded in 1987, the Pacific Institute is a global water think tank that combines science-based thought leadership with active outreach to influence local, national, and international efforts in developing sustainable water policies. From working with Fortune 500 companies to frontline communities, our mission is to create and advance solutions to the world's most pressing water challenges. Since 2009, the Pacific Institute has also acted as co-secretariat for the CEO Water Mandate, a global commitment platform that mobilizes a critical mass of business leaders to address global water challenges through corporate water stewardship. For more information, visit pacinst.org.

ABOUT 2NDNATURE

2NDNATURE Software Inc. is a pioneering force in geospatial science, dedicated to crafting cutting-edge solutions that empower municipalities, institutions, and corporate landowners to revolutionize their approach to stormwater management. Our mission is to bring peer-reviewed science in accessible map-based formats to inform more resilient land management decisions. With a widespread clientele across the United States, 2NDNATURE goes beyond conventional solutions, providing users with a comprehensive toolkit to understand their stormwater challenges, uncover opportunities, and transform stormwater into a valuable resource. We not only equip our clients to manage stormwater effectively but also enable them to communicate the substantial benefits of their investments with impact. For more information, visit 2ndnaturewater.com.

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Nicole Beck has a doctorate in aquatic chemistry and a career-long mission to bring science to decision-makers. She is motivated to apply her technical knowledge to develop practical science-based tools to inform land management decisions that protect our water resources. Her journey has landed her as the CEO of 2NDNATURE.

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Gary Conley is Chief Scientist at 2NDNATURE, leading a team that supports development of water quality modeling and effectiveness assessment tools that turn data into actionable knowledge. He combines expertise in hydrology, pollution dynamics, and applied math to develop watershed-based tools used by communities throughout the United States, with extensive experience helping local agencies mitigate water quality issues and develop plans to optimize multiple environmental benefits.

ACKNOWLEDGEMENTS

We would like to thank our Project Advisory Group, which provided valuable input on the project conception, results, recommendations, and draft report:

- Katherine Atteberry – Metropolitan North Georgia Water Planning District
- Pinar Balci – Johnson, Mirmiran & Thompson
- Nathan Campeau – Barr Engineering Co.
- Robin DeYoung and Chris Clipper – US Environmental Protection Agency
- Jacques Finlay – University of Minnesota
- Craig Holland – The Nature Conservancy
- Randy Neprash – National Municipal Stormwater Alliance
- Jeff Shoemaker – MSH Associates
- Dave Smith – Water Innovation Services
- Scott Struck – National Renewable Energy Laboratory
- Sri Vedachalam – Corvias Infrastructure Solutions, LLC
- Jennifer Walker – National Wildlife Foundation
- Miriam Hacker – Water Research Foundation

We acknowledge the partnership of the Strategic Communications and Outreach team to launch this work and ensure it reaches key decision-makers, audiences, and other levers of change toward the goal of building a more water resilient world. We specifically acknowledge: Amanda Bielawski, Sumbul Mashhadi, Tiffany Khoury, Robert Jensen, Dana Beigel, and Brendan McLaughlin.

Finally, we would like to thank the BHP Foundation for generously supporting this work.
All conclusions and recommendations represent the views of the authors and not the reviewers or funders.

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Executive Summary

Water is a precious and vital natural resource that is fundamental for human and ecological health and economic prosperity. In communities across the United States, however, water scarcity is a growing risk due in part to natural hydrologic variability, population and economic growth, and the intensifying effects of climate change. Yet, traditional water sources, such as freshwater from rivers and streams and underground aquifers, are increasingly facing peak water limits. These constraints have led water providers to adopt water conservation and efficiency to reduce demand and develop new, alternative water supply strategies, such as reusing treated wastewater and capturing urban stormwater runoff. These strategies can help "close the gap" between existing and anticipated water supply and demand and support long-term water resilience.

Perspectives on stormwater are changing—and it is increasingly viewed as an asset. Stormwater capture projects are being implemented in a growing number of communities to augment and diversify water supplies, as well as reduce flooding and pollution of nearby waterways. When using green infrastructure, stormwater capture projects can also support community greening and mitigate urban heat island effects. Despite growing interest, greater uptake of stormwater capture is hindered by a lack of comprehensive data characterizing the national volumetric potential of stormwater runoff.

This assessment finds that the average annual stormwater runoff potential is 59.5 million acre-feet per year, equivalent to 53,100 million gallons per day.

In this assessment, we quantify the volumetric potential for stormwater runoff in US Census Urban Areas across the entire United States. This assessment finds that the average annual volumetric potential for urban stormwater runoff is 59.5 million acre-feet per year (AFY), or 53,100 million gallons per day (MGD). This volume is equivalent to 93% of the water withdrawals for municipal and industrial uses in 2015, though not all of this runoff is necessarily feasible or desirable to capture. We estimate that 37% of this national volume (21.9 million AFY) is generated just in coastal areas, which presents an opportunity for increased stormwater capture in areas that are less likely to face challenges related to adverse impacts on downstream water rights holders.

We also examine potential uses of stormwater capture across four case examples that highlight opportunities to incorporate stormwater capture as a pathway to achieve water supply planning goals (Texas and North Georgia) and support water supply sustainability and resilience (Arizona and Minnesota). These examples can serve as models for increasing the role of stormwater capture as a water supply and resilience strategy for communities who have not previously considered stormwater capture as a viable alternative or are interested in increasing adoption of stormwater capture projects.

Our findings suggest that stormwater capture can serve an expanded role beyond its current level of implementation in Urban Areas across the United States, but this requires additional efforts by researchers, policymakers and regulatory bodies, and implementers (e.g. utilities, municipalities, landowners) to elevate the role of stormwater capture in the national conversation. Here, we offer recommendations for helping to realize this untapped potential of stormwater capture.

Quantify Regional, State, and Local Stormwater Capture Opportunities. Our results indicate that there are potentially large volumes of stormwater runoff available in urban communities across the United States. The amount of runoff that could be captured to meet local water needs will depend on a host of local factors, including precipitation and development patterns, feasibility of implementing stormwater capture in new development, redevelopment, and/or infrastructure retrofits, storage capacity, and water needs. More detailed assessments are needed at the regional, state, and local levels to determine the extent to which stormwater capture can help to augment and diversify water supplies in each area of interest.

Develop National Guidelines for Stormwater Capture. Few states have regulations that directly address stormwater capture, creating uncertainty and confusion among practitioners and end users. Currently, a poorly defined patchwork of state and local regulations is being applied to the authorization of stormwater capture projects, often on a case-by-case basis. The absence of clear guidelines and/or regulatory frameworks for stormwater capture has inhibited development and implementation of stormwater capture projects in many states.

Pursue Regional Approaches and Interagency Coordination and Collaboration. Stormwater capture projects can be cost-prohibitive for a single municipality or water provider to pursue by themselves. Collaboration between entities within a watershed can provide additional capacity and funding that facilitate stormwater project financing and implementation. Taking a regional view of water supply development opportunities can help utilities and agencies take advantage of economies of scope and scale to address opportunities and challenges more effectively.

Expand Applications of Stormwater for Additional Uses. Stormwater, like any other alternative water supply, can be sufficiently treated to provide a fit-for-purpose water supply. In several areas, however, restrictions on use of captured stormwater that exclude indoor end-uses, such as toilet flushing or industrial use, can limit the efficacy of stormwater capture as a water supply. Increasing the amount of stormwater capture nationwide should entail expanding allowable uses of stormwater beyond the most common current uses (i.e., non-potable uses) to include potable and indoor applications. Model guidelines at both the state and federal levels can support this expansion.

Expand Funding and Financing Opportunities for Stormwater Capture. Most federal funding for water capital projects is provided through the Drinking Water State Revolving Fund (DWSRF) and the Clean Water State Revolving Fund (CWSRF) programs. Only a small fraction of these funds is allocated to stormwater projects. In most cases, state DWSRF programs have not considered stormwater capture projects eligible for financial support. In some cases, stormwater capture projects are eligible for SRF-related funding streams, but there are real and perceived barriers to accessing these funds, such as the absence of dedicated repayment sources necessary to access loans, the requirements for project design details with funding applications, uncertainty regarding eligibility for funding streams, and the inability to leverage additional funding sources for source water and environmental protection. Changes are needed to ensure that stormwater capture projects have equal access to DWSRF and CWSRF financing compared to other traditional and non-traditional water supply projects.

Improve Regional, State, and Local Planning to Support Integration of Water and Non-Water Benefits into Water Management and Investment Decisions. Capturing the untapped potential for stormwater capture, and other alternative water supplies, would benefit from a broader approach to regional, state, and local water supply and land use planning.

For example, state and regional entities can advocate for and establish methods for valuing multiple benefits when determining funding criteria for capital projects (e.g., SRF financing programs). Efforts to incorporate multiple benefits—both water and non-water—into water management and investment decisions can improve a project's financial viability and public acceptance while helping to minimize adverse and unintended consequences.

Facilitate Public-Private Stormwater Capture Projects. Privately owned land can represent a large volumetric potential for stormwater capture. Public-private partnerships (as well as public-public partnerships between public agencies and schools, parks districts, and other large public landowners) can leverage private sector capacity and investment to implement stormwater capture projects more quickly. Designing stormwater credit trading programs to specifically enable partnering across ownerships to encourage stormwater capture would help build local capacity. A comprehensive database of cost benchmarks for different types of stormwater capture can improve the accuracy of financial analyses used to select projects.

Support Use of Green Infrastructure and Reuse for Stormwater Capture Projects. Although gray centralized conveyance infrastructure has traditionally been used for stormwater management, employing green infrastructure and reuse approaches for stormwater capture can help realize co-benefits (e.g., urban greening, reduced urban heat island effect, and flood risk reduction) that would not be produced by centralized approaches.

Investigate Research Gaps to Improve Efficacy of Stormwater Capture Projects. There remain important outstanding research questions that must be addressed to support even greater uptake of stormwater capture. State agencies, academics, water agencies, and community organizations all have a role to play in filling research gaps.

©Pinar Balci | A rain garden in New York City.

Abbreviations

ADWR – Arizona Department of Water Resources
AFY – Acre-feet per year
AMA – Active Management Area
AR – Aquifer Recharge
ASR – Aquifer Storage and Recovery
AWBA – Arizona Water Banking Authority
CN – Curve Number
CSO – Combined Sewer Overflow
CWSRF – Clean Water State Revolving Fund
DWSRF – Drinking Water State Revolving Fund
HUC – Hydrologic Unit Code
INA – Irrigation Non-Expansion Area
M&I – Municipal and Industrial
(M)AR – (Managed) Aquifer Recharge
MGD – Millions of Gallons Per Day
MNGWPD – Metropolitan North Georgia Water Planning District
MS4 – Municipal Separate Storm Sewer System
MSA – Metropolitan Statistical Area
NLCD – National Land Cover Database
NPDES – National Pollution Discharge Elimination System
NRCS – Natural Resource Conservation Service
SCS – Soil Conservation Service
TELR – Stormwater Tool to Estimate Load Reduction
TWDB – Texas Water Development Board
US EPA – US Environmental Protection Agency
USGS – US Geological Survey
WRAP – Water Reuse Action Plan

Section 1: Introduction

Water is one of our most precious and vital natural resources and is fundamental for human and ecological health and economic prosperity. Yet, water scarcity is a growing risk for communities across the United States due to, for example, natural hydrologic variability, population and economic growth, and the intensifying effects of climate change. In communities across the United States, traditional water sources, including freshwater from rivers and streams and underground aquifers, are increasingly facing peak water limits (Gleick and Palaniappan 2010).

The Fifth National Climate Assessment finds that in many parts of the United States, fresh water supplies are threatened by climate change due to increasing aridity, declining snow cover, declining groundwater levels, and drought (Payton et al. 2023). Under climate change, scientists expect a declining trend in the average amount of precipitation in the Caribbean, Hawaii, and the southwestern regions of the United States. As the climate changes, precipitation events are expected to become heavier and more sporadic across the nation, leaving water managers to contend with more water falling in shorter timeframes. In the eastern half of the United States, in particular, precipitation trends show increasing annual runoff variability (Payton et al. 2023).

The Colorado River, for example, is a lifeline for 40 million people across the western United States and Mexico, but demand for water exceeds the available supply such that the river dries up before reaching the Gulf of Mexico. Climate change is projected to reduce the Colorado River's annual baseflow up to 30% by 2050, with dire consequences for nature and people (Miller et al. 2021). In the Great Lakes region, watershed health and adequate supply are prioritized via the Great Lakes Compact, which requires careful coordination between water supply managers in the United States and Canada. However, communities surrounding Chicago have been seeking additional diversions from Lake Michigan (via service agreement with the City of Chicago) to combat unsustainable aquifer drawdown. This strategy is not sustainable, as additional diversions will eventually be restricted by diversion limits established by the US Supreme Court to protect Great Lakes watershed health, which could leave some communities without a reliable water supply (Havrelock et al. 2023). To the south, nearly 90% of the lower Mississippi River region is experiencing drought and more than 55% is in extreme drought or worse. Water levels in the Mississippi River have reached historic lows, disrupting critical shipping channels and threatening water supplies for communities in Louisiana as saltwater from the Gulf of Mexico moves further upstream (Cassidy 2023).

As many traditional water supplies have become increasingly constrained, there is growing interest in reducing demand through water conservation and efficiency and developing new, alternative water sources, such as desalinating brackish and ocean water, reusing wastewater, and capturing urban stormwater runoff. These strategies can help to "close the gap" between existing and anticipated water supply and demand and diversify water supplies to advance water resilience.[1]

This assessment quantifies the potential for capturing stormwater runoff, i.e., runoff generated by precipitation falling on roofs, roads, and other hard surfaces, in urbanized areas across the United States. Section 2 provides an overview of urban stormwater management and several examples of stormwater capture projects implemented across the United States, highlighting their diverse drivers and co-benefits. Section 3 describes the methodology used to quantify the volumetric potential for urban stormwater runoff. Section 4 presents key findings across multiple spatial scales, including several case examples that illustrate the opportunities in diverse geographies. Finally, Section 5 provides the conclusions and recommendations.

The findings from this assessment are intended to serve as a resource for communities, water supply planning professionals, and decision-makers that have not previously considered stormwater capture in their water supply planning efforts or are looking for further opportunities to build upon existing stormwater capture activities. Future assessments will quantify the potential to reduce urban water demand through conservation and efficiency and augment water supplies through reuse of municipal wastewater.

Section 2: Overview of Urban Stormwater Capture

Urban stormwater refers to the runoff generated from precipitation falling on rooftops, roads, and other impervious surfaces in urbanized areas. It has historically been considered a nuisance or hazard. Stormwater carries pollution from roads and other urban surfaces to rivers, lakes, estuaries, and the ocean, threatening both aquatic life and public health. It can also lead to flooding, causing property damage and risks for communities. As a result, urban areas were designed to collect stormwater through dedicated storm sewers and dispose of it as quickly as possible into nearby waterways or detention ponds. While we consider collection of precipitation from all impervious surfaces as stormwater capture for this report, some communities distinguish between rainwater capture and stormwater capture, whereby rainwater refers to precipitation collected directly from rooftops and stormwater refers to precipitation collected from all other impervious surfaces (streets, parking lots, sidewalks, etc.).

Stormwater capture projects are being implemented in a growing number of communities to augment water supplies and combat water scarcity.

However, perspectives on stormwater are changing—and it is increasingly viewed as an asset. Stormwater capture projects are being implemented in a growing number of communities to augment water supplies and combat water scarcity (Luthy 2019; Los Angeles County Sanitation Districts and Stantec Inc. n.d.; National Academies of Sciences, Engineering, and Medicine 2016) and reduce flooding and pollution of nearby waterways, sometimes as an alternative compliance mechanism to meet stormwater management requirements for a site (New York City Department of Environmental Protection 2021; Jack et al. 2022). When using green infrastructure, stormwater projects also support community greening and mitigate urban heat island effects (Lester 2022; Zhang et al. 2023).

There is also growing interest and attention to stormwater capture at the federal level, as evidenced by its inclusion in the US EPA's Water Reuse Action Plan (WRAP) (Box 1). Specifically, WRAP Action 3.3, completed in March 2022 and culminating in the publication of *Pure Potential: The Case for Stormwater Capture*, provides a framework and recommendations for establishing a unified community of practice around stormwater capture and coordinating action to address challenges to widespread implementation (US EPA 2022). Actions 5.5 and 5.8 are currently active, and these actions all share a goal of elevating stormwater capture and beneficial use and other forms of water reuse to nationwide consideration at multiple scales (local, state, watershed, etc.).

BOX 1. EPA Water Reuse Action Plan (WRAP)

The WRAP, released in January 2020, provides a roadmap for collaboration and action to implement water reuse strategies across the United States (US Environmental Protection Agency 2020). Stormwater capture is included across multiple action items, including the convening of experts to address opportunities and challenges of stormwater capture (WRAP Action 3.3), the quantification of national volumes of water potentially available for reuse of stormwater (WRAP Action 5.5), and the evaluation of the potential of urban stormwater capture in Colorado (WRAP Action 5.8) (US Environmental Protection Agency 2020).

RESIDENTIAL RAIN BARRELS TO REGIONAL RESILIENCE: STORMWATER CAPTURE ACROSS SCALES

Stormwater capture can be done at a variety of scales—from a single building to a collection of buildings or at a community scale. Stormwater capture methods include traditional gray infrastructure, such as storm sewers and combined sewers that route stormwater to a treatment facility or storage pond for infiltration. They also include green infrastructure, such as bioswales and rain gardens, that use plants and soils to slow, filter, and store stormwater before it enters the storm system, or a mix of the both gray and green infrastructure (US EPA 2015). Green infrastructure can also be used to divert stormwater runoff to a pervious surface for direct infiltration, effectively disconnecting the area served from the centralized collection system entirely and reducing the contributing area for the centralized collection system (Hoffman et al. 2020). Boxes 2 through 6 provide examples of the diversity of stormwater capture projects that can be found in communities across the United States.

BOX 2. Residential Rain Barrels

Rooftop runoff captured in rain barrels can be used at residential homes for activities including irrigation, car washing, and cleaning tools. This benefits both the customers by saving money and the water provider by reducing strain on municipal water supplies.

To incentivize rainwater harvesting and educate customers through active and hands-on engagement, some cities and water providers offer financial incentives. For example, the City of Tucson, Arizona, offers a rebate of up to $2,000 for customers on the purchase of a rain harvesting system (City of Tuscon n.d.). Before the rebate is approved and the system installed, customers must first attend a qualified water harvesting workshop and submit a plan. After installation, the system is inspected and approved before the customer receives the rebate.

BOX 3. Commercial and Institutional – Indoor and Outdoor Uses

The Philip Merrill Environmental Center in Maryland serves as the headquarters for the Chesapeake Bay Foundation. The center captures stormwater primarily to reduce the discharge of pollutants into sensitive waterways entering Chesapeake Bay. The stormwater is treated and used on-site for indoor fire suppression, cleaning, and laundry, as well as for irrigation. The building uses 80% less water than similar office buildings and is one of the most energy efficient buildings in the world (Chesapeake Bay Foundation n.d.).

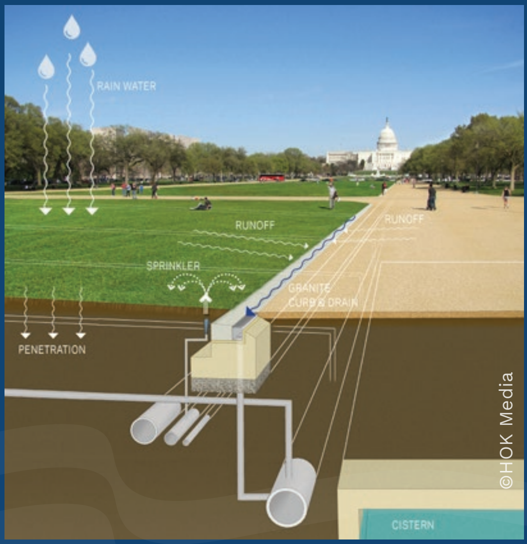
BOX 4. Green Infrastructure – Commercial and Institutional

At the headquarters of MEarth, an environmental nonprofit organization in Carmel, California, cisterns collect and store rainwater from the green roof during the rainy season (MEarth n.d.). The harvested rainwater is used to augment landscape irrigation during the dry season. The site serves as an educational center for residents, school groups, and other businesses to learn about the benefits of environmental stewardship, such as improved water and air quality, reduced strain on potable supplies, increased quality of life for individuals and communities, and protection of habitats and wildlife associated with green infrastructure.

BOX 5. Medium-Scale – Sub-Surface Storage, Treatment, and Distribution

The National Mall in Washington, D.C. hosts numerous events and over 25 million visitors throughout the year. High traffic takes a toll on America's historic and iconic "front yard," affecting the soils, grass, and trees.

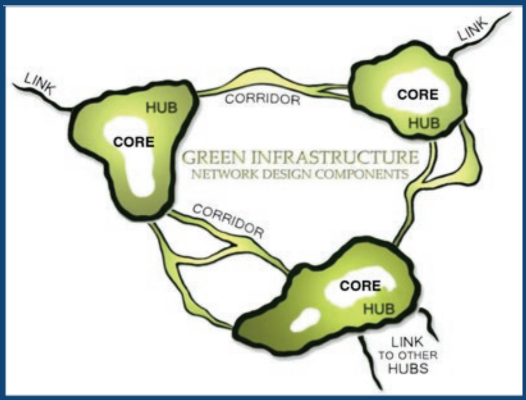
To mitigate these impacts and to reduce reliance on potable water supplies, the area was rehabilitated. Stormwater is now captured, stored, and reused via a sub-surface collection, storage, treatment, and distribution system. A central computer controls the entire system, detecting water levels and flow rates and troubleshooting problems (LILA n.d.; Pike 2013).



Box 6. Integrating Green Infrastructure at Multiple Scales

The Chicago Metropolitan Agency for Planning (CMAP) provides recommendations, strategies, and policies for using green infrastructure to improve the quality of life in communities throughout northeastern Illinois. To achieve this at a regional scale, site- and community-scale green infrastructure within areas identified as either the core lands or hubs are connected by corridors to create the regional green infrastructure network. The highest quality ecosystems, the core lands, provide important habitats for wildlife and are nested within protective buffer areas called hubs. These hubs protect ecosystem functions and are connected via corridors that support biodiversity by allowing plants and animals to move throughout the system (Chicago Metropolitan Agency for Planning n.d.).

Source: Cermak Road Sustainable Streetscape – Chicago, ©Center for Neighborhood Technology



Source: CMAP "Integrating Green Infrastructure"

For an individual site, the CMAP recommends a set of best management practices to integrate stormwater management and land-use development. These practices include rain gardens and bioswales (top photo) that use natural functions to manage stormwater, decrease flooding, and reduce air and water pollution.

At the community scale, increased access to parks and open green spaces is strongly encouraged to provide multiple community benefits and ecological functions.

Spatial datasets and policies from the city's Green Infrastructure Vision help stakeholders identify key areas for the strategic placement of green infrastructure. These areas, the core lands, hubs, and corridors, form the regional green infrastructure network (bottom photo).

MAJOR DRIVERS AND CO-BENEFITS

The major driver for adopting stormwater capture varies based on local needs (US EPA 2022). For example, in water-scarce areas, including across much of the Southwest United States, stormwater capture is seen as a way to augment and diversify water supplies. In other areas, such as in the Northeast and Midwest, water quality protection and flood mitigation have been key drivers for improving stormwater management (Philadelphia Water Department 2009; Landers 2021).[2] Still, other areas, including the Pacific Northwest and Atlantic Southeast, face both challenges of seasonal drought and flooding, a trend that is likely to increase in more and more regions as a result of climate change (Carter et al. 2018; May et al. 2018). Each of these stressors (scarcity, pollution, and cycles of extreme conditions) have led communities to reconsider the role stormwater capture can play (US EPA 2022; Luthy, Sharvelle, and Dillon 2019; National Academies of Sciences, Engineering, and Medicine 2016; California Department of Water Resources 2018; WateReuse Association 2023; Burgess 2017).

But even beyond these water-related benefits, stormwater capture projects can also provide additional co-benefits. This is especially true for projects incorporating green infrastructure. For example, in several cities nationwide, using green infrastructure practices effectively managed urban stormwater runoff while simultaneously increasing access to green space, improving community aesthetics, and mitigating urban heat island impacts for residents (NYCDEP 2021; Lester 2022; Cooley et al. 2019). Green infrastructure practices have also been adopted in response to regulatory action to reduce occurrence of combined sewer overflows, meet water quality targets, or recharge groundwater aquifers (NYCDEP 2021; California Department of Water Resources 2019; Cooley et al. 2019; WateReuse Association 2023). These examples and others underscore the diversity of drivers and co-benefits for stormwater capture implementation across the country.

BARRIERS TO GREATER UPTAKE

Despite growing interest in and implementation of stormwater capture projects, these projects face financial, institutional, regulatory, and technical barriers that limit uptake (Heidari et al. 2023; Shimabuku, Diringer, and Cooley 2018; Keeler et al. 2019; US EPA 2022). Examples include: difficulty accessing both public and private financing, limited private sector investment, absence of clear regulatory frameworks, impacts on downstream water rights holders, persistent perception of stormwater as a nuisance, and limited collaboration and competing priorities among governing entities (Heidari et al. 2023; Greenprint Partners and Catalyst Collaboratives 2022). These barriers can and must be overcome to realize the potential of stormwater capture to support community resilience.

2 In some instances, these projects were spurred by regulatory enforcement of municipal separate storm sewer system permits or consent decrees targeting reduction of combined sewer overflows.

Section 3: Approach for Quantifying the National Potential for Stormwater Runoff

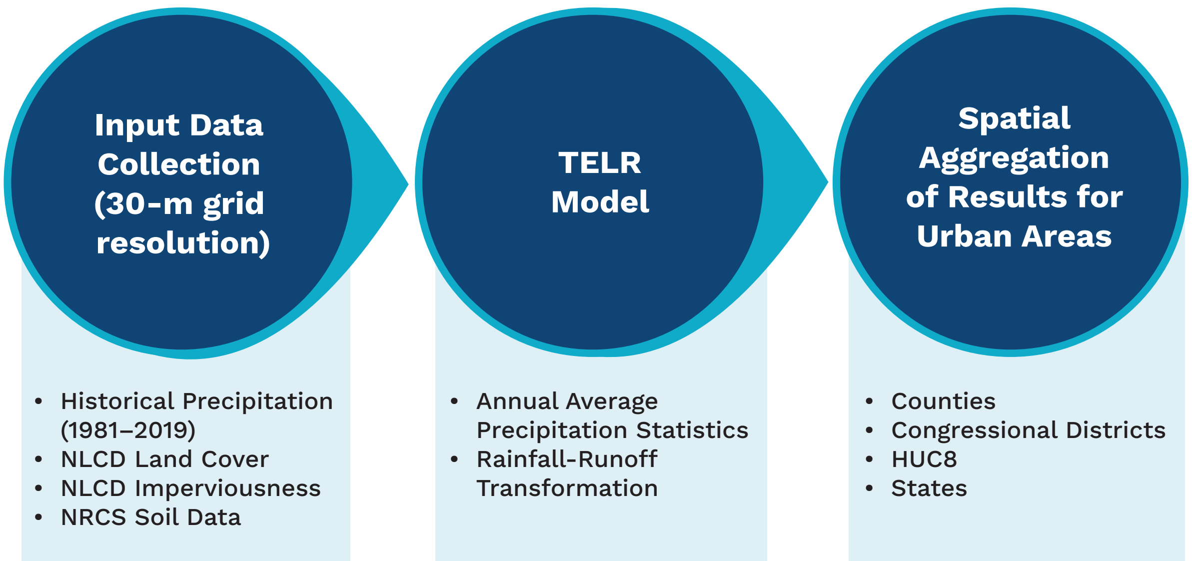
Urban stormwater runoff can be a highly localized phenomenon driven primarily by land cover characteristics and the amount of precipitation received. Several methods are available to estimate urban stormwater runoff volumes and methodologies vary based upon the intended use of the results, e.g., infrastructure design, water quality and quantity assessment, or site drainage analysis. For this study, stormwater runoff represents the overland flow generated from precipitation events when precipitation exceeds the infiltration and storage capacity and does not include precipitation that percolates into the ground and eventually becomes water in a stream or aquifer. Our approach estimates the amount of runoff from existing impervious surfaces under typical past climate regimes that could be captured for local uses instead of transported away via stormwater infrastructure, as most runoff currently is. Therefore, the estimates presented in this report represent the average annual historic volumetric potential of stormwater runoff.

This assessment is a high-level estimate of the national stormwater runoff potential and certain simplifying assumptions were needed due to the large geographic region covered. The total stormwater runoff potential estimated in this study represents all potential stormwater runoff generated from impervious surfaces based on average annual rainfall conditions, without consideration for method of capture or existing uses of stormwater. To interpret results for a local context, additional refinements would be needed, such as accounting for existing stormwater control and management measures (i.e., what is already being captured); limits in hydraulic and storage capacity of stormwater capture infrastructure; temporal and seasonal availability of stormwater and demand for stormwater reuse; environmental flow requirements for ecosystems downstream of urban areas; flow requirements related to water rights for users downstream of urban areas; and flood risk assessment/management for downstream users. Further, additional analysis would be needed to determine the portion of runoff potential that would be technically and economically feasible to capture to augment water supplies.

STORMWATER MODELING DESCRIPTION

For this analysis, Pacific Institute partnered with 2NDNATURE, a stormwater science and software company that provides stormwater management tools for policy and decision-making by the public and private sectors. We used one of 2NDNATURE's primary models, the Stormwater Tool to Estimate Load Reduction (TELR), to generate spatial estimates of annual stormwater runoff potential for US Census-designated Urban Areas in the United States. TELR is an urban runoff and pollutant loading model designed to provide a decision-support tool for stormwater management. The model leverages simplified analytical techniques and a fully spatially distributed approach using 30-m grid resolution to produce meaningful estimates of stormwater runoff generation. The approach is less resource intensive than computationally expensive hydraulic simulations that are typically employed in stormwater modeling tools used for infrastructure design and analysis. A conceptual diagram summarizing the modeling and analysis process is illustrated in Figure 1.

FIGURE 1. Conceptual Diagram of Stormwater Runoff Estimation Procedure



The primary data inputs for the TELR model were interpolated daily historical precipitation data records (years 1981–2019), US Natural Resource Conservation Service (NRCS) hydrologic soil group classifications, and US National Land Cover Database (NLCD) land cover and imperviousness. Precipitation data were spatially interpolated to establish complete coverage of the study area and summary statistics, including percentile precipitation values and average annual number of days with precipitation from the historical precipitation dataset, were calculated for each 30-m pixel. These summary statistics were resampled to produce a synthetic daily time series representing an average precipitation year. The precipitation time-series was then used to produce average annual runoff volume estimates for each pixel falling within an Urban Area using the Soil Conservation Service (SCS) curve number (CN) method, which provides an estimate of direct stormwater runoff after accounting for impervious cover, ground infiltration, absorption by vegetation, and surface evaporation (USDA NRCS 1986). Full descriptions of model functionality, inputs, estimation methods, validation, limitations, and references to peer-reviewed journal articles with additional information are provided in Appendix A.

SPATIAL SCALE OF ANALYSIS AND AGGREGATION OF RESULTS

The stormwater runoff estimates presented in this report were developed by clipping the raw 30-m grid resolution runoff estimates produced by the TELR model to Urban Areas using GIS software. We delineated Urban Areas using the definition and corresponding GIS shapefile provided by the U.S. Census Bureau as part of the 2020 Decennial Census, encompassing jurisdictions with at least 2,000 housing units or 5,000 people, in addition to other qualifying criteria (US Census Bureau 2022; 2020a). We then aggregated the Urban Areas results to multiple scales: county boundaries, districts for the 118th Congress, state boundaries, and Hydrologic Unit Code Subbasins (HUC8), as defined by the USGS in their Watershed Boundary Dataset (US Census Bureau 2020b; USGS 2022).

KEY CONSIDERATIONS OF MODELING APPROACH

One of the major benefits of the TELR model is that the modeling approach allows for rapid estimation of stormwater runoff across a large spatial area at a high spatial resolution with high accuracy (validated with USGS stream gauge records as detailed in Appendix A). While the TELR model has the capability to produce estimates for different time intervals, this initial study investigates stormwater runoff potential on an average annual basis based on historic precipitation. Future work to refine these estimates should account for seasonality of precipitation to better understand the availability of runoff for capture across time. Moreover, because precipitation for this analysis was derived from historical data, the model does not reflect potential changes in precipitation frequency, duration, and intensity that may result from climate change impacts in the future (though existing forecasts of anticipated climate change-adjusted precipitation characteristics by region could be incorporated into this modeling framework for future work).

The annual average stormwater runoff estimates generated by the model are appropriate for meeting the objective of this report, which is to quantify the national volume of stormwater runoff potential for the purpose of informing policy and identifying areas for further investigation. The total stormwater runoff potential estimated in this study represents all potential stormwater runoff generated from impervious surfaces based on average annual rainfall conditions, without consideration for method of capture or existing uses of stormwater. More detailed simulation software would be needed for design of engineered stormwater capture infrastructure in specific locations or to estimate stormwater capture within local geographic, physical, financial, regulatory, and other constraints.

The estimate also does not account for temporal variations in stormwater availability throughout the year. Our analysis also does not account for limitations in stormwater capture potential due to in-stream flow requirements related to environmental flows and downstream user water rights, or consideration of impacts on groundwater quality from stormwater capture. Nevertheless, the quantifications in this report provide insight into the approximate upper limit of available stormwater-generated water supplies (including existing uses of runoff as a current water supply) that can be obtained from capturing stormwater runoff.

CASE EXAMPLES

We have developed four case examples to provide potential applications of these results: groundwater management in Arizona and Minnesota, water supply planning and regional coordination in northern Georgia, and state water planning in Texas. These case examples highlight specific opportunities for stormwater capture to achieve policy goals, identify potential trade-offs, and/or provide direction for further investigation. Each case example was selected to explore major themes of considerations for stormwater capture: water supply resilience and diversification, potential co-benefits, integration into regional water planning processes, and major drivers and barriers.

©Dave Smith | Shelby White and Leon Levy Water Garden at the Brooklyn Botanical Garden, New York City.

Section 4: Key Findings

In this section, we present the results of our analysis and explore the volumetric potential for stormwater runoff in urbanized areas across the United States for a range of geographic scales and locations. We first present the national and statewide estimates. The statewide estimates reflect one of the primary levels for water management and planning in the United States and may provide state decision-makers with insight into opportunities for water supply planning. We also investigate results at the US Census Urban Area and HUC8 scales to highlight finer resolution spatial trends and provide additional interpretations of estimates. In addition, we identify areas where stormwater runoff estimates deviate from national trends and discuss possible reasons for these deviations. Finally, we discuss potential applications of urban stormwater runoff results using case examples that highlight the various drivers and co-benefits of stormwater capture. The results presented in this section represent the upper limit of urban stormwater volume potential, and not all of this volume is necessarily available or desirable for capture. Moreover, the volumetric potential of an area should not be taken as the sole criterion for implementation of stormwater capture but should be compared with the other drivers and potential for co-benefits.

> We estimate that the urban stormwater runoff potential across all urban areas in the United States is 59.5 million acre-feet per year (AFY).

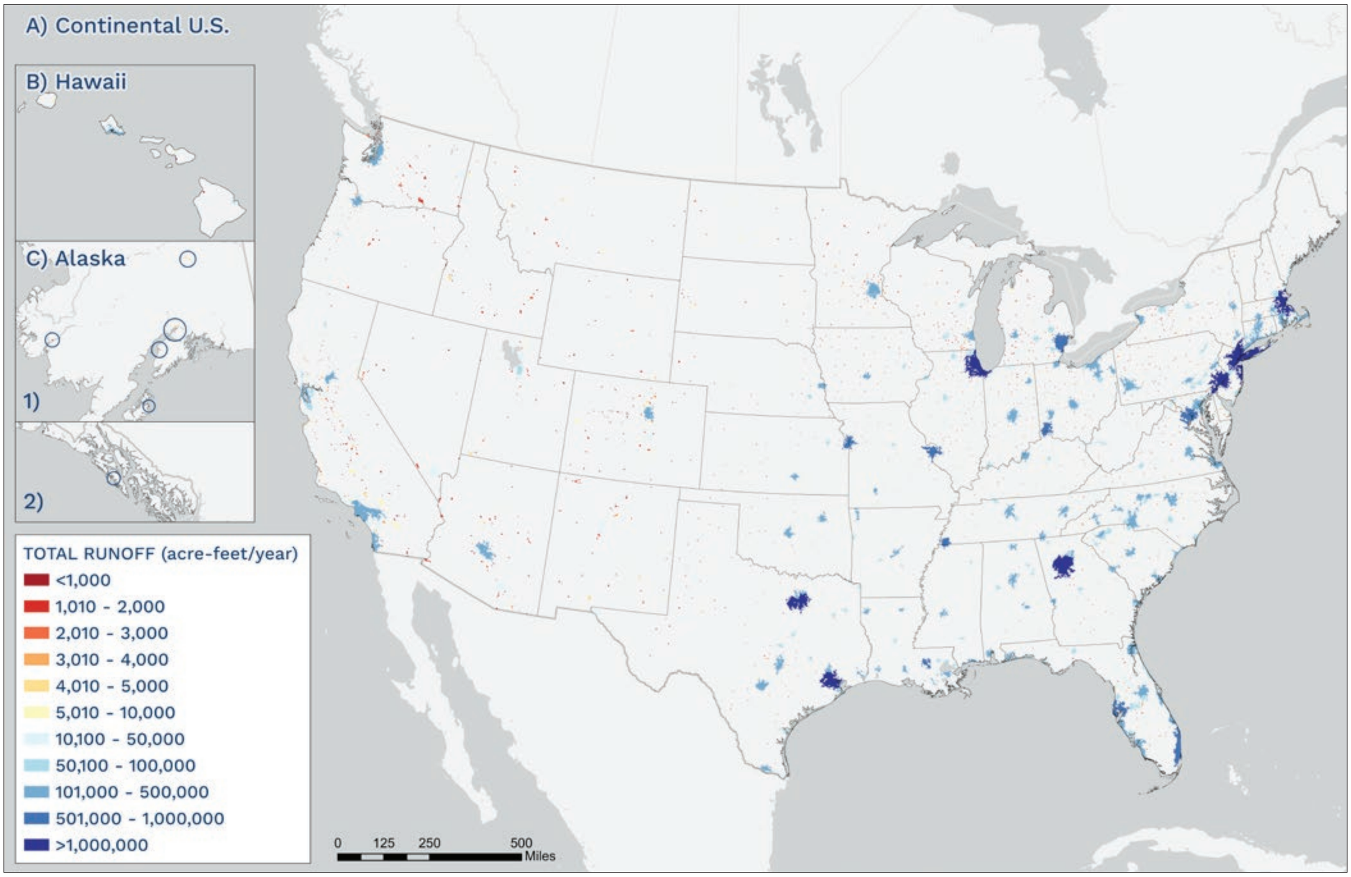
NATIONAL STORMWATER RUNOFF POTENTIAL

We estimate that the urban stormwater runoff potential across all urban areas in the United States is 59.5 million acre-feet per year (AFY), equivalent to approximately 53,100 million gallons per day (MGD) (Figure 2). This represents all stormwater runoff generated from hard surfaces, such as roofs and roads, and overland flow from pervious areas when the rate of precipitation exceeds the infiltration capacity.

Our estimate is consistent with previous estimates. For example, Aguilar and Brown (2020) estimated that 53.7 million AFY were potentially available. A much earlier estimate by the US EPA (US Environmental Protection Agency 2004) found that 30.9 million AFY of stormwater is generated from urbanized areas; however, this estimate does not include the growth in urbanized area over the last 20 years, which could in part explain the lower value.

By comparison, 63.9 million AFY of freshwater (from both surface water and groundwater sources) were withdrawn for municipal and industrial (M&I) use in the United States in 2015 (Dieter et al. 2018).[3] This does not mean that stormwater runoff can satisfy *all* municipal and industrial water demands. However, the finding suggests that stormwater capture can make a meaningful contribution to augment and diversify water supplies in more communities than are currently considering it.

FIGURE 2. Total Annual Estimated Urban Stormwater Runoff Potential, US Urban Areas



Note: Alaska map panels are labeled as follows: 1) South Central Alaska and portions of Southwest and Interior Alaska, and 2) Southern tip of Alaska Panhandle.

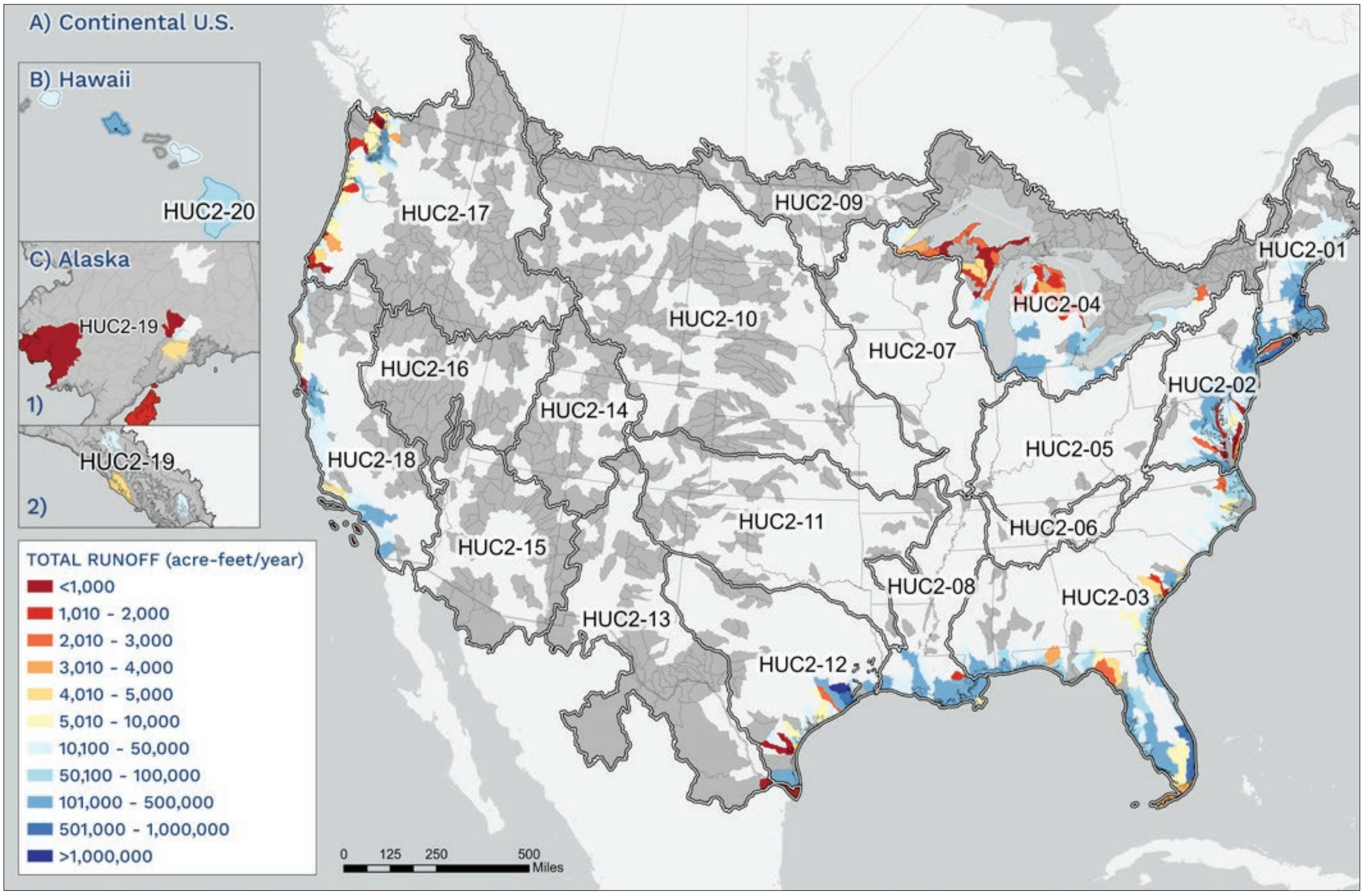
3 M&I is defined as: public supply, self-supplied domestic, and self-supplied industrial uses.

COASTAL SUBBASIN-LEVEL STORMWATER CAPTURE POTENTIAL

Stormwater capture in coastal areas is likely to have fewer adverse impacts on downstream water rights holders and freshwater ecosystems than in inland subbasins. Moreover, coastal subbasins have unique challenges that could potentially be addressed by greater stormwater capture, such as recharging groundwater to mitigate saltwater intrusion in coastal aquifers and reducing nutrient loading and eutrophication in receiving water bodies.

Figure 3 shows the hydrologic subbasins (i.e., HUC8) that border the Atlantic and Pacific Oceans and the Great Lakes. The total estimated stormwater runoff generated in these coastal subbasins totals 21.9 million AFY (Table 1). This volume represents approximately 37% of the total national stormwater runoff potential, while comprising just 12% of the nationwide urban land area.

FIGURE 3. **Total Annual Estimated Urban Stormwater Runoff Potential, Coastal HUC8 Subbasins**



Notes: Alaska map panels are labeled as follows: 1) South Central Alaska and portions of Southwest and Interior Alaska, and 2) Southern tip of Alaska Panhandle. HUC2 regional boundaries shown. Areas with a hatched line pattern in the figure indicate subbasins with zero urban stormwater runoff potential due to the absence of any Urban Areas. The total runoff for each subbasin only represents stormwater runoff generated within the subbasin and does not include contributions from upstream subbasins.

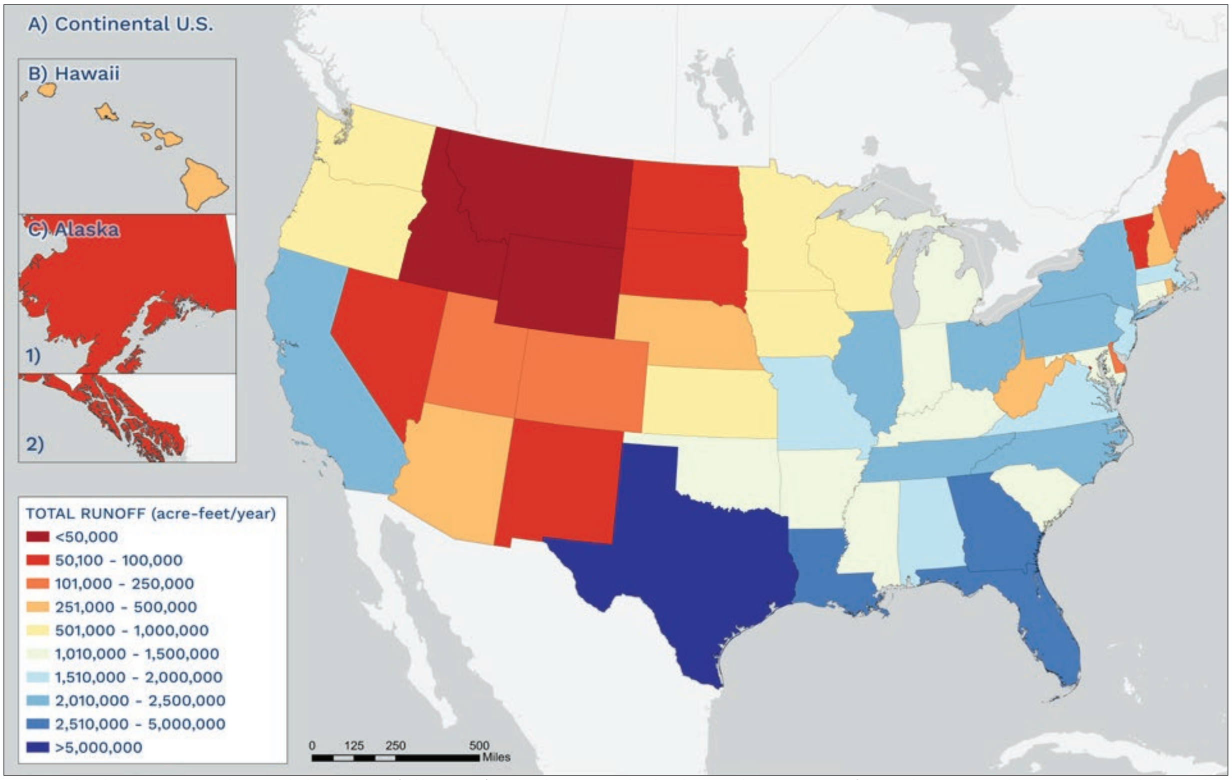
TABLE 1. Total Annual Estimated Urban Stormwater Runoff Potential for Coastal HUC8 Subbasins, Aggregated to HUC2 Region

REGION NAME (HUC2)	HUC2 REGION CODE	TOTAL VOLUME (acre-feet/year)
New England	1	2,760,000
Mid Atlantic	2	5,520,000
South Atlantic-Gulf	3	4,730,000
Great Lakes	4	2,240,000
Lower Mississippi	8	1,140,000
Texas-Gulf	12	2,830,000
Rio Grande	13	137
Lower Colorado	15	963
Pacific Northwest	17	794,000
California	18	1,540,000
Alaska	19	79,200
Hawaii	20	263,000
Coastal HUC8 Total		21,900,000
Nationwide Total		59,500,000

STATE-LEVEL AGGREGATED STORMWATER CAPTURE POTENTIAL

Figure 4 shows the state-level aggregation of results, and Table 2 shows the 10 states with the greatest volumetric potential. The Gulf Coast states of Texas and Florida have the highest urban stormwater runoff potential by volume, at 7.8 million AFY and 4.1 million AFY, respectively. Conversely, Idaho (38,000 AFY), Montana (29,600 AFY), and Wyoming (17,100 AFY) have the lowest stormwater runoff potential. These results are expected, as the former states both receive larger amounts of precipitation (34–48 inches per year, on average) and contain more urban land area, while the latter states receive relatively little precipitation (14–17 inches per year, on average) and have far less urban land area.

FIGURE 4. Total Annual Estimated Urban Stormwater Runoff, State-Level Aggregation



Note: Alaska map panels are labeled as follows: 1) South Central Alaska and portions of Southwest and Interior Alaska, and 2) Southern tip of Alaska Panhandle.

Table 2 provides characteristics for the 10 states with the greatest runoff potential. Total runoff volumes are compared to 2015 estimates of total water withdrawals for M&I use (Dieter et al. 2018). Stormwater runoff potential exceeds 2015 M&I water withdrawals in all states except Louisiana, Pennsylvania, and California. This result is encouraging, though it does not mean that these states could meet all M&I drinking water needs via stormwater capture alone.

TABLE 2. Stormwater Runoff Potential and Associated Characteristics, Top 10 States By Volume

STATE	AVERAGE ANNUAL URBAN AREA PRECIPITATION (inches/year)	TOTAL URBAN LAND AREA (million acres)	TOTAL ANNUAL URBAN AREA RUNOFF (million AFY)	2015 M&I WITHDRAWALS (million AFY)	AREA-NORMALIZED RUNOFF (inches/year)	RUNOFF RATIO
Texas	34.2	5.80	7.80	4.42	16.1	0.472
Florida	48.5	5.09	4.12	3.15	9.70	0.200
Georgia	46.1	2.99	2.77	1.85	11.1	0.242
Louisiana	55.4	1.25	2.61	3.24	25.2	0.455
Ohio	40.6	2.69	2.50	2.01	11.1	0.274
Illinois	39.2	2.38	2.47	2.24	12.5	0.319
North Carolina	44.5	2.89	2.38	1.46	9.90	0.222
Pennsylvania	44.6	2.68	2.35	2.51	10.5	0.235
California	15.7	4.98	2.27	6.35	5.50	0.347
Tennessee	49.0	1.85	2.17	1.82	14.1	0.287

Note: 2015 M&I withdrawals are summarized from Dieter et al. 2018.

In all cases, except for California, Urban Areas in each of the top 10 states receive an average of more than 30 inches of precipitation per year. California has relatively little annual rainfall (~16 inches/year) though it is the third-largest state in terms of urban land area (~50 million acres), which helps explain its relatively large urban stormwater runoff potential. By dividing the total runoff volume by the urban land area for each state, we estimate an area-normalized runoff volume that accounts for disparities in urban land area for each state. A further investigation of the relative influence of impervious area and precipitation inputs on stormwater runoff volume estimates is explored in Appendix B and Appendix C for States and Urban Areas, respectively.

Table 3 summarizes the state-level stormwater runoff potential and urban land area by US Census Division and US Census Region. States with the highest urban stormwater runoff potential tend to be clustered around the Southeast and Great Lakes regions of the United States and California. These states tend to have more precipitation and/or urban land area than states in the Mountain West, Great Plains, and Northeast regions, on average. The relatively low potential in the New England Census Division (Maine, New Hampshire, and Vermont) is somewhat surprising due to the large amounts of precipitation these states receive (42–51 inches per year) and suggests that limited impervious land area in these states reduces the stormwater capture potential. More detailed investigation of these trends, as well as a state-by-state summary of results, are presented in Appendix B and Appendix C for States and Urban Areas, respectively.

TABLE 3. **Summary of Total Urban Stormwater Runoff Potential, US Census Division and Regions**

CENSUS DIVISION	TOTAL RUNOFF POTENTIAL (acre-feet/year)	TOTAL URBAN LAND AREA (acres)	CENSUS REGION	CENSUS REGION TOTAL VOLUME (acre-feet/year)	CENSUS REGION TOTAL URBAN LAND AREAS (acres)
East North Central	8,560,000	10,000,000	Midwest	12,540,000	14,250,000
West North Central	3,980,000	4,250,000	Midwest	12,540,000	14,250,000
Middle Atlantic	6,190,000	6,870,000	Northeast	9,710,000	10,800,000
New England	3,520,000	3,930,000	Northeast	9,710,000	10,800,000
South Atlantic	13,800,000	16,000,000	South	32,330,000	29,300,000
West South Central	12,600,000	8,570,000	South	32,330,000	29,300,000
East South Central	5,930,000	4,730,000	South	32,330,000	29,300,000
Pacific	4,020,000	7,540,000	West	4,898,000	12,130,000
Mountain	878,000	4,590,000	West	4,898,000	12,130,000

Note: See https://www2.census.gov/geo/pdfs/maps-data/maps/reference/us_regdiv.pdf for listing of states within each Census Division and Region.

REGIONAL STORMWATER RUNOFF POTENTIAL

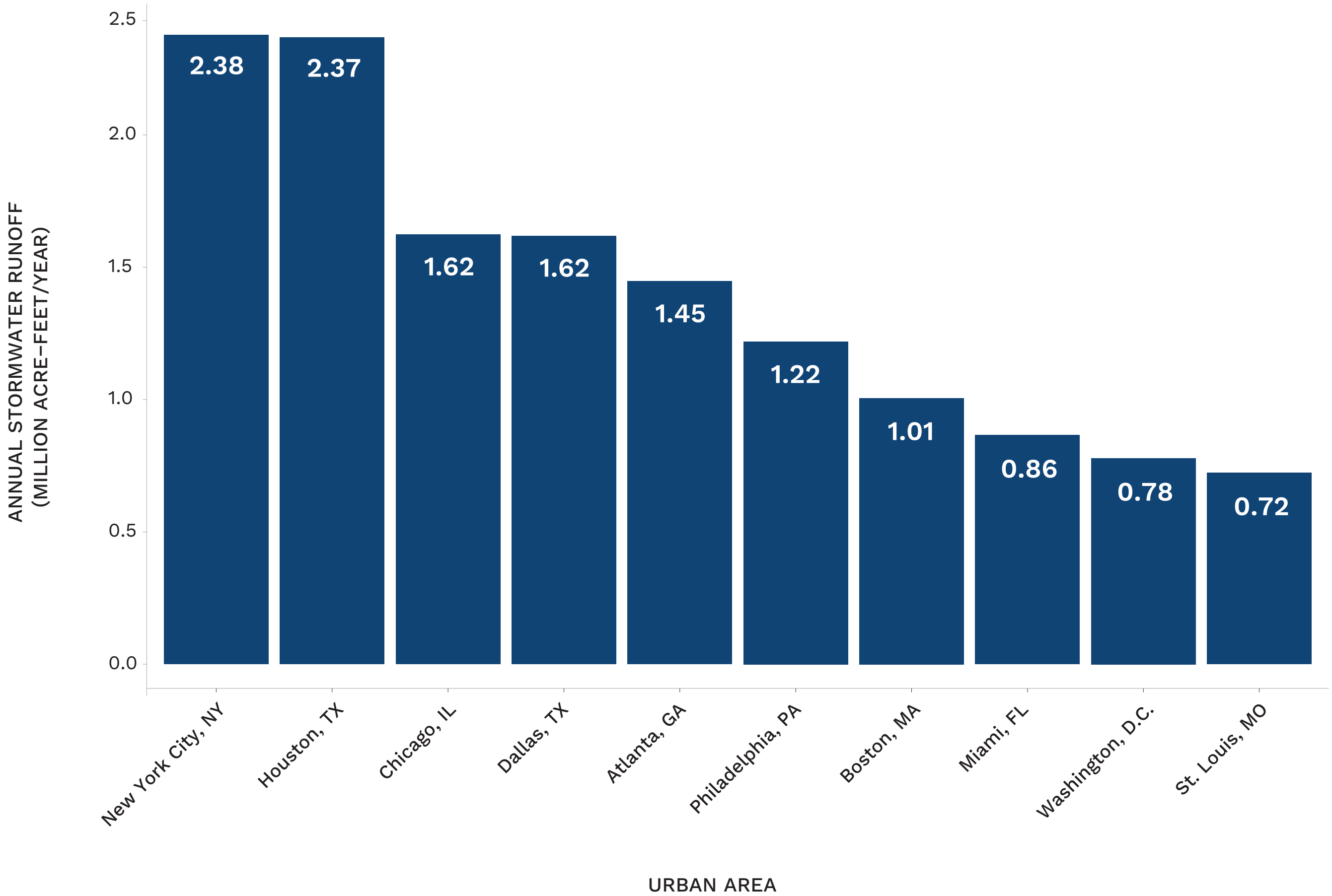
The results for the 2,645 US Census Urban Areas provide greater insight into the state-level estimates reported (summarized in Table 4). Spatial trends of volumetric runoff potential for Urban Areas are consistent with the state-level aggregation trends (Figure 2 and Figure 4), with the 10 Urban Areas with the highest volumetric stormwater runoff potential located in the eastern half of the United States (Figure 5). Seven of the highest-potential Urban Areas are located along the East Coast and Gulf Coast while the remaining three are in the Midwest.[4] Los Angeles represents the Urban Area with the greatest stormwater runoff potential in the West, ranking 19th among all urban areas in the country. Though the annual average precipitation in Los Angeles is relatively low (~13.4 inches per year for the historical record used, 9.5th percentile of Urban Areas), the city has the ninth-largest urban land area of all Urban Areas (~1.05M acres), which in part could explain the reason for the high stormwater runoff potential.

TABLE 4. Summary Statistics for Stormwater Capture Potential Estimates for All US Urban Areas

PARAMETER	STORMWATER RUNOFF (acre-feet/year)	AREA-NORMALIZED STORMWATER RUNOFF (inches/year)
Total	59,500,000	10.7
Mean	22,800	9.8
Median	3,900	9.54
St. Dev.	107,000	5.84
Inter-Quartile Range	1,780	5.65
	10,600	13
Minimum	20.6	0.17
Maximum	2,380,000	48.3

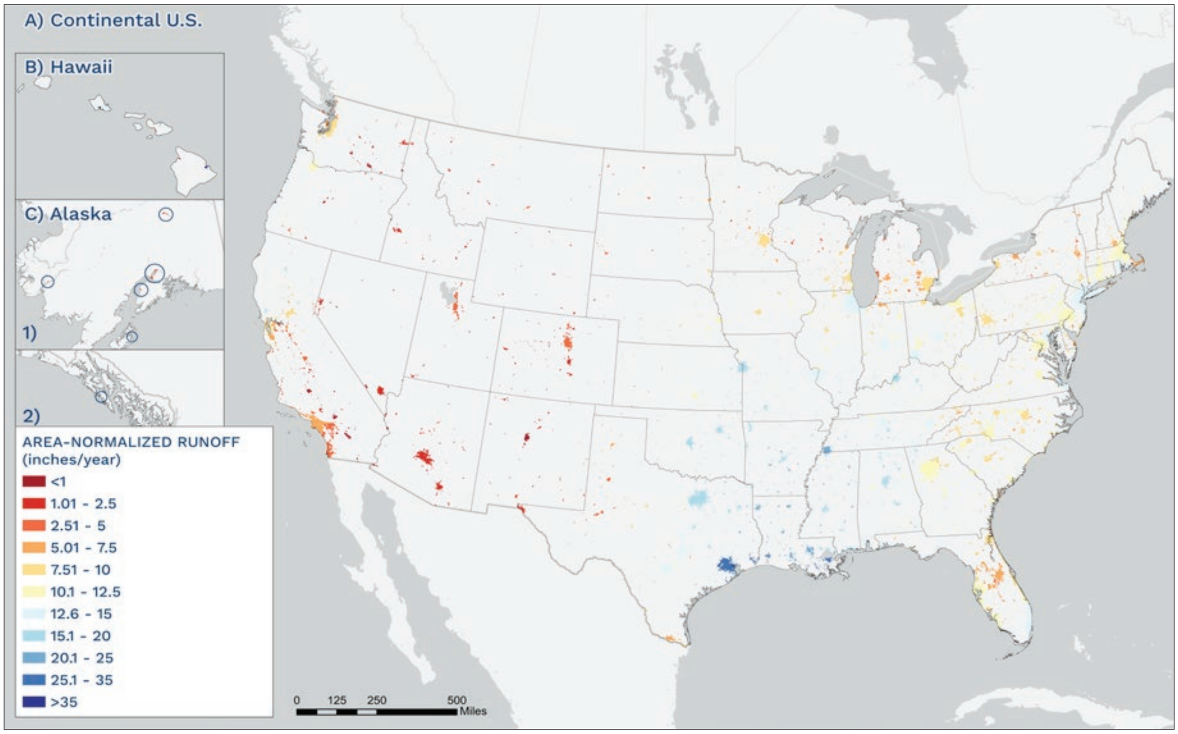
4 The relative influence of impervious area and precipitation inputs on stormwater runoff volume estimates is explored in further detail in Appendix B and Appendix C for States and Urban Areas, respectively.

FIGURE 5. Total Annual Estimated Urban Stormwater Runoff Potential for Top 10 US Urban Areas, By Total Volume



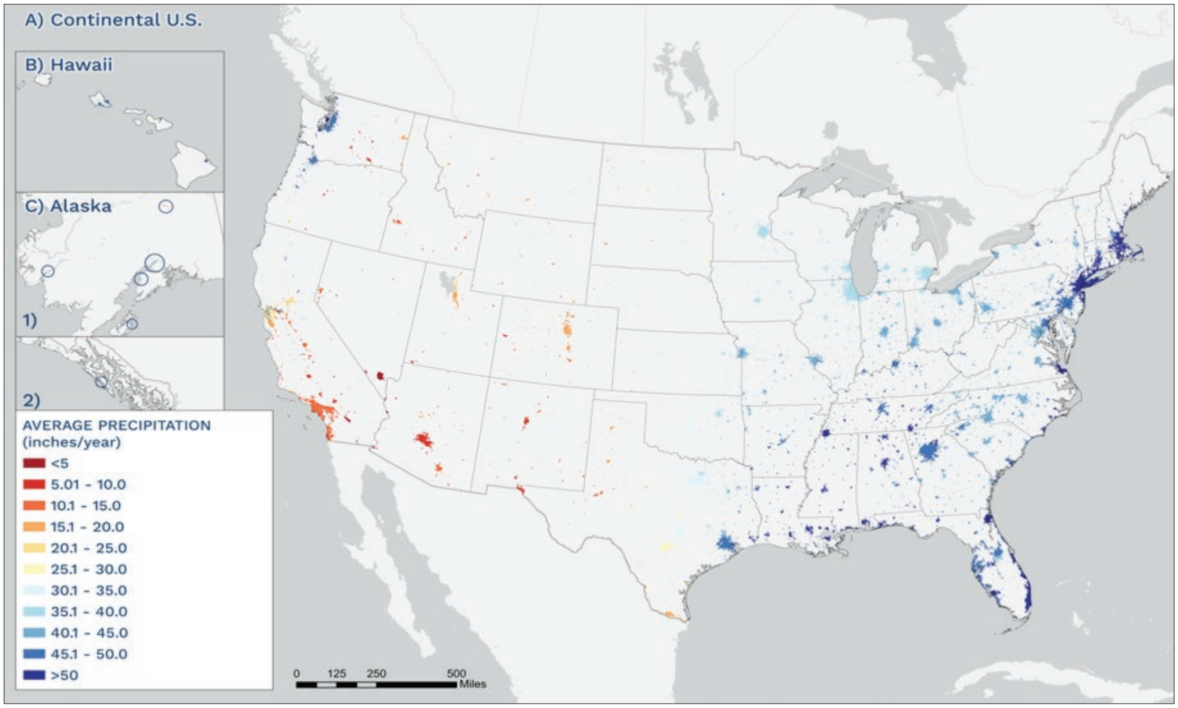
While these Urban Areas may rise to the top of the list for stormwater capture from a volumetric perspective, a smaller volumetric potential does not preclude an area from benefiting or implementing stormwater capture. Summary statistics for urban stormwater estimates in Urban Areas indicate volumetric variability ranges across five orders of magnitude between minimum and maximum values (Table 4). After normalizing total runoff estimates by their respective urban land area, the variability between minimum and maximum values decreases to two orders of magnitude, and spatial trends more closely align with those of annual urban precipitation (Figure 6 and Figure 7). This result suggests that while large Urban Areas can be correlated with high volumetric runoff potential, smaller Urban Areas with high rates of runoff generation per unit land area should not be overlooked.

FIGURE 6. Area-Normalized Annual Estimated Urban Stormwater Runoff Potential, US Urban Areas



Note: Alaska map panels are labeled as follows: 1) South Central Alaska and portions of Southwest and Interior Alaska, and 2) Southern tip of Alaska Panhandle.

FIGURE 7. Annual Average Precipitation for US Urban Areas



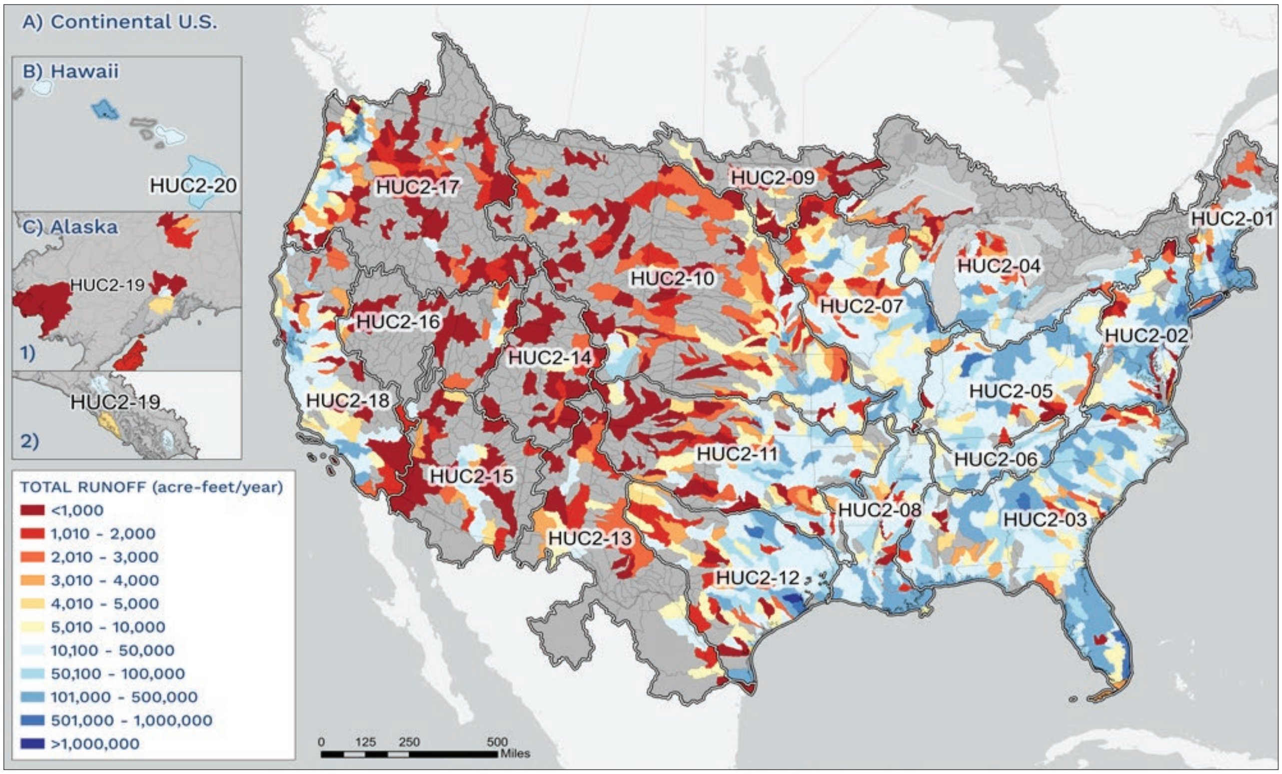
Note: Alaska map panels are labeled as follows: 1) South Central Alaska and portions of Southwest and Interior Alaska, and 2) Southern tip of Alaska Panhandle.

Even in areas with lesser volumetric potential, the drivers and potential co-benefits may still make a compelling case for adoption. Therefore, volumetric potential should not be considered as the sole criteria for prioritization of stormwater runoff capture efforts. Additional criteria can include storage and treatment capacity and cost, demand for alternative water sources, and potential for co-benefits to achieve additional community goals. Our analysis suggests that stormwater runoff capture can be a viable water supply strategy across the country.

SUBBASIN-LEVEL STORMWATER CAPTURE POTENTIAL

Results were also aggregated for hydrologic basins (i.e., HUC8) to examine potential watershed-scale implications of urban stormwater runoff capture. In general, the geographic variability follows precipitation trends across the country, with lower stormwater runoff generated within the Great Plains and Mountain West regions (Figure 8). These regions also tend to have higher stormwater runoff potential in the downstream portions of the region (as illustrated in HUC2 regions 10 (Missouri Region), 11 (Arkansas-White-Red Region), 12 (Texas-Gulf Region), 17 (Pacific Northwest Region), and 18 (California Region). Stormwater capture in the upstream areas of these regions could have minimal negative impacts for downstream users within the same basin, due to the difference in magnitude of stormwater runoff potential across upstream and downstream portions of these basins.

FIGURE 8. **Total Annual Estimated Urban Stormwater Runoff Potential, HUC8 Subbasins**



Notes: Alaska map panels are labeled as follows: 1) South Central Alaska and portions of Southwest and Interior Alaska, and 2) Southern tip of Alaska Panhandle. HUC2 region boundaries shown. Areas with a hatched line pattern in the figure indicate subbasins with zero urban stormwater runoff potential due to the absence of any Urban Areas. The total runoff for each subbasin only represents stormwater runoff generated within the subbasin and does not include contributions from upstream subbasins.

By contrast, in the eastern major river basins, the areas with the highest stormwater runoff potential are found across upstream, midstream, and downstream portions of their respective hydrologic regions. The relatively even distribution of stormwater runoff potential across each of these basins suggests that implications for downstream water users would need to be more carefully considered for mass adoption of stormwater capture in the upstream portions of these basins. For HUC regions that serve as tributaries to other watersheds, such as HUC2 Region 10 (Missouri Region), the impacts of stormwater runoff capture on water availability for the environment and downstream water rights holders would also need to be considered more heavily as adoption of stormwater capture increases over time.

CASE EXAMPLES

In this section, we present four case examples to highlight potential applications of these results across multiple water resource planning and management practices: groundwater management in Arizona and Minnesota, water supply planning and regional coordination in northern Georgia, and state water planning in Texas. These examples highlight specific opportunities for stormwater capture to achieve policy goals, identify potential trade-offs, and/or provide direction for further investigation. Each case example was selected to explore major themes of considerations for stormwater capture: water supply resilience and diversification, potential co-benefits, integration into regional water planning processes, and major drivers and barriers.

Arizona – Groundwater Recharge Potential

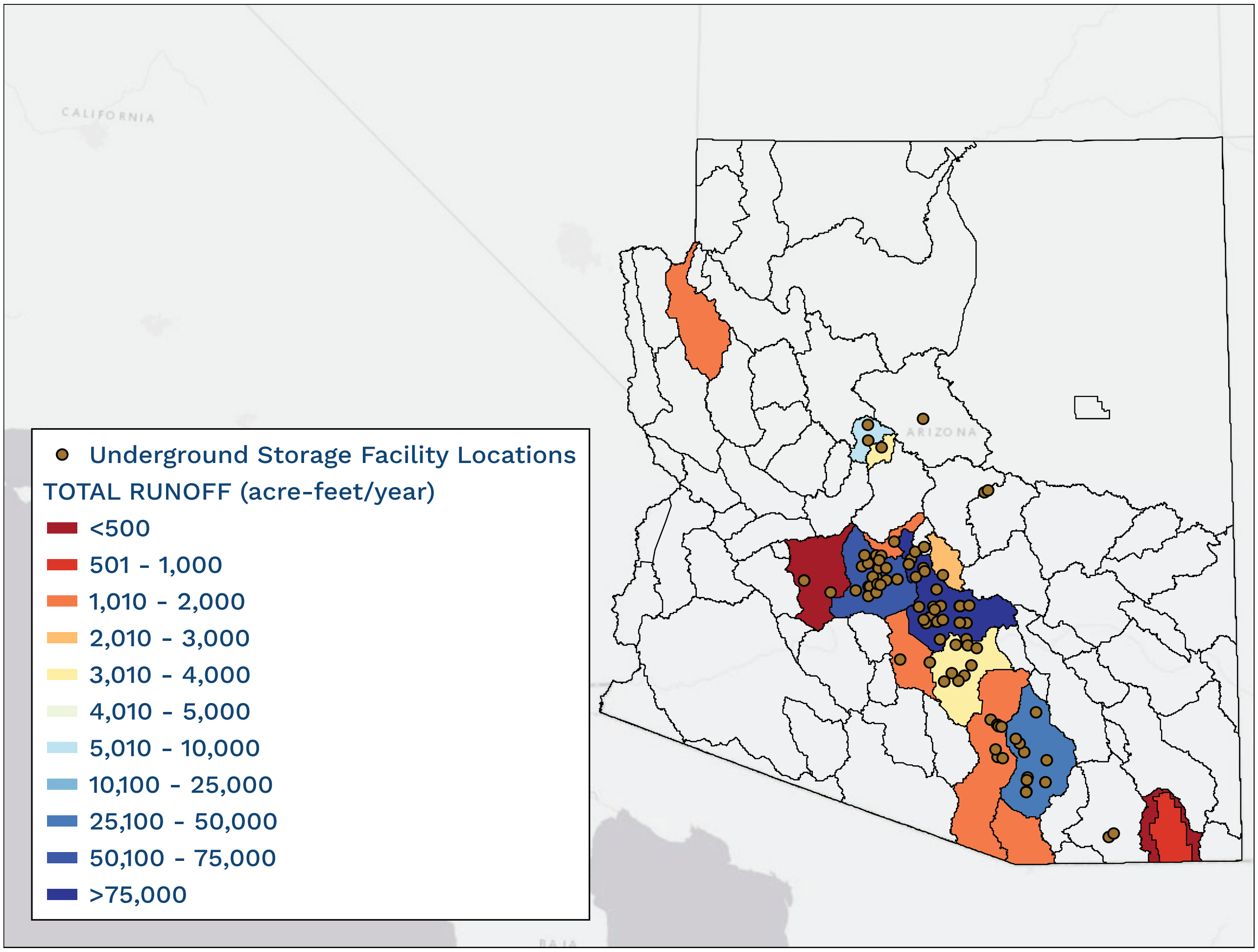
The State of Arizona has been facing dwindling water supplies for many decades. In some areas of the state, unsustainable rates of groundwater extraction for municipal use from rapid population growth and agricultural and industrial demands have stressed existing groundwater supplies. To ensure an adequate supply of groundwater in the future, the state passed legislation in 1980 to designate Active Management Areas (AMAs) and Irrigation Non-Expansion areas with the expressed goal of controlling groundwater overdraft and augmenting groundwater through water supply development (Arizona Department of Water Resources n.d.). AMAs exist for six major population centers in Arizona (Douglas, Phoenix, Pinal, Prescott, Santa Cruz, and Tucson) that collectively comprise approximately 82% of the state population (Arizona Department of Water Resources 2016).

Beyond the creation of these AMAs, in 1996, the state legislature also established the Arizona Water Banking Authority (AWBA) to store unused surface water from the Colorado River (conveyed to the state by the Central Arizona Project). Renewable water supplies, such as treated municipal wastewater, via direct and indirect recharge, are also used for water banking efforts (Arizona Water Banking Authority n.d.). Direct recharge is accomplished using several recharge ponds and injection wells in the Phoenix, Pinal, and Tucson AMAs, illustrated in Figure 9. In recent years, however, reduced surface water availability from the Central Arizona Project has limited the amount of groundwater recharged from these facilities (Arizona Water Banking Authority 2023).

A Potential Role of Stormwater Capture: Supplementing Groundwater Recharge

Despite these efforts, the Arizona Department of Water Resources (ADWR) recently estimated that water demand in the City Phoenix will exceed available supplies by an average of 48,600 AFY over the next 100 years (LoDolce and Mitchell 2023). This identified water need reveals a potential opportunity for stormwater capture in the Phoenix AMA to supplement groundwater recharge efforts and/or expand the uses for Colorado River water (including ecosystem protection). We estimate that the overall annual stormwater runoff potential identified for the Phoenix-Mesa-Scottsdale, AZ Urban Area amounts to roughly 140,000 AFY, which translates to 14 million acre-feet over the next 100 years. This is almost three times the unmet demand estimated for the Phoenix AMA and suggests stormwater capture should be investigated further as a viable recharge source.

FIGURE 9. Arizona Urban Stormwater Runoff Potential, by Groundwater Subbasin



Data Source: Arizona Department of Water Resources, 2023

Metropolitan North Georgia Water Planning District – Regional Water Planning

The Metropolitan North Georgia Water Planning District (MNGWPD) is a regional water planning entity comprised of 96 municipalities across 15 counties in the greater Atlanta metropolitan area. The MNGWPD supports partner communities, residents, and businesses with technical and educational resources; facilitates coordination across six river basins in the region; and oversees the development and implementation of a holistic regional water resources management plan within the framework of the state's regional water planning process.

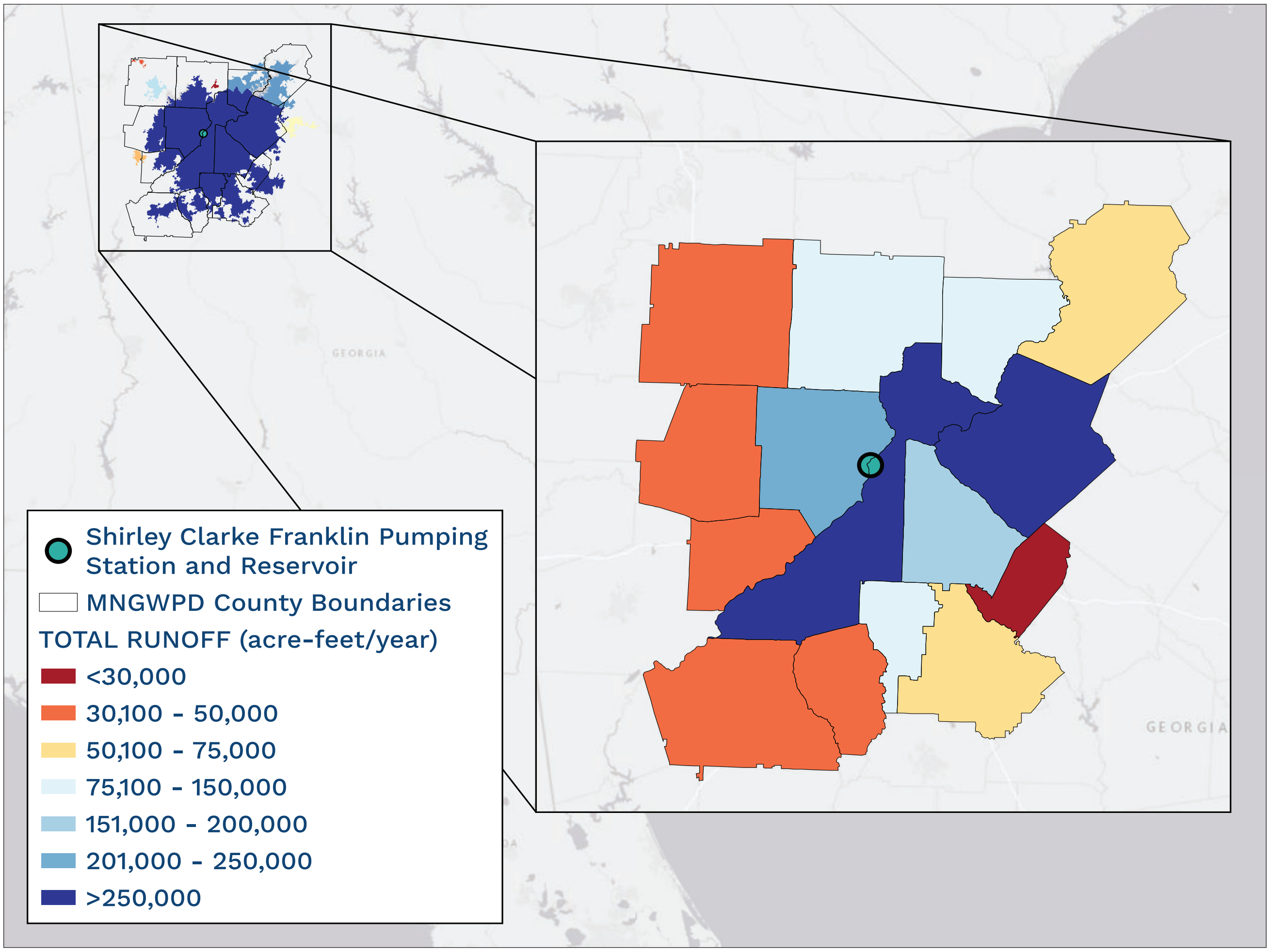
The region relies almost entirely on surface water supplies from the six river basins and faces challenges related to cycles of drought and flood, persistent population growth, impacts of urbanization on watershed health and water quality, and needs of downstream water users. To this end, the MNGWPD has identified several action items for its constituent members in its 2022 Water Resources Management Plan to advance policy goals for water supply and conservation, municipal wastewater and stormwater management, and water quality protection while accommodating persistent population growth in the region.

A Potential Role of Stormwater Capture: Improving Regional Collaboration and Coordination

The volumetric potential for urban stormwater runoff in the MNGWPD service area varies widely by county, ranging from less than 30,000 AFY to over 250,000 AFY (Figure 10). While some of this water serves as a water source for downstream water users east and south of the MNGWPD, the variability of precipitation in the region exposes it to both drought and flood risks that require careful management of surface water supplies. This challenge could present an opportunity to integrate stormwater capture to achieve multiple policy goals for the region.

For example, in 2016 the City of Atlanta's Department of Watershed Management began to transform a defunct quarry into a 2.4-billion-gallon emergency water supply reservoir (location shown in Figure 10). The reservoir, which also captures stormwater from the surrounding area, expanded the City of Atlanta's water storage capacity from 3–5 days to up to 90 days. The reservoir also provides community benefit in the form of the city's largest public park and infrastructure to mitigate excess stormwater in the area. Though the project was not initiated by the MNGWPD, the estimates of urban stormwater runoff presented in this report could be used in the region to facilitate coordination of similar innovative stormwater management activities between partner communities to meet regional water supply and watershed management goals.

FIGURE 10. **Metropolitan North Georgia Water Planning District's Urban Stormwater Runoff Potential, By County**



Minnesota – Environmental Drivers and Perceived Barriers to Stormwater Capture

Minnesota is a relatively water-rich state that is highly dependent on groundwater as a primary source to meet municipal and agricultural demands, and is characterized by a strong northwest-to-southeast precipitation gradient (Delin and Falteisek 2007). The Minnesota Department of Natural Resources (MDNR) is charged with protecting domestic water supplies for drinking, bathing, and sanitation, though there are several recent challenges to this mission (Minnesota Department of Natural Resources 2023). While groundwater quality varies around the state, most of the state's groundwater supplies (serving 75% of Minnesota's population) are threatened by limited availability and/or pollution from multiple contaminants (Minnesota Pollution Control Agency n.d.; Minnesota Center for Environmental Advocacy n.d.). Groundwater withdrawal volumes in some areas of Minnesota have been determined to be unsustainably large. The MDNR has designated these portions of the state as Groundwater Management Areas (Minnesota Department of Natural Resources n.d.). Surface water supplies and associated ecosystems are also at risk, as heavy reliance on groundwater can reduce surface water extent and availability during droughts and increase pollutant concentrations in rivers and streams (Minnesota Center for Environmental Advocacy n.d.).

Stormwater in Minnesota has typically been captured on-site or at a district-scale and used to meet non-potable water demands, primarily for landscape spray irrigation with additional non-potable uses such as fire suppression, toilet-flushing, cooling, and vehicle washing. These uses come with different treatment requirements or recommendations, depending on stormwater source and intended use (Minnesota Pollution Control Agency 2022). The Minnesota Pollution Control Agency also differentiates between stormwater collected solely from roofs (referred to as rainwater) and stormwater collected from the ground, including roads and other impervious surfaces (referred to as stormwater), which has implications for treatment requirements due to differences in water quality between these sources (Minnesota Pollution Control Agency 2022). Recent examples of rainwater and stormwater capture projects include the Towerside District Stormwater System in Minneapolis where water is used for irrigation, the Water Works Pavilion facility in Minneapolis where water is used for toilet flushing and irrigation, and the Allianz Field soccer stadium in Saint Paul where water is used for irrigation and future non-potable indoor uses (Mississippi Watershed Management Organization n.d.; Minneapolis Parks & Recreation Board n.d.; Capitol Region Watershed District n.d.).

Stormwater capture and reuse in Minnesota has historically been driven by three factors: 1) meeting volume control regulatory requirements, 2) protecting groundwater supplies by reducing potable water use, and 3) promoting sustainable practices to respond to public expectations around efficient resource use as well as a changing climate the increases uncertainty around water supply reliability. Most of the urbanized areas in Minnesota have stormwater volume control regulations for development, which typically results in the construction of infiltration-based stormwater capture projects.

An important context to these drivers is the regulatory environment that has fostered this innovation in stormwater capture and subsequent use.

In many cases however, local conditions can limit or prohibit infiltration-based practices (Minnesota Pollution Control Agency 2020). Major considerations include groundwater contamination, high groundwater table, clay soils that limit infiltration rates, or shallow/karst bedrock with very high infiltration rates that limit attenuation of pollutants before entering deep aquifers. Still, stormwater capture and reuse can be an effective method to partially or fully meet volume control requirements without a concentrated infiltration-based system. However, this method is only one of several alternative regulatory compliance pathways. If a project developer determines that stormwater capture and reuse is too expensive or complicated, they can opt for a different alternative compliance method.

An important context to these drivers is the regulatory environment that has fostered this innovation in stormwater capture and subsequent use. Except for plumbing code requirements for uses inside a building (including non-potable uses), there is little regulation around stormwater capture for reuse. The lack of regulatory barriers has allowed for the proliferation of irrigation as a use of captured stormwater. To date, when state regulation has been proposed, local (municipal- and watershed-level) stakeholders have voiced concerns with the potential for regulation that would limit the adoption of stormwater capture for certain uses.

In 2017, after an extensive stakeholder process that included multiple state agencies, Minnesota statutes were revised to specifically state that the MDNR would not permit the "appropriation or use of stormwater collected and used to reduce stormwater runoff volume, treat stormwater, or sustain groundwater supplies when water is extracted from constructed management facilities for stormwater" (State of Minnesota 2023). Since 2017, there has been an effort in Minnesota to develop guidelines for stormwater capture and reuse. This has been led by the MN Department of Health (MDH) because of concerns about the possible risks to public health due to the chemical and pathogen loads in stormwater. This work is underway and has not yet reached final conclusions or recommendations[5].

A Potential Role of Stormwater Capture: Augmenting Water Supply and Improving Water Quality

While stakeholder conversations around appropriate regulatory requirements for use of captured stormwater are ongoing, managed aquifer recharge (MAR) has seen increasing interest in recent years as a means of temporary water storage and sustainable aquifer management in the face of impacts from climate change on water. Managed Aquifer Recharge technologies include infiltration-based practices commonly used for stormwater runoff management but can also include deep injection of water directly into aquifers to augment groundwater supplies. Alternatively, Aquifer Storage and Recovery (ASR) can provide a mechanism to temporarily store treated wastewater in aquifers and subsequently extract some or all of the stored volume to improve water supply reliability, help meet peak water demands, create a water supply less susceptible to contamination, conserve land area that would be used for water storage, and sustain groundwater-fed ecosystems (Bilotta et al. 2021). Both techniques can represent an additional option for stormwater capture (groundwater replenishment vs. water supply supplement), and the appropriateness of adoption will depend on the local needs and priorities of the area where the project is implemented.

We estimate the total stormwater runoff potential for Urban Areas in Minnesota is approximately 630,000 AFY (Figure 11), which is roughly twice the annual M&I water withdrawals reported for 2015 (Dieter et al. 2018). This result suggests a significant potential role for stormwater as a water supply for Minnesota, and efforts to study the recharge potential of aquifers within the state are currently underway (O'Brien 2023).

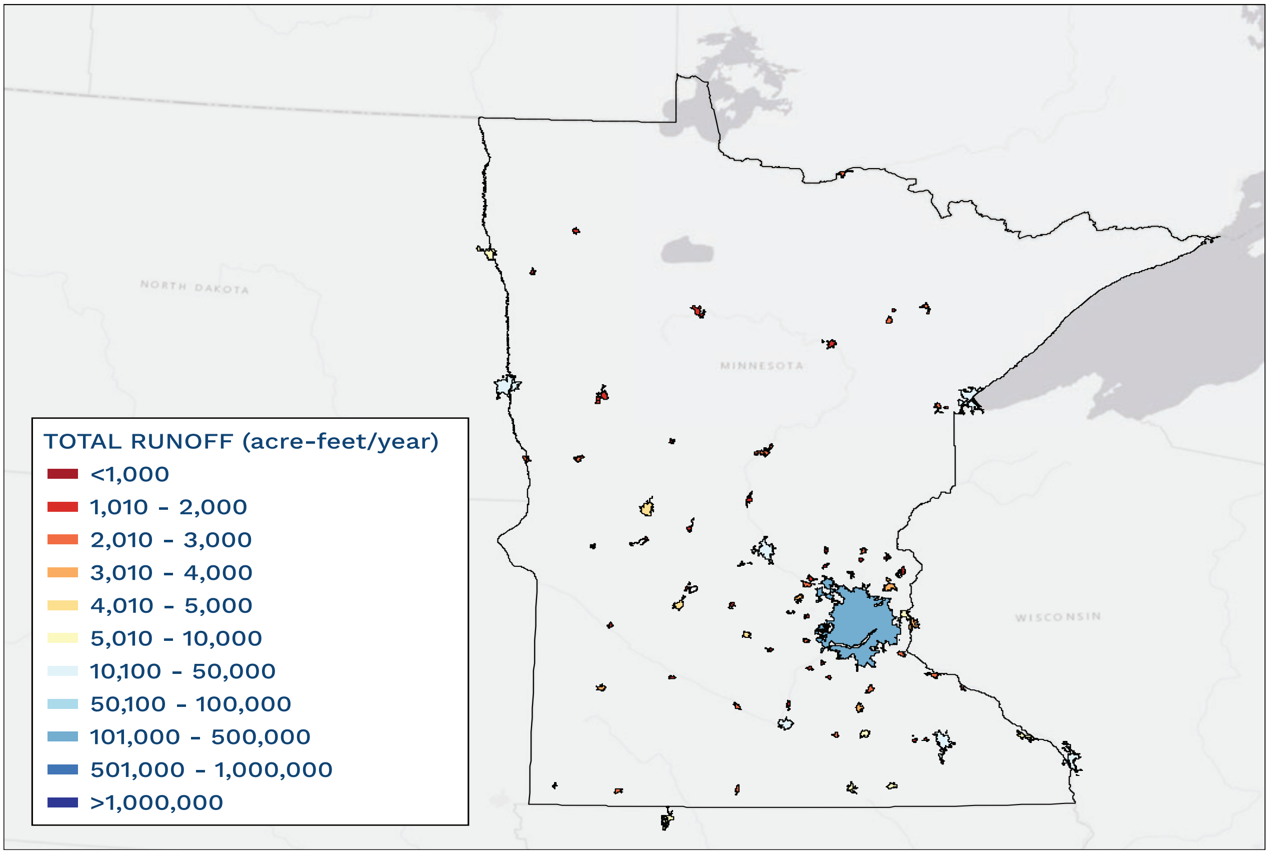
While stormwater capture is not yet heavily regulated in Minnesota, there are several barriers for the method of capture and allowable uses that must be overcome to allow for greater use of stormwater in Minnesota. While the state already allows stormwater to be used for multiple non-potable demands, it currently disallows wells or borings to be used for injection of surface water or groundwater due to concerns over impacts to underground drinking water sources (though variances to this rule have been granted in select cases), thus limiting the potential efficacy of stormwater as a water supply via ASR (State of Minnesota 2021; Minnesota Pollution Control Agency 2022; Bilotta et

5 Additional information related to this process can be found at the following: Minnesota Department of Health n.d.; Minnesota Department of Health 2022a; Minnesota Department of Health 2018; Minnesota Department of Health 2022b; Dooling 2019; Ishii et al. 2020; Ishii and Shoemaker 2022; Shoemaker and Stone 2020

al. 2021). Moreover, the strong northwest-to-southeast precipitation and groundwater recharge rate gradients in the state could lead to a potential mismatch between where stormwater is available for capture and where it is needed to meet demands (Delin and Falteisek 2007).

Broadly speaking, MAR can improve groundwater quality. However, there may be places where existing or legacy contaminants are mobilized or new contaminants, such as salts from winter road treatments, are introduced (Bilotta et al. 2021). As a result, recharge sites will need to be evaluated carefully. These challenges are not insurmountable, however, and the volumetric potential for stormwater capture in the state suggests that stormwater capture in Minnesota can be expanded beyond its current role.

FIGURE 11. Minnesota Urban Stormwater Runoff Potential by Urban Area



Texas – State Water Planning

The State of Texas conducts a statewide water planning process every 5 years to identify future water needs (i.e., gaps between projected demands and available supplies) and strategies to meet these needs. The planning process is conducted for 16 water planning regions primarily organized along major river basin boundaries. Each planning region is responsible for developing and submitting projections of available water supplies and water demands by sector for a 50-year planning horizon; these are then compiled and published as the State Water Plan.

The latest iteration of Texas' State Water Plan identifies the municipal sector as the largest source of additional water needs (~3.14 million AFY by 2070), driven primarily by projected rapid population growth (Texas Water Development Board 2022). To meet these needs, regional planning groups identified about 5.17 million AFY of new water supplies for the municipal sector. These include new traditional water supply strategies (i.e., new surface water reservoirs and groundwater wells) and alternative water sources, such as recycled water, seawater and brackish groundwater desalination, and aquifer storage and recovery using treated surface and groundwater supplies (Table 5).

Within the State Water Plan, traditional water supplies make up 52% of total identified new water supplies (2.7 million AFY), followed by demand reduction (21%, 1.11 million AFY) and water reuse (18%, 940,00 AFY). Together, these three strategies represent 92% of the total anticipated volume for all water management strategies proposed.

TABLE 5. Water Management Supply Strategies Identified in 2022 State Water Plan for Texas

SUPPLY STRATEGY	PROJECTED YIELD IN 2070 (AFY)	NUMBER OF PROJECTS IDENTIFIED	PERCENTAGE OF TOTAL VOLUME
"Traditional" Supplies	2,700,000	3,070	52%
Demand Reduction (Municipal Conservation & Drought Management)	1,110,000	2,480	21%
Reuse (Direct & Indirect)	940,000	869	18%
Aquifer Storage and Recovery	174,000	166	3%
Desalination (Brackish Groundwater & Seawater)	141,000	50	3%
Conjunctive Use and Other Strategies	112,000	191	2%
Total	**5,170,000**	**6,820**	**100%**

Notes: "Traditional" supplies denotes new major reservoirs and new groundwater wells. "Conjunctive Use" refers to strategies that combine multiple water sources, usually surface and groundwater, to yield additional firm water supplies (e.g., use of groundwater to supplement surface water supplies during drought conditions and vice versa for over-extracted groundwater aquifers). "Other Strategies" denotes additional surface water strategies, such as minor reservoirs, subordination of water rights, long-range conveyance, reassignment of existing water supplies, and water transactions.

A Potential Role of Stormwater Capture: Increasing State-Wide Use of Alternative Water Supplies

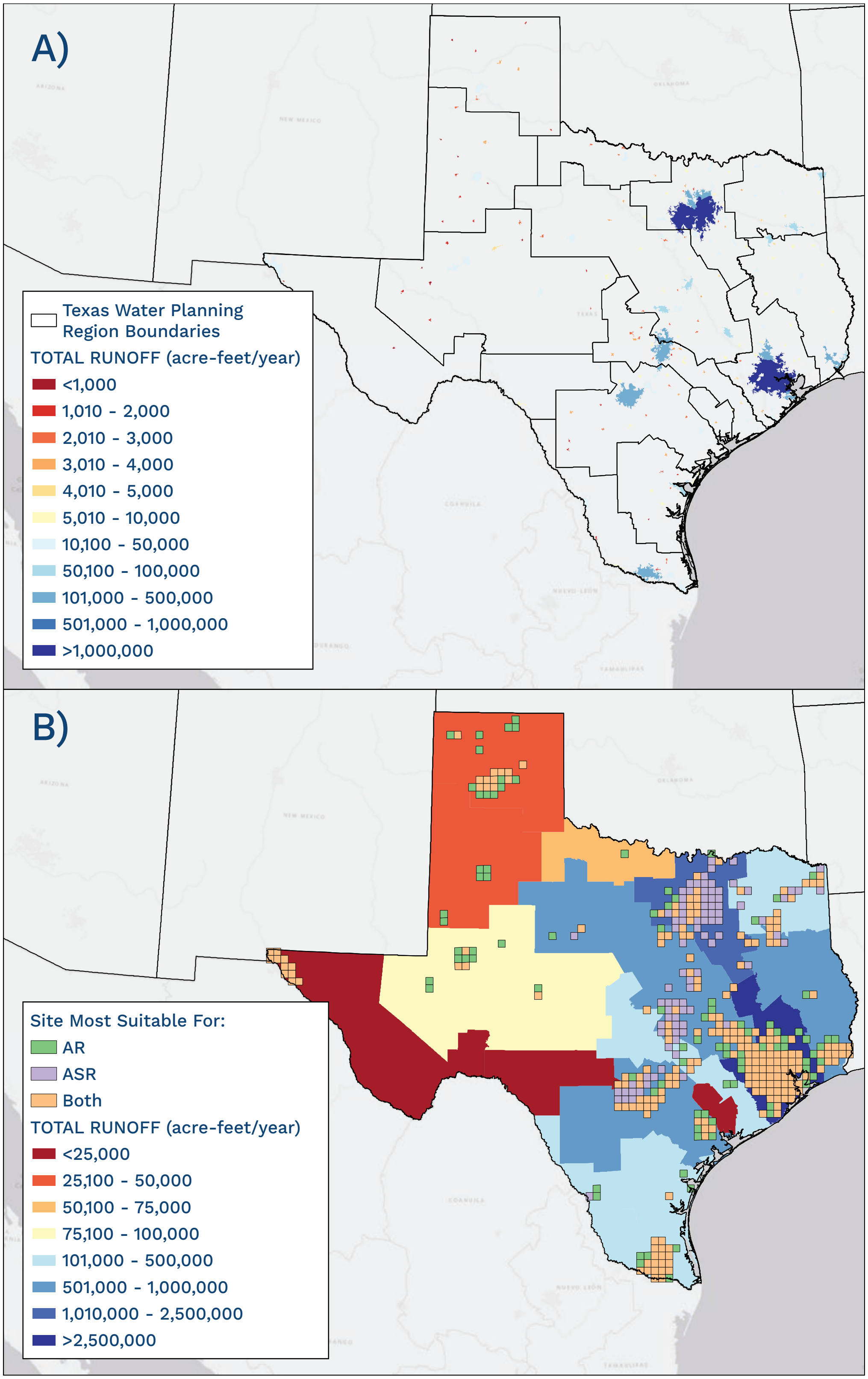
For comparison, we estimate that the urban stormwater runoff potential for Texas is 7.80 million AFY, or 1.5 times the gap between projected municipal sector water demands and estimated supplies for 2070. Some portion of urban stormwater runoff is likely already accounted for in existing surface water supplies and would not represent a new supply. However, this estimate suggests a significant opportunity for stormwater capture to meet projected municipal water needs in Texas.

While stormwater capture appears explicitly as a water management strategy for just one Water Planning Region (Region K – Lower Colorado River), the majority of regions have included ASR as a proposed water management strategy (Texas Water Development Board 2022). Water sources for ASR typically include surface water (both raw and treated) and groundwater. However, the significant amount of stormwater runoff in Texas should prompt the consideration of stormwater capture (after sufficient treatment) as an additional source. Moreover, urban stormwater runoff potential exists in each of the Texas Water Planning Regions and is frequently co-located with areas designated as most suitable for ASR projects (Figure 12). This overlap presents an opportunity to elevate the role of ASR as a water management strategy, by providing supplemental water supplies from stormwater capture that can potentially be used to increase ASR project yields.

Beyond these water-supply benefits, stormwater capture can also be used to supplement aquifer recharge programs being undertaken in the state.

Beyond these water-supply benefits, stormwater capture can also be used to supplement aquifer recharge programs being undertaken in the state. For example, we estimate that the highest urban stormwater runoff potential exists within Water Planning Region H, which contains the greater Houston metropolitan area. This region has historically relied on groundwater as a primary water source and aquifer depletion is resulting in ground subsidence. In response, several water jurisdictions have adopted Groundwater Reduction Plans to curb groundwater extraction in favor of surface water and, where possible, promote aquifer recharge. The capture of urban stormwater runoff could help to recharge aquifers, reducing subsidence in these areas and help to mitigate flooding. While additional impacts to downstream water users and environmental flow requirements would require further investigation, these results suggest that urban stormwater capture should be elevated for consideration by water planning regions across the state.

FIGURE 12. **Texas Urban Stormwater Runoff Potential and AR/ASR Site Suitability, By Water Planning Region**



Data Source: Shaw et al. 2020

Section 5: Conclusions & Recommendations

CONCLUSIONS

Increasing water scarcity and supply uncertainty have spurred interest in stormwater capture as a tool to support water resilience. As traditional water supply projects become more expensive and difficult to permit and build, stormwater capture and other alternative water supplies can provide a holistic means to address a range of water-related challenges. Perceptions around stormwater runoff are shifting from viewing stormwater as a nuisance to recognizing it as a potential opportunity. While the water supply benefits of stormwater capture often drive this adoption, stormwater capture (especially when implemented as green infrastructure) can provide additional co-benefits such as water quality protection, groundwater recharge, and community benefits such as urban heat island effect mitigation.

In this report, we estimate that the average annual urban stormwater runoff potential is 59.5 million AFY. This estimate represents 93% of total M&I water withdrawals in 2015. The greatest potential was found in states with significant urban land area and/or annual precipitation. More specifically, Urban Areas in eastern states tend to have much higher total urban stormwater runoff potential than those in western states, although this trend is not uniform.

There are several cases where it is not feasible, legal, or desirable to capture all urban stormwater runoff. Capturing all available stormwater for use would require widespread implementation of stormwater capture projects and practices across most of the built environment, which is likely infeasible in most urban settings. In addition, applicable water rights laws in some states limit the ability to capture and use urban stormwater to protect the rights of downstream rights holders. Moreover, stormwater flows are critical to protecting and restoring riparian and aquatic ecosystem uses in many watersheds, and extensive stormwater capture could adversely affect those downstream uses.

Coastal subbasins, however, are typically located at the farthest downstream end of their respective watersheds, and stormwater capture in these areas is less likely to have adverse impacts on downstream users or water rights holders. We estimate that approximately 37% (21.9 million AFY) of the nationwide estimate is generated in coastal subbasins bordering the Atlantic and Pacific Oceans and Great Lakes.

The case examples presented in this report also highlight existing and potential use cases for stormwater capture in a range of geographies. These include integration of stormwater capture into state water planning processes (Texas), recharge of groundwater aquifers to counteract aquifer depletion and environmental degradation (Arizona and Minnesota), and cooperation/coordination across municipalities to facilitate regional water supply and watershed management goals (Metropolitan North Georgia Water Planning District). While these examples can spur further action in other parts of the country, additional information is needed to refine our estimates and frame them within their respective local contexts.

This study quantifies the total nationwide volumetric potential for stormwater runoff in Urban Areas across the United States, the priority focus of national efforts to elevate the role of stormwater capture as a water supply strategy nationwide, as identified by the US EPA in their Water Reuse Action Plan (WRAP Action 5.5). We conclude that there are significant opportunities to incorporate stormwater capture into water resources planning and management activities nationwide beyond current levels. Even in areas with less urban runoff, stormwater capture can supplement and diversify water supplies. It can also provide important co-benefits, especially when using green infrastructure.

These estimates do not distinguish between runoff that is currently used and runoff that would constitute new water supplies, nor represents the proportion of stormwater runoff that is economically and technically feasible to capture (i.e., the volume of stormwater runoff available after consideration of required storage capacity, treatment methods, available demands, and costs to evaluate stormwater capture as a water supply strategy). To refine these estimates, subsequent studies at the state and local levels should also consider requirements for downstream water users (including ecosystems) and demands for non-potable water supplies from stormwater capture projects.

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RECOMMENDATIONS

This report outlines the potential to expand stormwater capture, identifying large volumes of stormwater that could, under certain circumstances, be captured, used, or stored to augment and diversify water supplies. This is an important first step in understanding and raising awareness about the opportunity. Realizing this potential will require changing local infrastructure and updating federal, state, and local policies and programs to overcome real and perceived barriers. In this section, we offer recommendations to advance opportunities and remove barriers to realize the untapped potential of stormwater capture.

Quantify State, Regional, and Local Stormwater Capture Opportunities. Our results indicate that there are potentially large volumes of stormwater runoff available in urban communities across the United States. The amount of runoff that could be captured to meet local water needs will depend on a host of local factors, including precipitation and development patterns, feasibility of implementing stormwater capture in new development, redevelopment and/or infrastructure retrofits, storage capacity, and water needs. More detailed assessments are needed at the state, regional, and local levels to determine the extent to which stormwater capture can help to augment and diversify water supplies in each area of interest.

- State agencies, including agencies responsible for water supply, should provide financial and technical support for feasibility studies of stormwater capture opportunities across multiple scales of implementation and beneficial uses (e.g., meeting potable and non-potable water demand, increasing groundwater recharge and supply, etc.).
- Regional, state, and local agencies should investigate the implications of stormwater capture method (e.g., decentralized/site-level green infrastructure and on-site reuse, conveyance via gray infrastructure to centralized facilities, hybrid green-gray infrastructure configurations, etc.) and applicable end-uses in assessing volumetric potential of stormwater capture.

Develop National Guidelines for Stormwater Capture. Few states have regulations that directly address stormwater capture, creating uncertainty and confusion among practitioners and end users. Currently, a poorly defined patchwork of state and local regulations is being applied to the authorization of stormwater capture projects, often on a case-by-case basis. The absence of clear guidelines and/or regulatory frameworks for stormwater capture has inhibited development and implementation of stormwater capture projects in many states.

- Federal agencies should continue to develop and disseminate national guidelines that frame the opportunities for water supply enhancement via stormwater capture and proposes strategies for removing barriers to uptake.
- US EPA should develop model guidelines for capturing and treating stormwater and rainwater for different end uses. Non-regulatory federal guidelines should be developed with an eye toward assisting adoption as a regulatory framework at the state/local levels where appropriate. While creation of a national regulatory program for stormwater capture is likely infeasible in the short term, national leadership in determining how to effectively regulate or guide stormwater capture in different settings and for different end uses would greatly assist in clearing up existing regulatory uncertainties and creating consistency across jurisdictions.

- Federal and/or regional entities should create and maintain a national database of state and local stormwater capture requirements (e.g., treatment requirements, allowable uses, etc.) for reference by design professionals and other entities involved in the implementation of stormwater capture projects. This database should also include local rainwater harvesting regulatory codes and requirements. The existing US EPA-developed REUSExplorer system may provide either an appropriate location to house this information or a model to replicate (US EPA 2021).
- State entities should evaluate the specific effects of individual state water rights limitations on stormwater capture potential and develop methods for determining whether and to what extent different levels of stormwater capture affect the ability of downstream rights holders to exercise their rights. Where appropriate, state entities should also evaluate policy options for modifying state water rights limitations on stormwater capture to enable stormwater capture while protecting the rights of downstream rights holders.

Pursue Regional Approaches and Interagency Coordination and Collaboration. Stormwater capture projects can be cost-prohibitive for a single municipality or water provider to pursue by themselves. Collaboration between entities within a watershed can provide additional capacity and funding that facilitate stormwater project financing and implementation. Taking a regional view of water supply development opportunities can help utilities and agencies take advantage of economies of scope and scale, to address opportunities and challenges more effectively.

- Water supply planners and managers should foster collaboration at the watershed scale to incorporate stormwater as part of an integrated water resources management approach that includes alternative water supplies.
- State and federal agencies should provide more incentives and opportunities to leverage multiple funding sources for stormwater capture projects that provide multiple benefits for drinking water, wastewater, flood control, and local land use management.
- State and federal agencies should also support efforts for interagency collaboration within municipalities and watersheds on stormwater capture projects by providing technical assistance, coordination services, and increased funding for interagency projects. For example, state revolving funds could earmark funds to support planning of interagency projects to yield multiple benefits associated with innovative stormwater management.

Expand Applications of Stormwater for Additional Uses. Stormwater, like any other alternative water supply, can be sufficiently treated to provide a fit-for-purpose water supply. In several areas, however, restrictions on use of captured stormwater that exclude indoor end-uses, such as toilet flushing or industrial use, can limit the efficacy of stormwater capture as a water supply strategy. Increasing the amount of stormwater capture nationwide should entail expanding allowable uses of stormwater beyond the most common current uses (i.e., non-potable uses) to include potable and indoor applications. Model guidelines at both the state and federal levels can support this expansion. States should clarify how and when existing health and safety-based water treatment requirements apply to stormwater to efficiently ensure local agencies have a consistent understanding of how to treat and monitor stormwater capture for reuse in different applications. Additional research on pollutant characteristics of stormwater and treatment requirements is needed to improve our understanding of how to safely capture and use stormwater in different settings.

Expand Funding and Financing Opportunities for Stormwater Capture. Most federal funding for water capital projects is provided through the Drinking Water State Revolving Fund (DWSRF) and the Clean Water State Revolving Fund (CWSRF). Only a small fraction of these funds is allocated to stormwater projects. In most cases, state DWSRF programs have not considered stormwater capture projects eligible for financial support. In some cases, stormwater capture projects are eligible for SRF-related funding streams, but there are real and perceived barriers to access these funds, such as an absence of dedicated repayment sources necessary to access loans, the requirement of completed design of projects prior to funding availability, uncertainty of eligibility for funding streams, and inability to leverage additional funding sources for source water and environmental protection. Changes are needed to ensure that stormwater capture projects have equal access to DWSRF and CWSRF financing compared to other traditional and non-traditional water supply projects.

- Federal funders should reduce DWSRF barriers to accessing water supply-related capital project funding for stormwater capture projects.
- Where feasible, states should fund new grant programs to support stormwater capture projects. This approach would help make funding available to stormwater management programs that have difficulty obtaining SRF financing. Innovative financing (e.g., through public-private partnerships, stormwater credit trading, and finance leveraging strategies) is needed to fund both capital and operations and maintenance expenses associated with support stormwater capture projects that are otherwise not competitive for funding that typically supports water and wastewater infrastructure.

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Improve State, Regional, and Local Planning to Support Integration of Water and Non-Water Benefits into Water Management and Investment Decisions. Capturing the untapped potential for stormwater capture, and other alternative water supplies, would benefit from a broader approach to state, regional, and local water supply and land use planning. For example, state and regional entities can advocate for and establish standard methods for valuing multiple benefits when determining funding criteria for capital projects (e.g. SRF financing programs). Incorporating multiple benefits—both water and non-water—into water management and investment decisions can improve a project's financial viability and public acceptance while helping to minimize adverse and unintended consequences.

- State, regional, and local water managers should expand the types of benefits and trade-offs evaluated in water management decisions, and meaningfully engage with stakeholders in these evaluations.
- State, regional, and local water managers should evaluate the distribution of costs and develop an understanding of the levelized costs and benefits of a project to promote more equitable distribution. Equity should serve as an essential lens for evaluating water management strategies.
- State, regional, and local entities should pursue legal avenues and National Pollution Discharge Elimination System (NPDES) municipal stormwater permitting provisions that strongly promote the use of low-impact development and use of stormwater and graywater outdoors.
- Local agencies and organizations should partner to provide incentives that capture the full scope of multiple benefits that can be produced by a stormwater capture project (combining incentives for water supply benefits, stormwater management, etc.). Providing these "stacked incentives" comprised of funding from multiple agencies can reduce the financial burden placed on any single agency and increase the overall level of funding available to incentivize stormwater capture adoption (though caution should be taken such that public funds are not awarded for the same co-benefit more than once).

Facilitate Public-Private Stormwater Capture Projects. Privately-owned land can represent a large volumetric potential for stormwater capture. Public-private partnerships (as well as public-public partnerships between public agencies and schools, parks districts, and other large public landowners) can leverage private sector capacity and investment to implement stormwater capture projects more quickly. Designing stormwater credit trading programs to specifically enable partnering across ownerships to encourage stormwater capture would help build local capacity. These partnerships between public and private entities often require financial analyses, but data accuracy and availability for this type of analysis has to date been low. A comprehensive database of cost benchmarks for different types of stormwater capture can improve the accuracy of financial analyses used to select projects.

- US EPA should develop guidance addressing the use of public-private partnership approaches to stormwater capture, including use of stormwater credit trading concepts, to help build regional and state capacity to implement policies and programs to enable broader participation of private landowners in stormwater capture project delivery.
- State agencies should develop state and/or regional coordination policies and programs that

facilitate public-private stormwater projects, such as through alternative compliance options for municipal and industrial stormwater permits.

- State and local agencies should create and maintain a database of cost data for stormwater capture projects implemented within their service areas. These data can be used to inform private-sector evaluations for project selection and prioritization.

Offer Incentives to Customers to Promote Adoption of Stormwater Capture at Multiple Scales. Site-scale stormwater capture may require high upfront investment that creates a financial barrier to adoption and can discourage otherwise interested parties from implementing sustainable water practices. Reducing the financial barrier to adoption can spur additional uptake by customers wishing to reduce their water demands.

- Water providers, local agencies, and community organizations should provide incentives aimed at reducing upfront costs (i.e., rebates, in-kind installation, financing) for households and other properties to encourage adoption of on-site stormwater capture.

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Investigate Research Gaps to Improve Efficacy of Stormwater Capture Projects. There remain outstanding research questions that must be addressed to support even greater uptake of stormwater capture. State agencies, academics, water agencies, and community organizations all have a role to play in filling research gaps.

- Future quantification efforts should include considerations for:
  - Downstream water rights holders and instream flow requirements for environmental protection.
  - Anticipated impacts of climate change on precipitation frequency, duration, and intensity.
  - The extent to which stormwater runoff currently contributes to regional water supplies.
  - Current levels of stormwater capture to develop estimates of additional “new” supply.
  - Temporal alignment between urban stormwater runoff availability and time of use (i.e., how do storage capacity requirements change for hourly, daily, weekly time scales).
- Researchers and stakeholders should identify real and perceived barriers to implementation of stormwater capture projects and co-develop resources to support overcoming these barriers.
- Researchers should develop methods for assessing what level of stormwater capture is technically and economically feasible in different local settings. These methods should consider factors such as the level of existing development and rate of redevelopment, the spatial concentration of impervious surfaces, the relationship between locally available stormwater that can be captured and the presence of suitable surface storage or aquifer storage capacity, and other physical and logistical factors affecting the feasibility of stormwater capture in specific areas.
- Researchers and stakeholders should further identify the extent to which real and perceived barriers (financial, regulatory, social, etc.) impede implementation of stormwater capture projects and co-develop resources to support overcoming these barriers.
- Researchers and stakeholders should identify the potential effects of and ways to mitigate stormwater capture and recharge impacts on the water quality of public supply aquifers.
- Researchers and stakeholders should develop tools and resources to support communities in accounting for the co-benefits of stormwater capture projects, such as case studies and a library of project-level cost-benefit analyses.

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Appendices

APPENDIX A
TELR MODEL METHODOLOGY AND TECHNICAL DETAILS MEMORANDUM

This appendix communicates a summary of the Stormwater Tool to Estimate Load Reductions (TELR) as implemented to quantify runoff capture potential for urban areas throughout the United States. This work is the result of a collaboration between the Pacific Institute and 2NDNATURE to improve understanding of urban stormwater capture opportunities. The TELR model has been developed by 2NDNATURE over several years and includes contributions from several research scientists, regulatory agency staff, and municipal stormwater managers. The modeling concepts and implementation procedures employed in TELR are described in several peer-reviewed journal articles (Beck et al. 2017; Conley et al. 2020; Conley et al. 2021; Conley et al. 2022), and additional details are provided in this memo.

1 Introduction

Stormwater capture presents a significant opportunity to address water scarcity and mitigate the impacts of urbanization on our environment. As precipitation patterns become increasingly impacted by climate change and the demand on municipal water supplies increases, capturing stormwater can serve as a valuable resource for sustainable water management. By implementing innovative techniques such as rainwater harvesting systems and green stormwater infrastructure, communities can capture and store stormwater runoff for later use in irrigation, industrial processes, and potable water demands after treatment. This approach not only reduces the stress on traditional water sources but also helps to alleviate flooding, improve water quality by reducing pollutant delivery, and enhance overall water resilience in urban areas.

A key first step towards realizing the capture opportunities is to quantify the volumes of stormwater generated in urban landscapes across the nation. Since measurements of urban runoff are generally unavailable at these scales, extensive spatial data and modeling tools are required to produce these estimates. The Pacific institute and 2NDNATURE have been a leader in this type of model-based assessment for the State of California by quantifying the potential to both reduce inefficient and wasteful water use and capture urban stormwater (Cooley et al. 2022; California Stormwater

Capture Story Map n.d.). The resulting modeling outputs can inform further planning processes that consider other factors affecting the feasibility, appropriateness, and prioritization of stormwater capture in specific regions or cities.

2 Modeling Concepts and Approach

This study used TELR to generate urban stormwater runoff estimates. Stormwater TELR is a critical component of the 2NFORM Stormwater Software suite (www.2nform.com), designed to simplify Municipal Separate Storm Sewer System (MS4) permit compliance and empower municipalities to make more informed stormwater program decisions. Stormwater TELR is an urban runoff and pollutant loading model that is integrated with a best management practice asset management and spatial data visualization system in a web-based platform, and can also be run as a stand-alone program.

TELR has been designed to provide a model structure that is fit-for-purpose as a support tool for stormwater management decisions. As such, it was designed to eliminate any unnecessary complexity that does not serve that purpose (e.g., Box 1976; Beven 2001; Beck 2002). Most available stormwater modeling tools are either intended exclusively for expert users (e.g., Atchison et al. 2012) or do not provide an efficient method for modeling multiple catchments or generating spatial outputs (e.g., Tetra Tech 2011; Rossman 2013). Inspired by evidence that simpler approaches to hydrologic modeling may provide comparable performance to more complex ones (Kokkonen and Jakeman 2001; Perrin et al. 2001; Bormann and Diekkruger 2003; Reed et al. 2004; Petrucci and Bonhomme 2014), TELR employs an economical representation of the urban stormwater system, optimized to efficiently prioritize urban catchments for action, estimate the effectiveness of these actions, and track reductions to receiving waters over time. Model verification experiments (see Section 6) have shown that runoff estimates align closely with high-resolution monitoring data (Conley et al. 2021) as well as estimates from more complex, commonly used continuous simulation models (Beck et al. 2017).

The model employs a fully spatially distributed approach in which landscape characteristics and process representation are calculated at the sub-parcel level. Runoff generation employs a probabilistic representation of long-term gridded precipitation and well-tested USDA algorithms for precipitation-runoff transformation and routing to generate average annual runoff estimates. Runoff estimates are driven by the precipitation inputs and the catchment attributes (land use, impervious area, hydrologic connectivity, soils, etc.) used to parameterize precipitation-runoff transformation. Except where noted, all calculations are performed on a 30-m grid to capture unique, location-specific attributes for sub-drainages. The output can then be summarized to polygons such as watershed and municipal boundaries.

3 TELR Runoff Computations

3.1 Scale of Simulation

Stormwater runoff models typically incorporate one of two approaches for the precipitation-runoff transformation: a single storm event methodology or a multi-year, high-resolution (sub-hourly) continuous simulation. Each approach has its advantages and disadvantages. TELR employs a hybrid event-based approach that combines a set of 24-hour duration events drawn from a long-term precipitation distribution to quantify the range of expected runoff responses probabilistically using event percentiles. The efficiency of this method allows a distributed spatial approach in which runoff calculations are discretized on a 30-m grid so that site-specific runoff generation is explicitly represented. This also allows derivation of the model parameterization from widely available spatial data sets, rather than a calibration process which requires flow data that are typically unavailable at urban drainage scales. Two trade-offs are 1) the flow routing is simplified, and 2) the detailed evolution of a particular storm or sequence of storms is not included.

3.2 Rainfall-Runoff Transformation

Stormwater TELR relies on the Soil Conservation Service (SCS) curve number (CN) method for runoff generation, and the approach detailed in Technical Release 55 (TR-55) to estimate runoff from small urban catchments (USDA 1986). The CN approach provides an estimate of direct stormwater runoff, which is the volume remaining after precipitation infiltrates into the ground, is absorbed by vegetation, or evaporates from the surface. The equation for calculation of direct runoff via the SCS CN is:

(eq. 3.1) $$QG = \frac{(PPT - I_a)^2}{(PPT - I_a) + S}$$

QG is the runoff depth (inches) for each grid cell, PPT is the 24-hour precipitation volume (inches), S is the potential maximum retention after runoff begins (inches), and I_a is the initial abstraction (inches). The initial abstraction incorporates all losses before runoff begins, including water retained in surface depressions, intercepted by vegetation, evaporated, or infiltrated. Runoff does not begin until the initial abstraction has been met. I_a is variable across the landscape but is highly correlated to the curve number. The initial abstraction is typically assumed as 20% of the storage:

(eq. 3.2) $$I_a = 0.2S$$

and

(eq. 3.3) $$S_{0.20} = \frac{1000}{CN} - 10$$

More recent data suggest that 20% is likely too high, and that 5% is a more appropriate value (Woodward et al. 2003; Lim et al. 2006; Shi et al. 2009) especially for hydrologic soil groups C and D (Jiang 2001). If 5%, rather than 20%, is used, S must also be modified. The relationship between S0.05 and S0.20 obtained from model fitting results is (Lim et al. 2006; Hawkins et al. 2002):

(eq. 3.4) $$S_{0.05} = 1.33 * (S_{0.20})^{1.15}$$

We use the adjusted initial abstraction ratio (I_a = 0.05*S) and combine these equations to obtain:

(eq. 3.5) $$Q_G = \frac{(PPT - 0.05 * S_{0.05})^2}{PPT + 0.95 * S_{0.05}}$$

The conversion to the total stormwater runoff volume (ac-ft) is the product of the runoff depth (in) and the grid cell area AG (acres):

(eq. 3.6) $$Q_G = \frac{Q_G}{12 * A_G}$$

Curve numbers range from 30 to 98, with higher numbers indicating higher potential runoff (USDA 1986). The major factors that determine SCS curve numbers are the soil permeability and infiltration classified into the Natural Resources Conservation Service (NRCS) hydrologic soil groups (HSGs, see section 4.2), the impervious coverage, land cover types, and the hydrologic condition. For developed areas, impervious cover is the primary factor that determines CN variation beyond the HSGs. Thus, for grid cells with impervious cover >5%, CNs are estimated using a starting pervious CN and the percent impervious coverage by the following equation (USDA 1986):

(eq. 3.7) $$CN_c = CN_p + \frac{PIA_G}{100}(98 - CN_p)$$

CN_c is the composite runoff curve number, CN_p is the pervious runoff curve number based on HSG and hydrologic condition, and PIAG is the percentage of impervious area for each grid cell. The pervious runoff curve numbers are based on the USDA-specified values for developing urban areas (USDA 1986).

3.3 Average Annual Runoff Calculation

The approach to estimating runoff use metrics calculated from the long-term 24-hour precipitation distributions above a precipitation cutoff of 0.01 inches derived from data collected by the PRISM climate group at Oregon State University (http://prism.oregonstate.edu/). Using 24-hour events, the precipitation-runoff transformation uses the 24-hour runoff depth estimate (inches) for the x^{th} percentile event ($Q_G(x)$). A Reimann sum is performed to estimate the integral of a 24-hour event frequency distribution and obtain an average 24-hour runoff depth for days on which measurable precipitation occurs. We approximate the integral using the following equation for non-uniform intervals of x:

(eq. 3.8) $$\int_0^{100} Q_G(x)dx \approx \frac{1}{2}\sum_{k=1}^{N}(x_{k+1} - xk) * (Q_G(x_k + 1) + Q_G(x_k))$$

where x is a number between 0 and 100, exclusive, k is a number in the sequence of total percentile events N used to estimate the integral [0, 0.125, 0.50, 0.85, 0.95 and 1.0] and N = 6 (Figure A1). The percentile distribution is assumed to go through the origin, where zero precipitation equates to zero runoff, $Q_G(0)=0$. Storm events larger than the 95th percentile are not estimated and $Q_G(1.0)$ is assumed to be equal to $Q_G(0.95)$. Validation of this approach was conducted for nine cities across a variety of climate regimes, with an average of 3.5% error, with the greatest error (up to 16%) in drier climates.

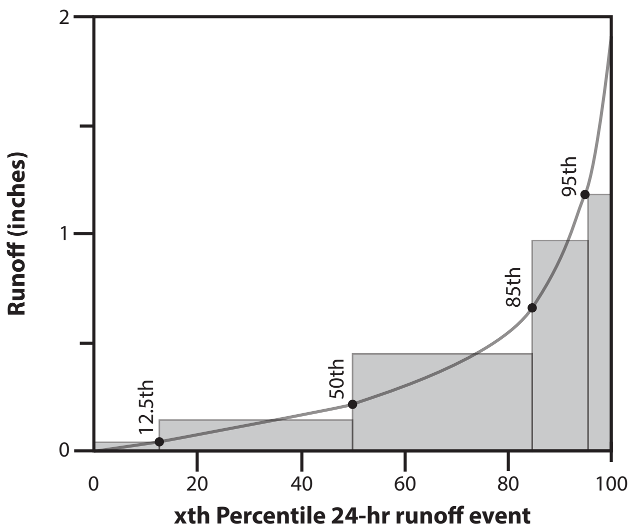
The average 24-hour runoff depth, Q_G, is converted to volume using the size of the grid cell, A_G, within the catchment:

(eq. 3.9) $$QG = \frac{Q_G}{12} * A_G$$

Average annual runoff for each grid cell, Q_{365-G}, is determined by the product of the 24-hour runoff volume for days with rain and the average annual number of measurable rain days per year, d:

(eq. 3.10) $$Q_{365-G} = d * \int Q_G(x)dx$$

FIGURE A1. **Reimann Sum Approach Used in TELR to Estimate Total Runoff**



The final annual average runoff volume, Q_{365}, for a given area is the sum of the grid cell runoff volumes:

(eq. 3.11) $$Q_{365} = Q_{365-G1} + \dots + Q_{365-Gi}$$

where *i* is the total number of grid cells within the area.

Stormwater runoff volumes can be compared within and across catchments, drainages, municipalities, or other spatial boundaries by normalizing by the area, A, and obtaining a runoff depth {Q}.

4 TELR Model Inputs

4.1 Precipitation Data

Precipitation is a key driver of any stormwater model. Stormwater TELR is designed to focus on long-term average annual runoff by fixing precipitation inputs for all scenarios using an approach that classifies the seasonal and inter-annual variability demonstrated by historic data from any climatic region. TELR uses interpolated precipitation data produced by PRISM to estimate precipitation across the entire landscape, not just where precipitation gauges are located. The PRISM group compiles climate observations from a wide range of monitoring networks across the country, applies robust quality control and spatial interpolation techniques, and provides climate data at various spatial/temporal resolutions covering the period from 1895 to the present. These data provide a high-quality representation of the precipitation spatial distribution, which accounts for factors such as elevation and aspect that strongly affect precipitation patterns.

To generate inputs for TELR for the conterminous United States, we created a script using Google Earth Engine to acquire and process PRISM historical raster layers between 1981 and 2019. Using the 39-year daily precipitation sequence (13,870 raster layers), a time series of precipitation values was created for each 800-m pixel. The TELR-required percentile precipitation values and annual rain days were then calculated for each pixel and resampled to align with the 30-m US Landsat Analysis Ready Data (https://www.usgs.gov/landsat-missions/landsat-us-analysis-ready-data) grid used by TELR. The raster-based precipitation estimates from PRISM were validated using Western Regional Climate Center (WRCC) (https://wrcc.dri.edu/) rain gauges throughout the United States (see Beck et al. 2017).

Because the daily PRISM inputs are not available in Alaska and Hawaii, alternative precipitation sources were identified. For Alaska, precipitation data were from the ERA5 dataset (Hersbach et al. 2020; https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels) and processed using Google Earth Engine. These data are similar to PRISM but at 27,830-m resolution. For Hawaii, finer spatial resolution is needed because of the strong precipitation gradients. Therefore, we used daily precipitation data downloaded from the WRCC to determine the relationship between mean annual precipitation and the different precipitation percentiles needed in TELR. The input metrics for TELR were then calculated based on the regressions applied to average annual precipitation maps (250-m resolution) from the Hawaii Climate Data Portal (McLean et al. 2020; https://www.hawaii.edu/climate-data-portal/).

4.2 Soils

The NRCS defines four hydrologic soil groups (HSGs): A, B, C, and D. HSG A has the highest infiltration rate potential and is associated with the areas of lower runoff whereas HSG D has the lowest infiltration potential and is associated with areas of greater runoff. The classification of soils is determined by the soil layer with the lowest saturated hydraulic conductivity and the depth to any layer that is impermeable or depth to a water table. HSGs reflect infiltration in the subsurface at depths of up to 2 feet or greater.

HSGs are based on precipitation-runoff data and infiltrometer measurements (NRCS 2004) and available from NRCS using the 30-m US Landsat ARD grid. The NRCS Soil Survey Geographic (SSURGO) database is typically used as the primary data source, and the State Soil Geographic (STATSGO2) database (which provides lower resolution) is used to fill in spatial gaps that occur in the SSURGO data. Remaining data gaps in the Hawaii soils data (nearly exclusively outside of the Census Urban Areas) were filled using the ArcGIS “Nibble” tool, which replaces cells of a raster corresponding to a mask with the values of the nearest neighbors.

4.3 Impervious Coverage

A key input for runoff generation in TELR is satellite-derived impervious cover derived from the Landsat satellite series and available from the USGS as part of the National Land Cover Dataset (NLCD) at 30-m resolution (Dewitz 2021; Yang et al. 2018). Impervious cover dramatically reduces runoff infiltration to soils and thus transforms incident precipitation to runoff at substantially higher proportions than undeveloped areas. Use of satellite imagery to quantify impervious cover has several important benefits for estimating urban runoff. Satellite impervious coverage data is widely available, regularly updated, and can be easily accessed for any municipality. Given that trees substantially impact precipitation-runoff transformation in urban drainages (Dwyer et al. 1992; Roy et al. 2012), the fact that the satellite data accounts for the urban tree canopy provides a better estimate of the effective impervious cover for precipitation-runoff transformation purposes compared to ground-based data.

For the conterminous United States, we used the percent imperviousness from the NLCD from 2019 (https://www.mrlc.gov/data/nlcd-2019-percent-developed-imperviousness-conus). Neither Alaska nor Hawaii are included in that data release however. An analysis was performed by sampling ~50,000 randomized points across the conterminous United States to determine the relationship between land cover classes and imperviousness. We then generated percent imperviousness by assigning the average impervious cover values to each developed land cover class. Alaska imperviousness was derived from the 2016 NLCD land cover layer for the state (https://www.mrlc.gov/data/nlcd-2016-land-cover-alaska). For Hawaii, the most recent high-resolution land cover data available is from 2012 (Jacobi et al. 2017; https://www.sciencebase.gov/catalog/item/592dee56e4b092b266efeb6b). In addition to cross-walking the developed land areas to percent imperviousness, we also cross-walked the land cover classes to be the same as the NLCD classes. The results were comparable to the 2001 NLCD imperviousness layer for the state (https://www.mrlc.gov/data/nlcd-2001-percent-developed-impervious-hawaii-0).

4.4 Land Cover

For undeveloped areas, the land cover type is likely to be an important determinant on runoff transformation, rather than the proportion of impervious cover. For grid cells with <5% impervious cover, we rely on satellite-based land cover classifications from the Landsat NLCD to determine runoff curve numbers for each hydrologic soil group by mapping NLCD Land Cover Types to the USDA cover types, classified as “fair” or “poor.” While there is certainly variation of land cover conditions across municipalities, land cover within MS4 boundaries is more likely to be disturbed by human activities, hence the use of the lower condition categories.

Datasets used are from 2019 for the conterminous United States and 2016 for Alaska. As noted above, we used a separate 2012 land cover dataset for Hawaii, cross-walked to the NLCD land cover classes.

5 Quality Checks And Runoff Summarization

Model runoff outputs are checked for accuracy and quality before summarizing them to the relevant spatial units. Quality assurance checks for this project included spatial sampling, plotting runoff distributions, and assuring that outputs were within expected ranges in areas with measured runoff amounts. Scatterplots between the estimated runoff and landscape factors controlling runoff generation were examined. Finally, runoff ratios were examined to assess alignment between the outputs of the conceptual relationships between these ratios and other landscape factors (e.g., impervious cover).

High spatial resolution runoff outputs from TELR provide the flexibility to analyze the results for various regions. The project team in coordination with the project advisory group decided that the relevant area for analysis of the TELR outputs would be US Census Bureau Urban Areas. These are defined as areas containing at least 2,000 housing units or having a population of at least 5,000 (full definition is at https://www.govinfo.gov/content/pkg/FR-2022-03-24/pdf/2022-06180.pdf). There are more than 2,600 distinct areas and include most of the developed landscape across the United States (formerly defined separately as Urban Areas and Urban Clusters). Grid cells within these areas were included in the analysis using the “Extract by Mask” tool in ArcGIS Pro. An analysis of the acreage of the analyzed areas versus the original acreage of the Urban Area dataset for the conterminous United States shows a slight overestimate of the TELR runoff area of 2.2%, though the exact offset differs for each Urban Area.

Spatial summaries for runoff outputs from TELR were generated from the 30-m raster outputs using the ArcGIS Spatial Analyst Toolbox. The “Zonal Statistics” tool was used to summarize the raster outputs from TELR to produce tabular summaries for each polygon area of interest for urban areas of the continental United States, Alaska, and Hawaii.

6 TELR Model Validation

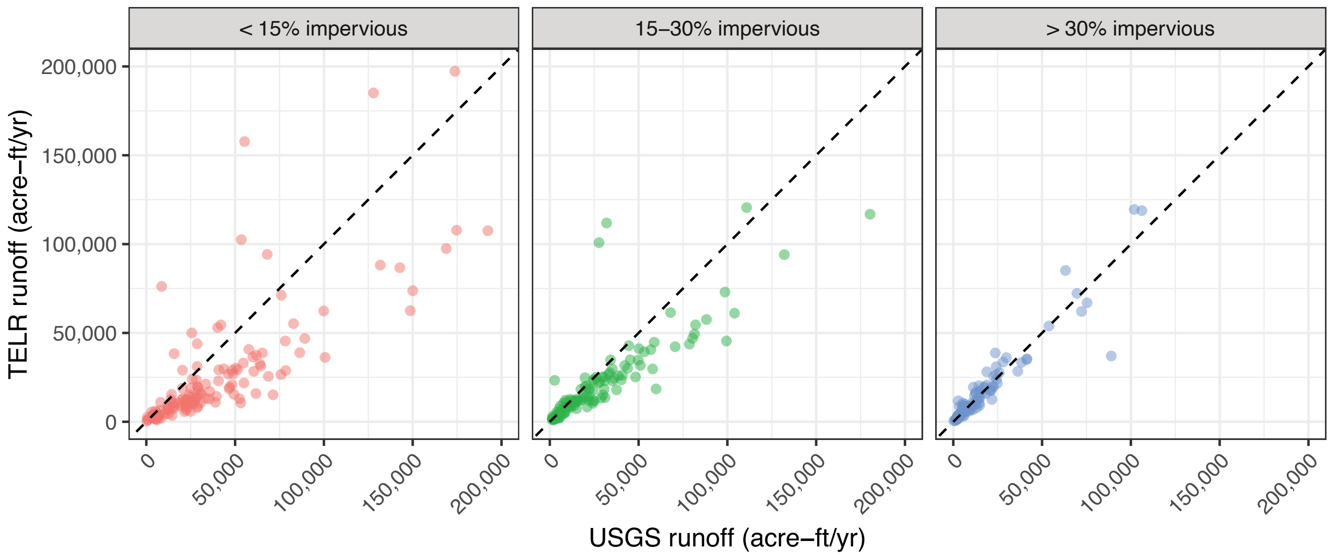
Stormwater TELR has been validated at multiple spatial scales, including urban catchments and watersheds. TELR runoff computations have been validated in three ways: (1) comparison with event-based and continuous-simulation models, (2) comparisons with monitoring data at the urban catchment-scale (e.g., 100-500 ac), and (3) comparisons with streamflow data at the watershed scale (>500 ac). At the catchment scale, model predictions have been validated against long-term measurements at urban catchment outfalls in Lake Tahoe Basin, City of Salinas and Ventura County. Each study included continuous hydrology measurements. A full description of the approach, methods, and results of these monitoring data comparisons are reported in Beck et al. (2017), Conley et al. (2021), and Nodine et al. (2023). Here we provide a summary of the nationwide watershed scale validation results.

We selected a set of watersheds for model output validation based on USGS streamflow data availability (GAGES n.d.; Falcone et al. 2010) and proportional impervious coverage as defined by the National Land Cover Database (NLCD) (Homer et al. 2020). Potential watersheds were filtered using two criteria: 1) >5% NLCD impervious coverage in the watershed in 2016, and 2) <10% missing streamflow data for at least two-thirds of the years from 1985 to 2019. For watersheds with nested streamflow gauges, we selected the one with the highest proportion of impervious cover, so that there were no overlapping watersheds. This filtering process resulted in a total of 372 watersheds distributed across the United States representing a wide range of hydroclimate conditions and environmental regulatory regions. Mean daily discharge data were downloaded from USGS, quality checked, and processed using the R statistical programming software (De Cicco et al. 2018; R Core Team 2018) for the period 1985–2019.

Because TELR models stormflow runoff, which includes surface and shallow subsurface flow (otherwise termed "direct flow"), we separated baseflow from the USGS gauge data using the Hydrostats package in R (Bond 2019). For additional details on the watershed filtering process and USGS streamflow data processing, please see Conley et al. (2022).

Results of the watershed-scale comparisons, separated by impervious cover, are shown in Figure A2. TELR performs well in all categories with R2 values ranging from 0.75-0.88 and an overall percent bias of 4.2%, with the best performance in watersheds with >30% impervious cover. Better performance in more heavily urbanized watersheds reflects the purpose of the TELR: to inform watershed and municipal stormwater decision-making in urban environments.

FIGURE A2. TELR Model Outputs Validation Against 372 USGS Gauged Urbanized Watersheds Throughout the Continental United States



IMPERVIOUS CLASS	R-SQUARED	NSE	BIAS (%)
Low < 15%	0.77	0.63	-37.2
Medium 15–30%	0.82	0.80	-19.4
High > 30%	0.89	0.87	5.7
Overall	0.77	0.68	-28.2

The validation experiments performed to date provide strong support for the applicability of TELR across a wide range of scales, geographies, and hydroclimatologies in the United States. Additional model validation experiments at the urban drainage scale are ongoing as it is applied in new regions and those outfall data are collated.

7 Limitations

While TELR produces stormwater runoff estimates that can be used to quantify the opportunity for stormwater capture, there are clear limitations that should be considered when interpreting the results.

First, as with all hydrologic models, some measure of the uncertainty in the outputs results directly from the input datasets. TELR relies on national datasets that are necessarily generalized by category (e.g., four soil hydrologic groups) and spatially (e.g., 30-m or 800-m grid cells). Some datasets, like the National Landcover Database, are derived from satellite imagery and thus may miscategorize on-the-ground conditions at some locations. Land cover conditions also may have changed since these data were acquired (e.g., the NLCD data are from 2019). For Alaska and Hawaii, the national datasets are incomplete, as noted above, and thus have additional uncertainties as a result of the added data processing needed.

Second, as with all models, elements of the hydrologic processes are simplified for practicalities related to computational limitations and input data availability. The SCS CN method is one of the most widely used and well-tested methods available for precipitation-runoff transformation, but it is a relatively simple way to estimate runoff that includes no detailed representation of physical hydraulic or soil processes. Given that much more complex and widely used models also employ the CN approach, which often show comparable performance to other more sophisticated methods (e.g., King et al. 1999), it was judged a good fit for the model purpose.

Third, precipitation inputs are simplified in several ways, including 1) the use of a finite number of storm percentiles to drive stormwater runoff, rather than direct use of time series data, and 2) the use of annual runoff metrics instead of considering seasonal precipitation (though seasonal results could be produced by TELR in a future project). Runoff generation is also simplified by considering all types of precipitation to produce runoff at the same rates (i.e., the same curve number). Areas that receive considerable snowfall may have different runoff results for that precipitation, although an even bigger concern in those areas might be the removal of snow from the urban footprint, thereby transferring any runoff from eventual snowmelt to another location. Finally, precipitation inputs are based on historic precipitation and do not account for potential future changes in precipitation due to climate change (though results using estimates of future precipitation could be produced by TELR in a future project).

Fourth, there are potential errors introduced by GIS processes, including the conversion of the Urban Areas as polygons into raster data to extract TELR results. The use of the “Nibble” tool also creates results that may not represent real-world conditions.

Given these limitations, we caution that the results should not be overinterpreted. TELR provides estimates of direct stormflow runoff, which includes surface runoff and shallow subsurface flow, also called as quick return flow. The model does not simulate baseflow, which is usually derived from groundwater discharge. Also, the model estimates may not be not equivalent to outputs from hydraulic models used to design engineered structures to capture stormwater. Finally, the results also do not incorporate any existing stormwater control measures. Nevertheless, the model output can be a powerful estimate of the magnitude of stormwater runoff to foster policy discussions as our urban areas plan for managing our water systems more sustainably.

8 Appendix A References

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APPENDIX B
STORMWATER RUNOFF POTENTIAL ESTIMATES FOR US STATES

FIGURE A3. Histogram of Annual Stormwater Runoff Potential Estimates, US States

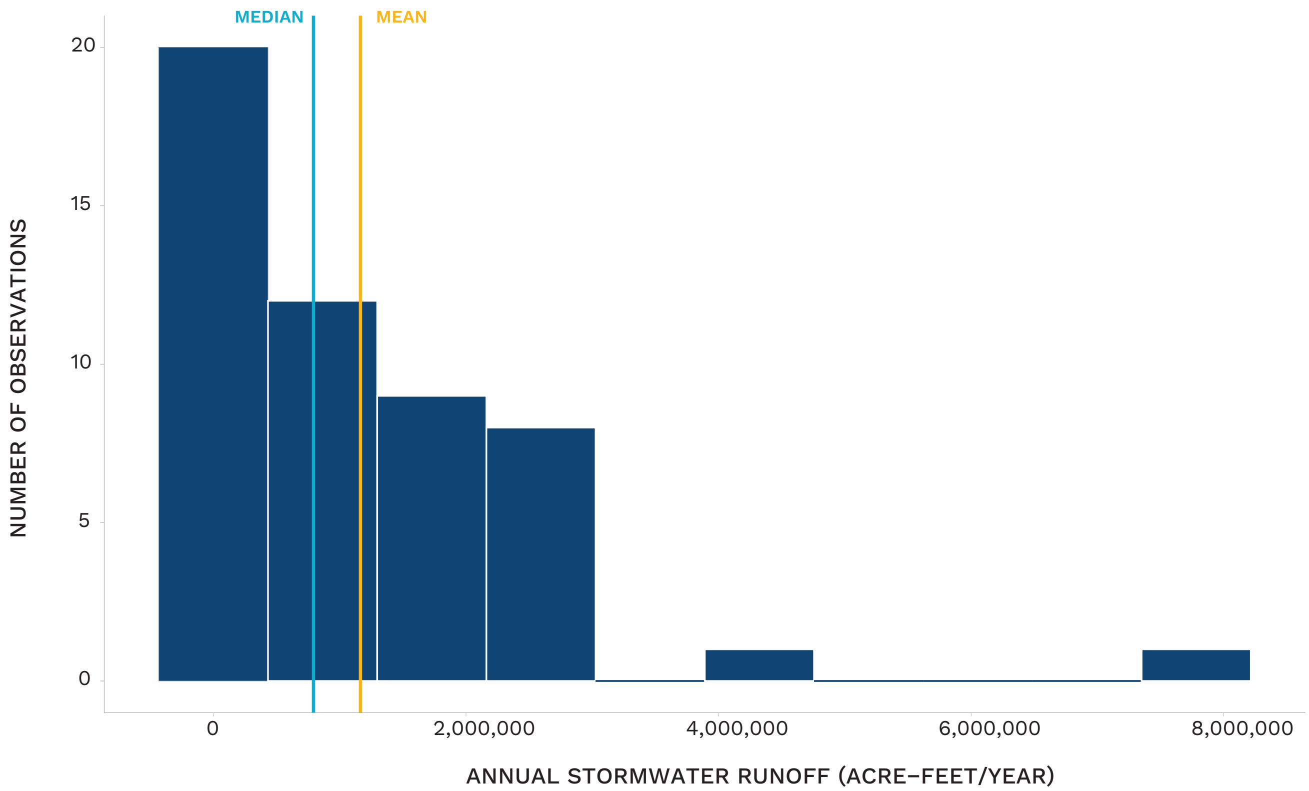


TABLE A1. Summary Statistics for Stormwater Runoff Potential Estimates, US States

PARAMETER	RUNOFF VOLUME	URBAN LAND AREA	AREA-NORMALIZED RUNOFF	POPULATION	AVERAGE PRECIPITATION	RUNOFF RATIO
Units	(acre-feet/year)	(acres)	(inches/year)	-	(inches/year)	-
Total	59,500,000	66,500,000	510	331,000,000	1,930	13.0
Mean	1,160,000	1,300,000	10.0	6,500,000	37.8	0.255
Median	793,000	1,010,000	10.5	4,510,000	42.8	0.235
Standard Deviation	1,330,000	1,280,000	5.09	7,340,000	13.1	0.086
Inter-Quartile Range	241,000	348,000	6.79	1,820,000	34.8	0.201
	1,650,000	1,730,000	13.20	7,430,000	47.1	0.297
Minimum	17,100	39,300	1.340	577,000	6.62	0.101
Maximum	7,800,000	5,800,000	25.2	39,500,000	55.4	0.472

FIGURE A4. Runoff Potential Variation Along Input Variables, US States

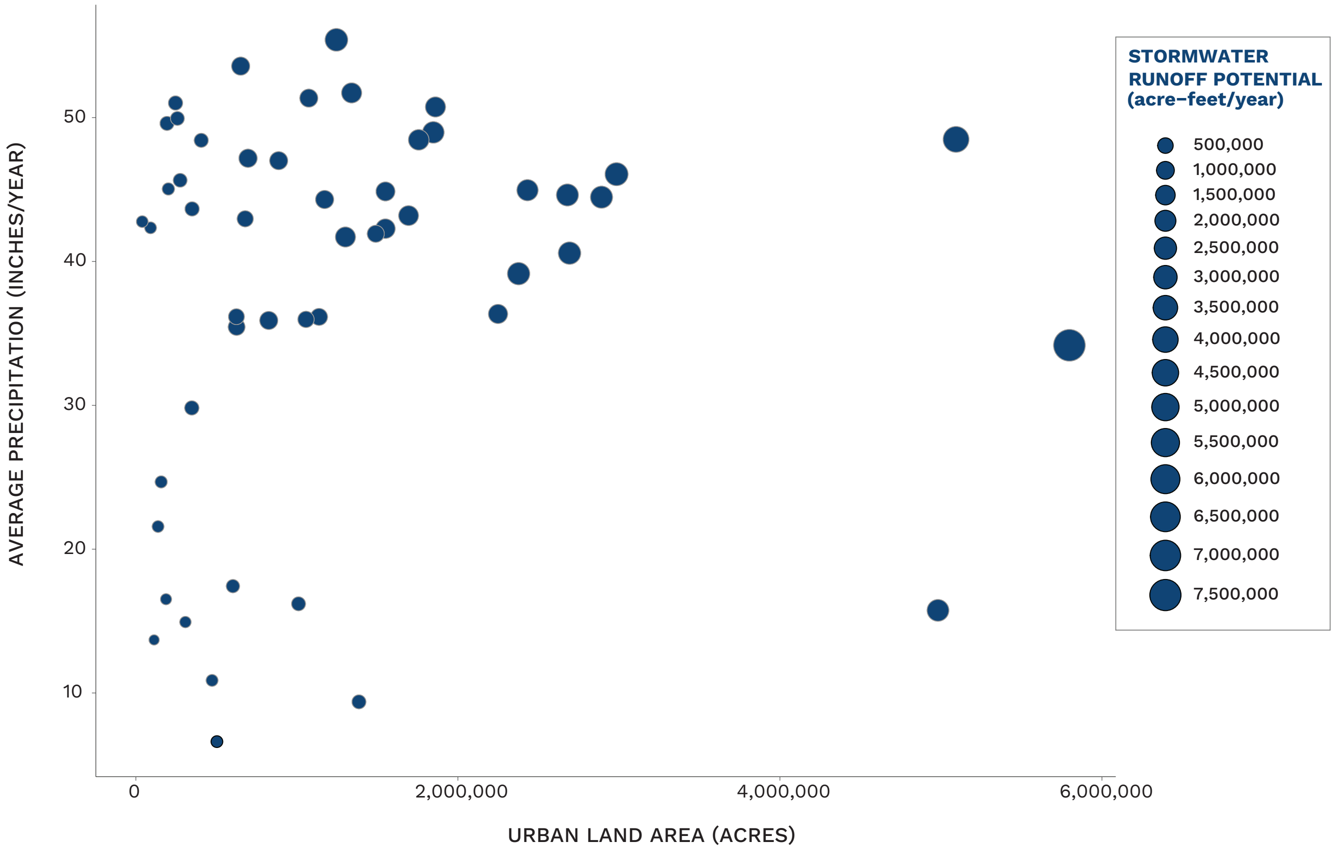
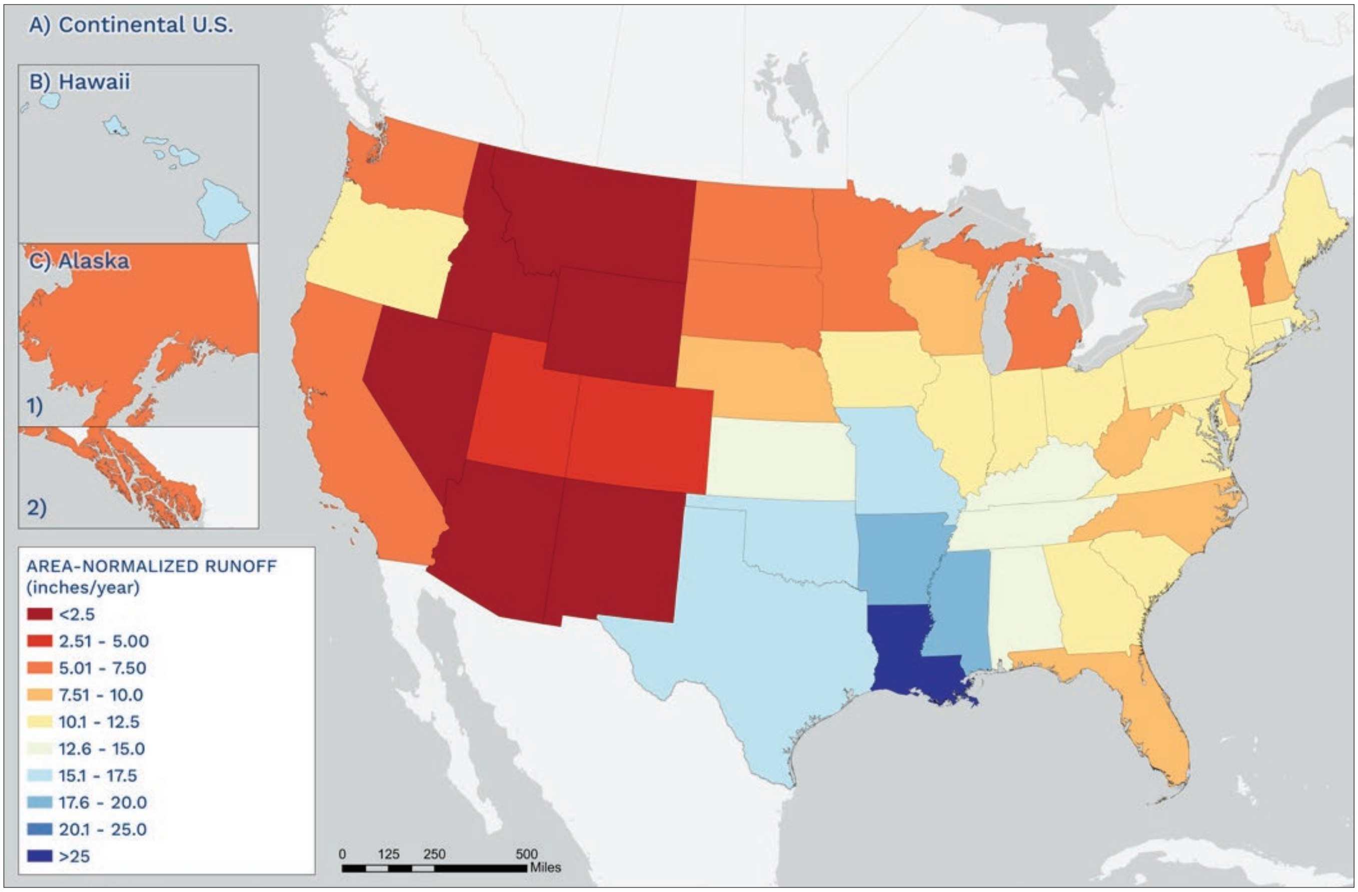


TABLE A2. Summary of TELR Results and Associated Characteristics, US States (including District of Columbia)

STATE	RUNOFF VOLUME	URBAN LAND AREA	RUNOFF DEPTH	POPULATION	AVERAGE PRECIPITATION
	(acre-feet/year)	(acres)	(inches)	-	(inches/year)
TX	7,800,000	5,800,000	16.1	29,100,000	34.2
FL	4,120,000	5,090,000	9.70	21,500,000	48.5
GA	2,770,000	2,990,000	11.1	10,700,000	46.1
LA	2,610,000	1,250,000	25.2	4,660,000	55.4
OH	2,500,000	2,690,000	11.1	11,800,000	40.6
IL	2,470,000	2,380,000	12.5	12,800,000	39.2
NC	2,380,000	2,890,000	9.88	10,400,000	44.5
PA	2,350,000	2,680,000	10.5	13,000,000	44.6
CA	2,270,000	4,980,000	5.47	39,500,000	15.7
TN	2,170,000	1,850,000	14.1	6,910,000	49.0
NY	2,040,000	2,430,000	10.1	20,200,000	45.0
NJ	1,800,000	1,760,000	12.3	9,290,000	48.5

STATE	RUNOFF VOLUME	URBAN LAND AREA	RUNOFF DEPTH	POPULATION	AVERAGE PRECIPITATION
	(acre-feet/year)	(acres)	(inches)	-	(inches/year)
MA	1,650,000	1,860,000	10.6	7,030,000	50.7
AL	1,650,000	1,340,000	14.8	5,020,000	51.7
MO	1,640,000	1,300,000	15.1	6,150,000	41.7
VA	1,570,000	1,690,000	11.1	8,630,000	43.2
IN	1,450,000	1,550,000	11.3	6,790,000	42.3
MI	1,350,000	2,250,000	7.23	10,100,000	36.4
SC	1,300,000	1,550,000	10.1	5,120,000	44.9
AR	1,100,000	696,000	19.0	3,010,000	47.2
MS	1,070,000	651,000	19.7	2,960,000	53.6
MD	1,070,000	1,170,000	10.9	6,180,000	44.3
OK	1,050,000	825,000	15.3	3,960,000	35.9
KY	1,050,000	887,000	14.2	4,510,000	47.0
CT	1,030,000	1,070,000	11.6	3,610,000	51.4
WA	793,000	1,490,000	6.38	7,710,000	41.9
WI	781,000	1,140,000	8.24	5,890,000	36.1
KS	739,000	625,000	14.2	2,940,000	35.4
MN	633,000	1,060,000	7.19	5,710,000	36.0
OR	609,000	679,000	10.8	4,240,000	43.0
IA	550,000	624,000	10.6	3,190,000	36.2
RI	288,000	246,000	14.0	1,100,000	51.0
NE	287,000	347,000	9.91	1,960,000	29.8
WV	284,000	349,000	9.78	1,790,000	43.7
HI	263,000	193,000	16.3	1,460,000	49.6
NH	260,000	406,000	7.68	1,380,000	48.4
AZ	253,000	1,390,000	2.19	7,150,000	9.38
CO	249,000	1,010,000	2.95	5,770,000	16.2
ME	233,000	258,000	10.8	1,360,000	49.9
DE	227,000	275,000	9.90	990,000	45.6
UT	173,000	603,000	3.44	3,270,000	17.4
AK	85,200	202,000	5.07	733,000	45.0
SD	75,800	157,000	5.80	887,000	24.7
NM	61,700	473,000	1.56	2,120,000	10.9
ND	57,700	137,000	5.04	779,000	21.6
NV	56,100	503,000	1.34	3,100,000	6.62
VT	55,700	91,100	7.34	643,000	42.3
DC	52,100	39,300	15.9	690,000	42.8
ID	38,500	307,000	1.50	1,840,000	14.9
MT	29,700	187,000	1.90	1,080,000	16.5
WY	17,100	113,000	1.81	577,000	13.7
Total	**59,400,000**	**66,500,000**	**-**	**331,000,000**	**-**

FIGURE A5. **Area-Normalized Estimated Urban Stormwater Runoff Potential, State-Level Aggregation**



APPENDIX C
STORMWATER RUNOFF POTENTIAL ESTIMATES FOR US URBAN AREAS

TABLE A3. Summary Statistics for Stormwater Runoff Potential Estimates and Relevant Characteristics, US Urban Areas

PARAMETER	RUNOFF VOLUME	URBAN LAND AREA	AREA-NORMALIZED RUNOFF	POPULATION	AVERAGE PRECIPITATION	RUNOFF RATIO
Units	(acre-feet/year)	(acres)	(inches/year)	-	(inches/year)	-
Total	59,500,000	66,600,000	25,600	265,000,000	-	-
Mean	22,800	25,500	9.80	102,000	37.4	0.254
Median	3,900	5,030	9.54	12,200	40.6	0.242
Standard Deviation	107,000	97,900	5.84	613,000	14.7	0.111
Inter-Quartile Range	1,780	2,850	5.65	6,720	31.1	0.171
	10,600	12,900	13.00	30,800	46.3	0.321
Minimum	20.6	401	0.170	773	2.26	0.0226

FIGURE A6. Histogram of Urban Stormwater Runoff Estimates, US Urban Areas (Log$_{10}$ X-Axis Scale)

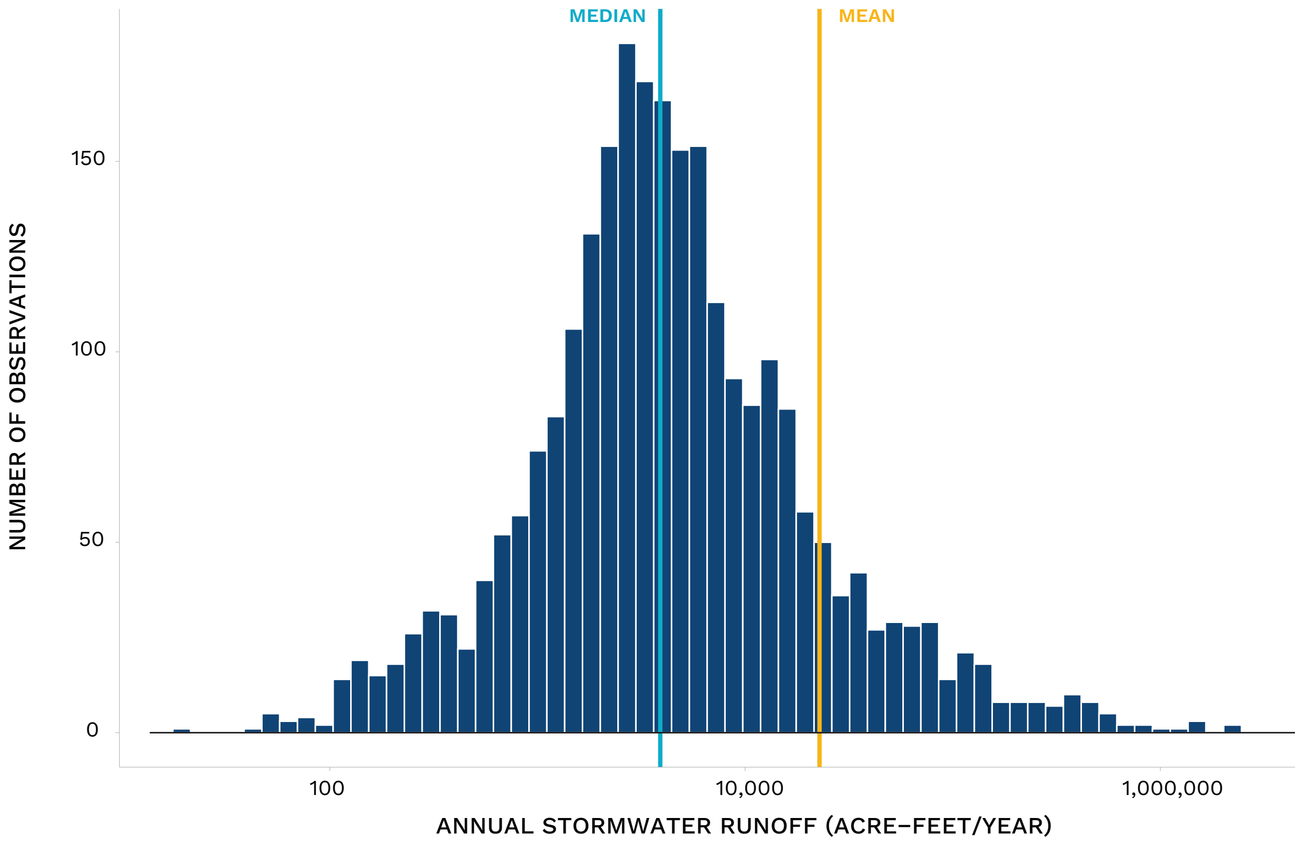


FIGURE A7. Variation of Stormwater Runoff Estimates Along Precipitation and Urban Land Area Inputs, US Urban Areas

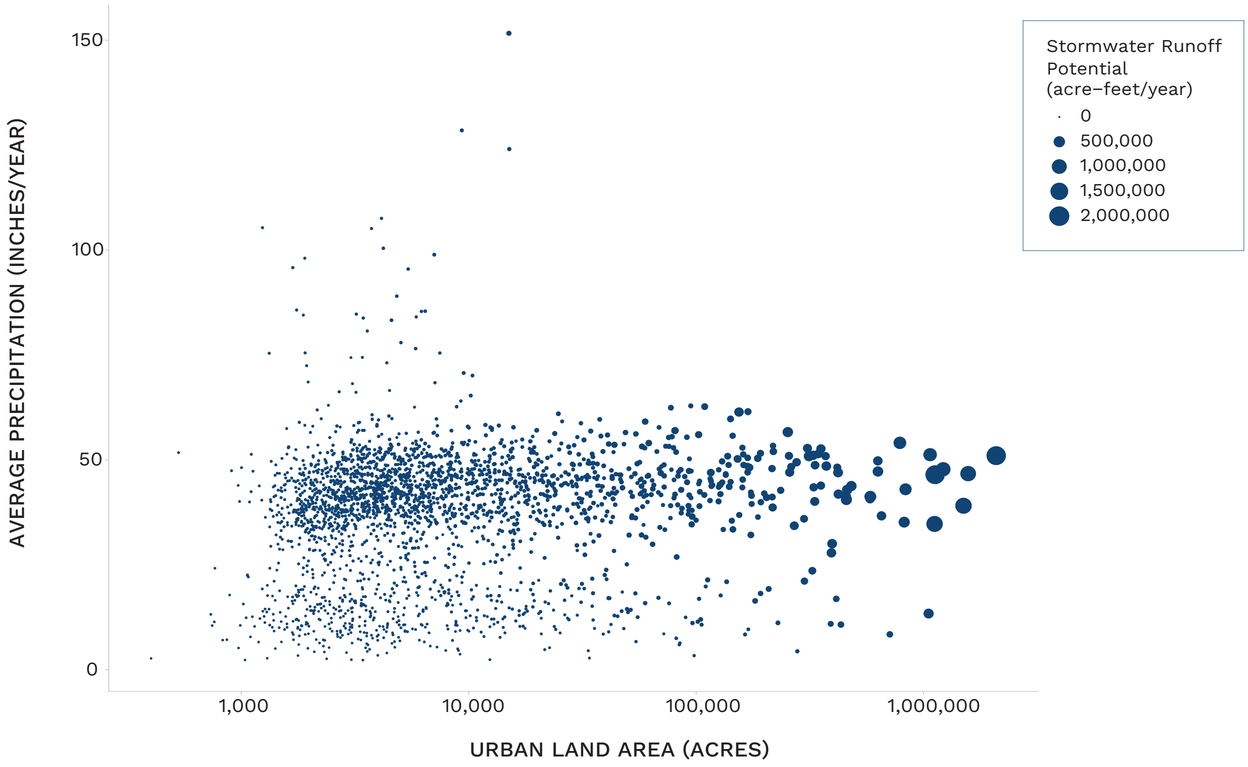
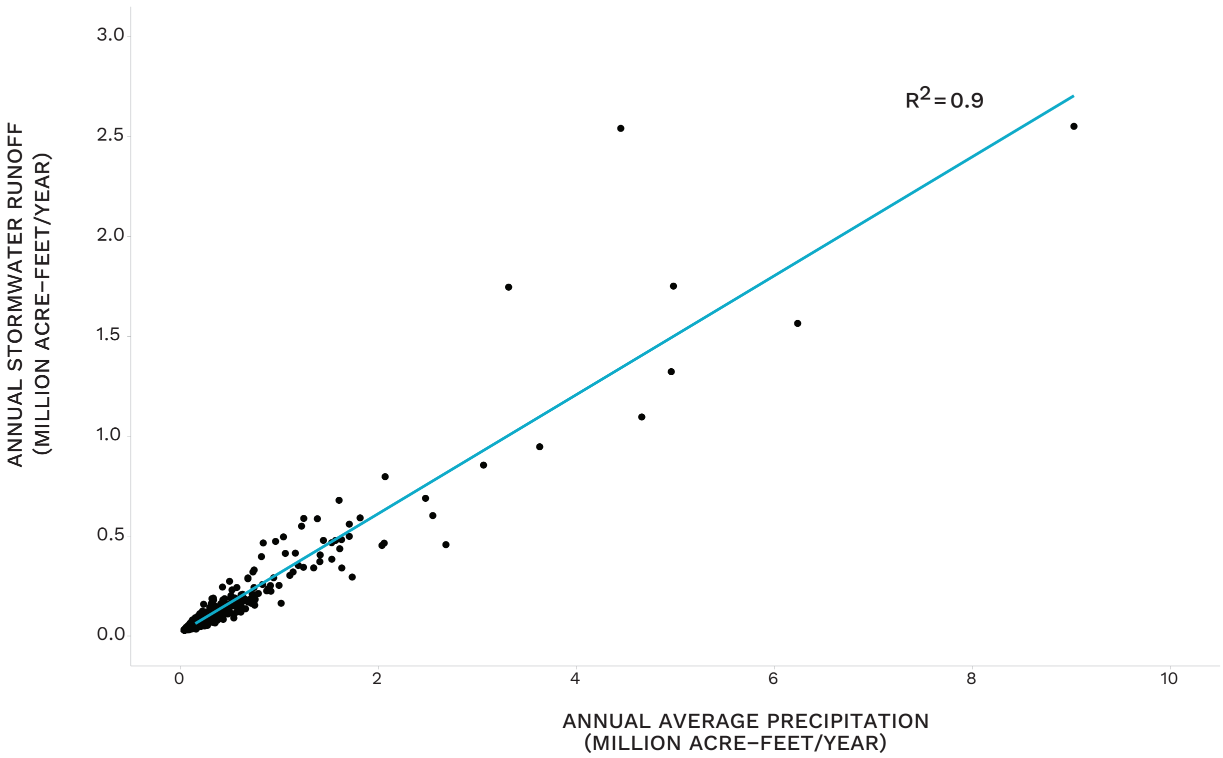


FIGURE A8. Relationship Between Annual Average Precipitation and Annual Average Stormwater Runoff Potential for Urban Areas



APPENDIX D
STORMWATER RUNOFF POTENTIAL ESTIMATES FOR HUC8 SUBBASINS

FIGURE A9. Histogram of Urban Stormwater Runoff Estimates, HUC8 Subbasins (Log10 X-Axis Scale)

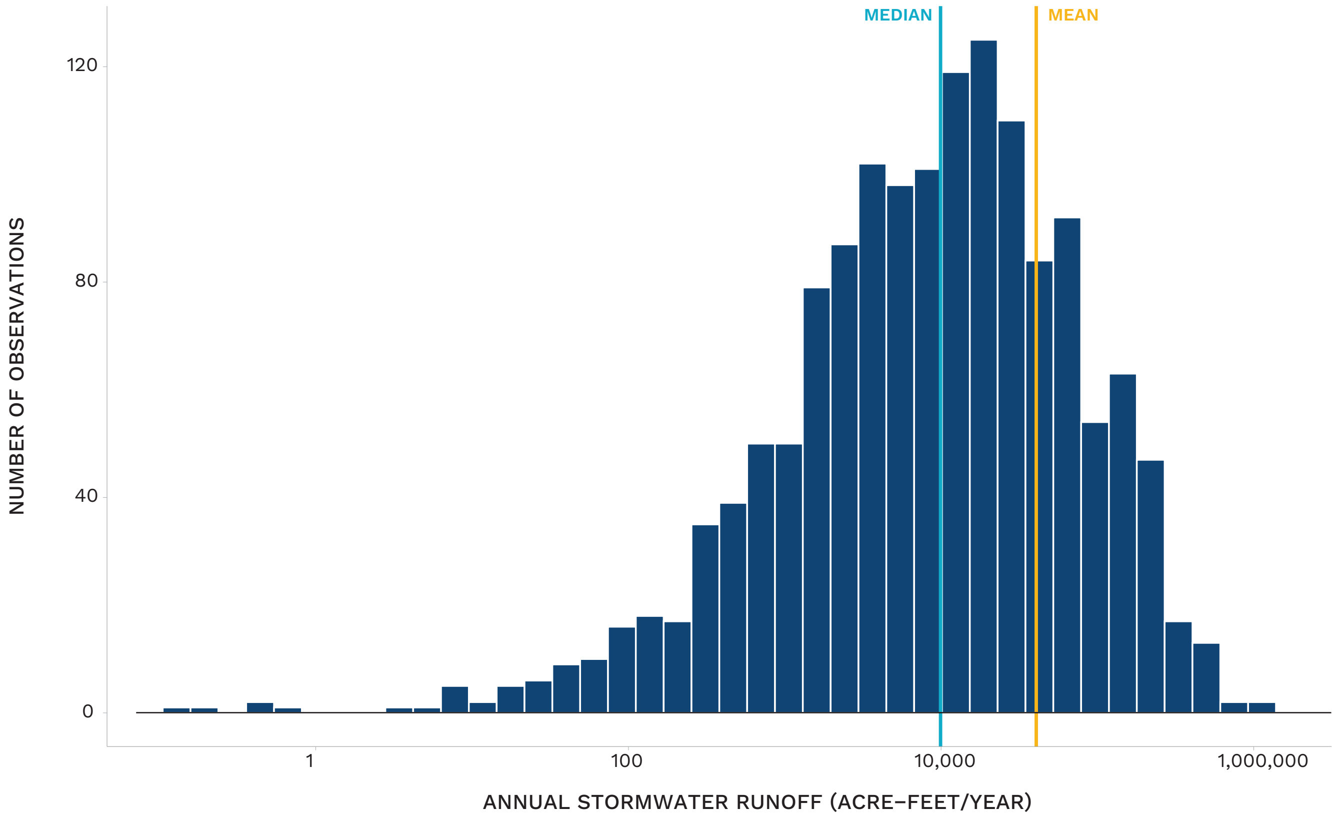
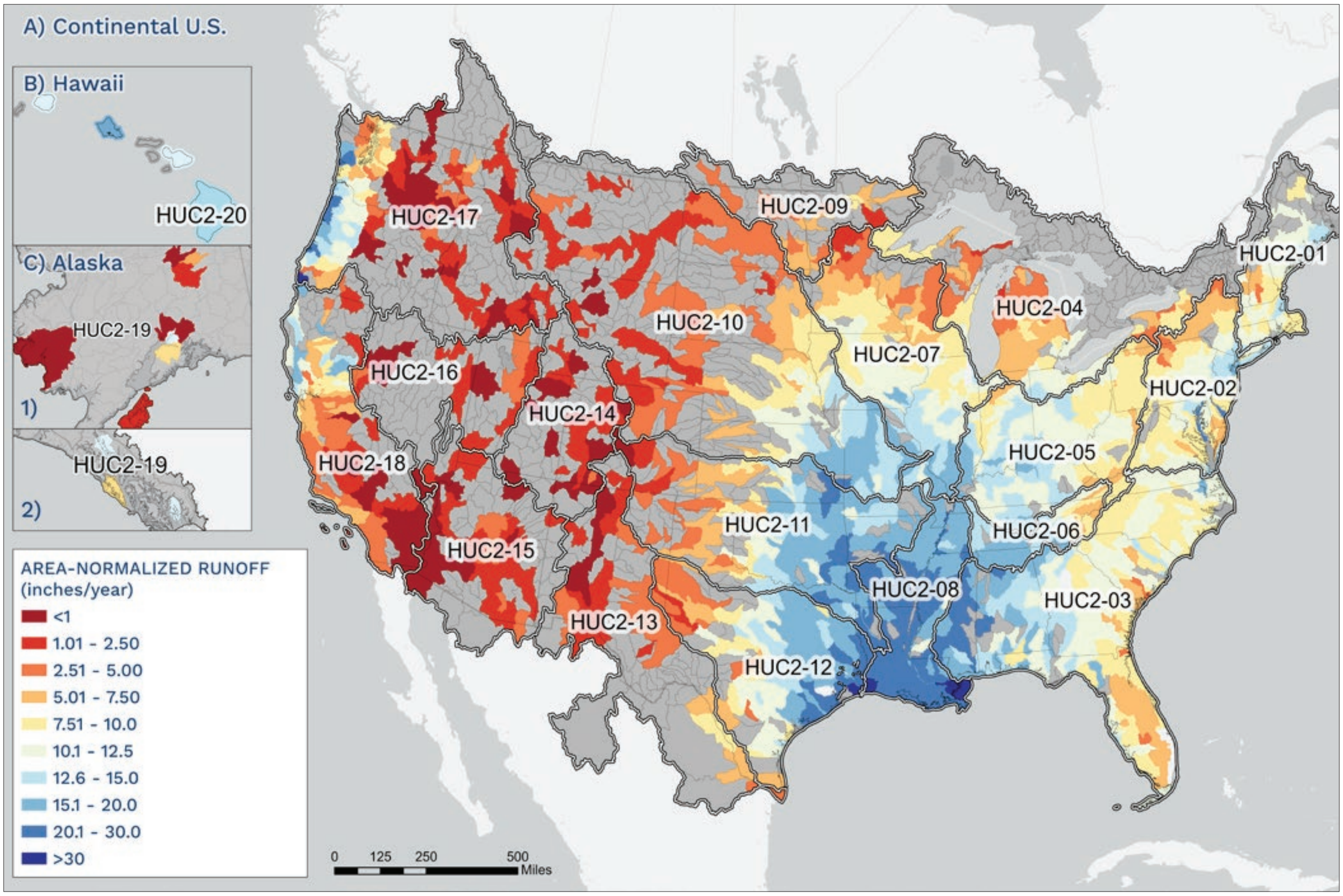


TABLE A4. Summary Statistics for Stormwater Runoff Potential Estimates, HUC8 Subbasins

PARAMETER	RUNOFF VOLUME	URBAN LAND AREA	AREA-NORMALIZED RUNOFF
Units	(acre-feet/year)	(acres)	(inches/year)
Total	59,500,000	66,600,000	14,400
Mean	40,600	45,500	9.83
Median	9,920	13,200	9.58
Standard Deviation	89,100	83,800	6.19
Inter-Quartile Range	2,120	4,560	4.94
	36,200	44,500	13.3
Minimum	0.16	0.22	0.0269
Maximum	1,390,000	901,000	33.5

FIGURE A10. Area-Normalized Estimated Urban Stormwater Runoff, HUC8 Subbasins



Notes: Alaska map panels are labeled as follows: 1) South Central Alaska and portions of Southwest and Interior Alaska, and 2) Southern tip of Alaska Panhandle. HUC2 region boundaries shown. Areas with a hatched line pattern in the figure indicate subbasins with zero urban stormwater runoff potential due to the absence of any Urban Areas. The total runoff for each subbasin only represents stormwater runoff generated within the subbasin and does not include contributions from upstream subbasins.

APPENDIX E
STORMWATER RUNOFF POTENTIAL ESTIMATES FOR US COUNTIES

TABLE A5. Summary Statistics for Stormwater Runoff Potential Estimates, US Counties

PARAMETER	RUNOFF VOLUME	URBAN LAND AREA	AREA-NORMALIZED RUNOFF	POPULATION
Units	(acre-feet/year)	(acres)	(inches/year)	-
Total	59,400,000	66,600,000	21,900	320,000,000
Mean	29,200	32,700	10.7	157,000
Median	7,800	9,410	10.3	47,700
Standard Deviation	68,700	64,100	5.67	408,000
Inter-Quartile Range	2,910	4,000	7.16	25,600
	26,100	32,600	13.70	124,000
Minimum	0.293	0.890	0.241	2,240
Maximum	1,790,000	877,000	35.1	10,000,000

FIGURE A11. Histogram of Urban Stormwater Runoff Estimates, US Counties (Log_{10} X-Axis Scale)

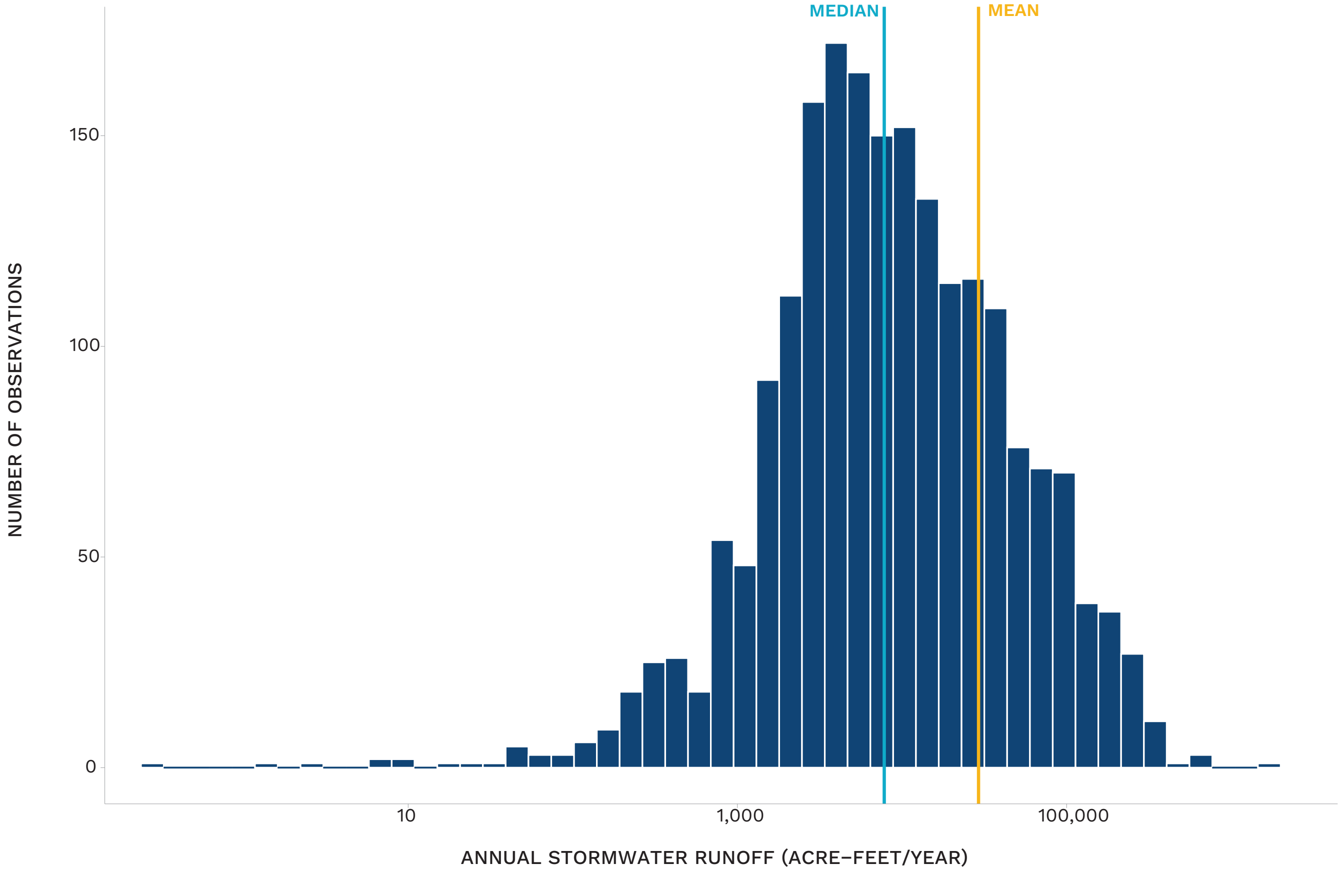
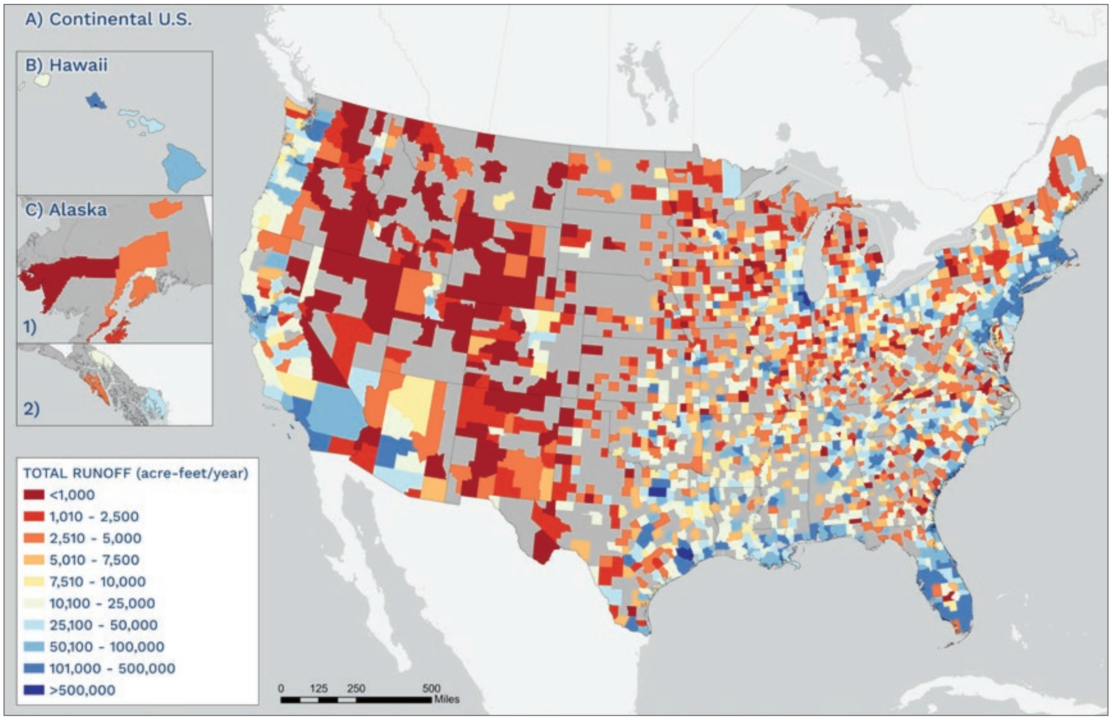
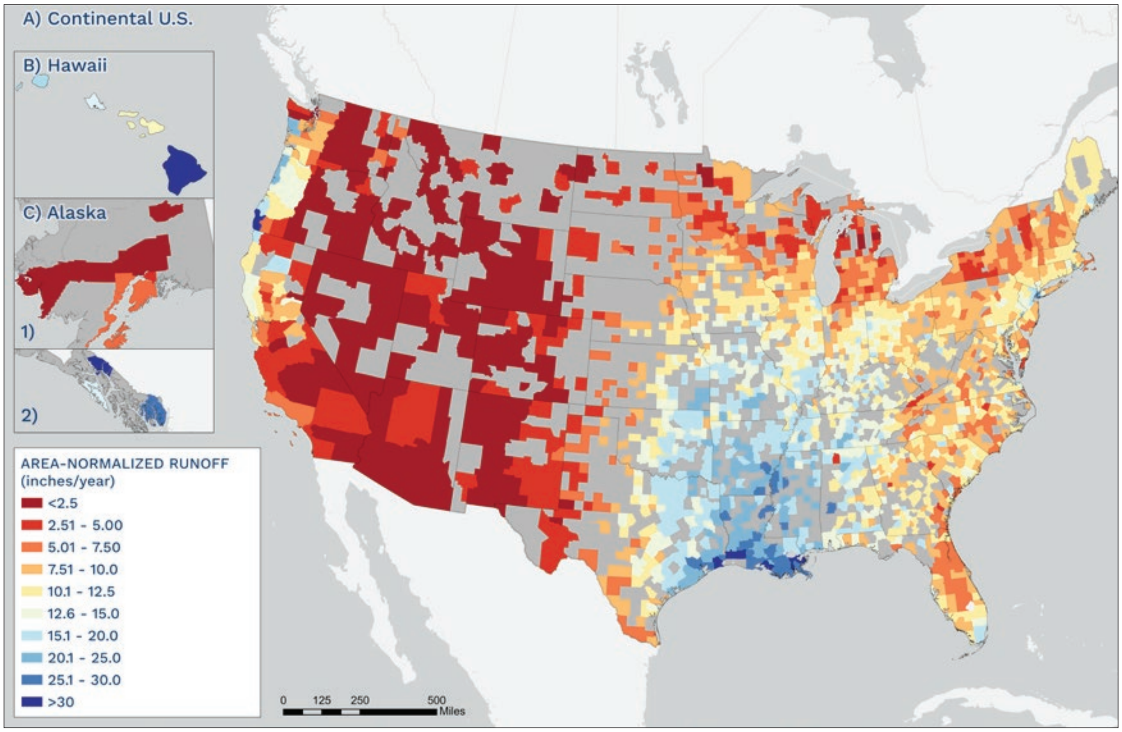


FIGURE A12. Total Stormwater Runoff Estimates, US Counties



Alaska map panels are labeled as follows: 1) South Central Alaska and portions of Southwest and Interior Alaska, and 2) Southern tip of Alaska Panhandle.

FIGURE A13. Area-Normalized Stormwater Runoff Estimates, US Counties



Alaska map panels are labeled as follows: 1) South Central Alaska and portions of Southwest and Interior Alaska, and 2) Southern tip of Alaska Panhandle.

APPENDIX F
STORMWATER RUNOFF POTENTIAL ESTIMATES FOR 118TH CONGRESSIONAL DISTRICTS

TABLE A6. Summary Statistics for Stormwater Runoff Potential Estimates, US Congressional Districts

PARAMETER	RUNOFF VOLUME	URBAN LAND AREA	AREA-NORMALIZED RUNOFF
Units	(acre-feet/year)	(acres)	(inches/year)
Total	59,400,000	66,500,000	4,760
Mean	136,000	153,000	10.9
Median	139,000	154,000	10.4
Standard Deviation	86,700	57,900	5.75
Inter-Quartile Range	68,200	118,000	6.93
Inter-Quartile Range	186,000	190,000	13.70
Minimum	7,430	6,140	0.548
Maximum	551,000	393,000	30.7

FIGURE A14. Histogram of Urban Stormwater Runoff Estimates, US Congressional Districts

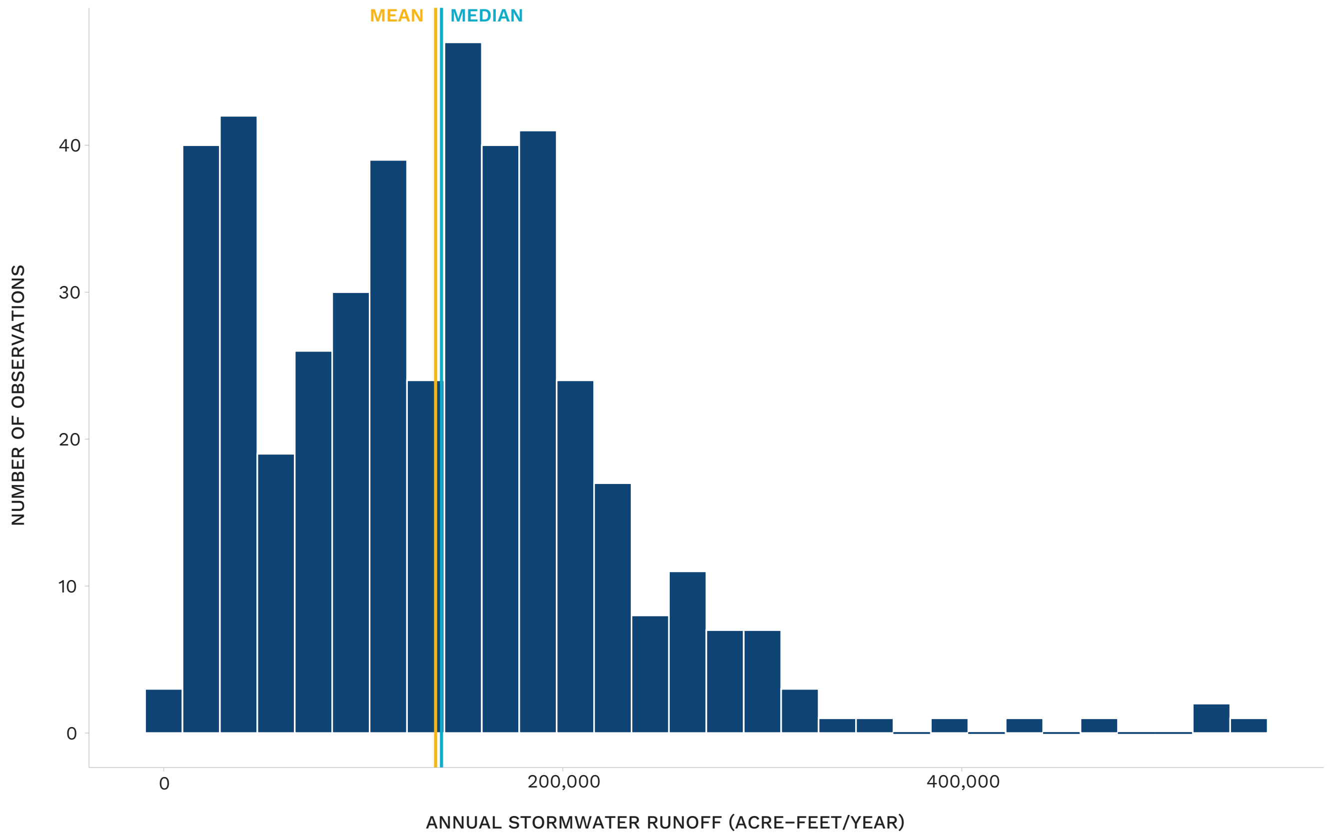


FIGURE A15. Total Stormwater Runoff Estimates, US Congressional Districts

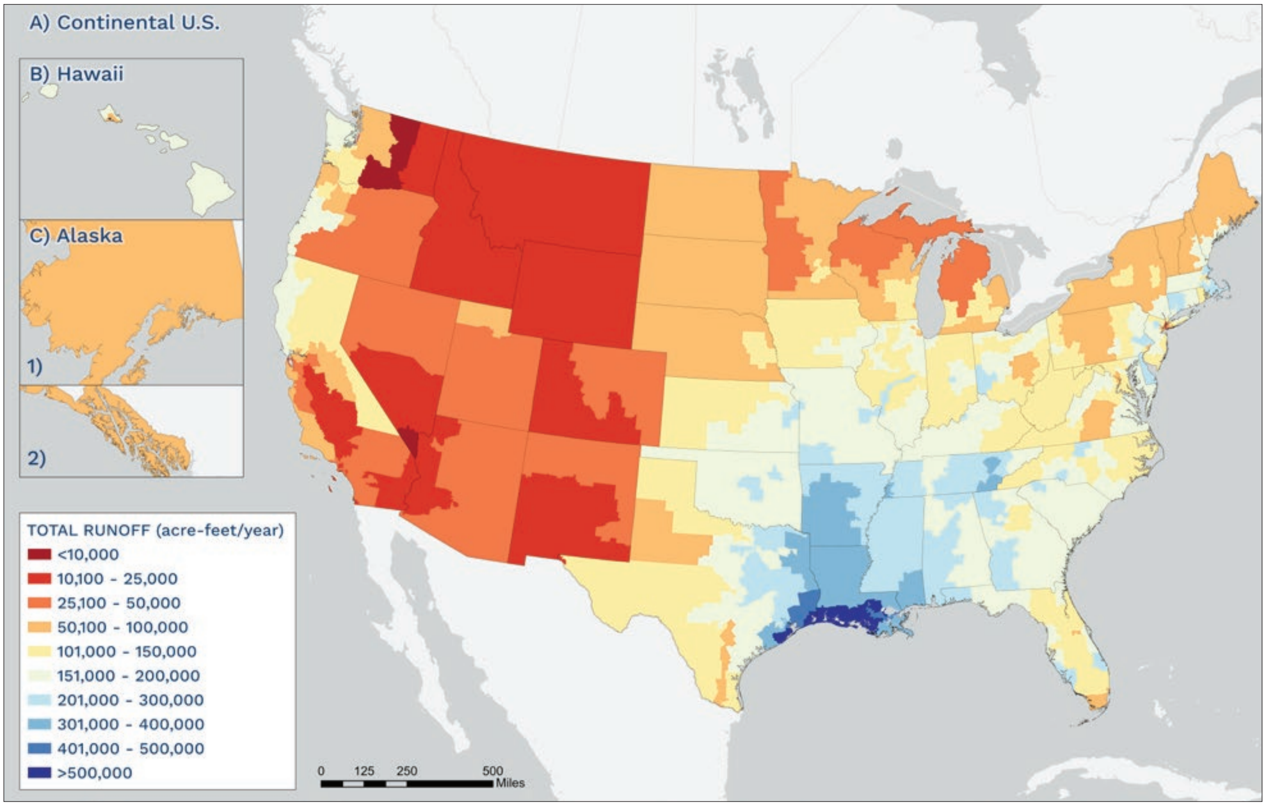
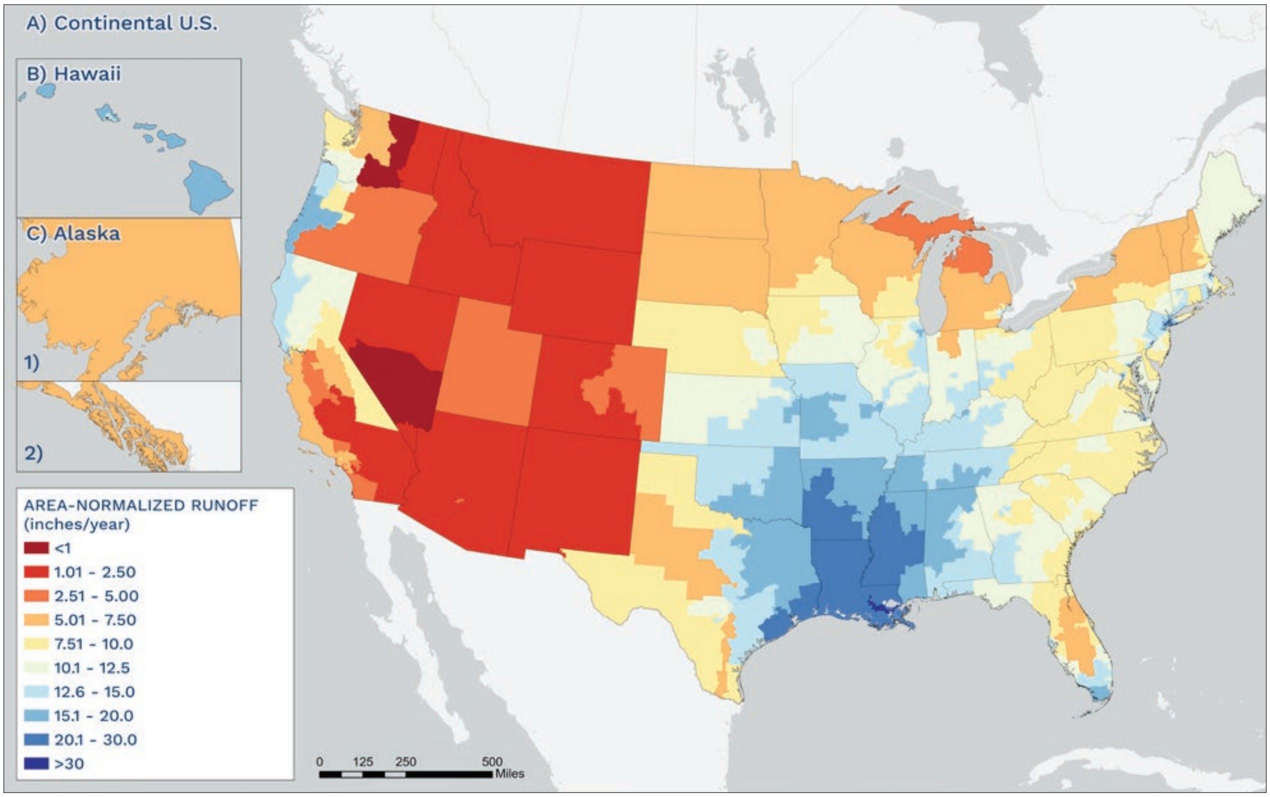


FIGURE A16. Area-Normalized Stormwater Runoff Estimates, US Congressional Districts



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