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Calibrated methodology for assessing climate change adaptation costs for urban drainage systems

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Abstract

Changes in precipitation patterns associated with climate change may pose significant challenges for storm water management systems across the U.S. In particular, adapting these systems to more intense rainfall events will require significant investment, though no method currently exists for estimating the costs of these investments on a national scale. To support assessment of these costs at the national level, this paper presents a reduced-form approach for estimating changes in normalized flood depth (the volume of node flooding normalized by the area of the catchment) and the associated costs of flood prevention. This reduced form approach is calibrated to results generated by the U.S. Environmental Protection Agency's Storm Water Management Model (SWMM) for city-wide or neighborhood-level catchments in seven cities across the U.S. Estimates derived from this approach represent a reasonable approximation of storm water management adaptation costs and exhibit no systematic bias relative to results derived from SWMM.

Keywords

climate change; flood forecasting; infrastructure

Introduction

Changes in precipitation patterns associated with climate change may pose significant challenges for storm water management systems across much of the U.S. Because the capacity of urban drainage systems is designed based on historical rainfall patterns, systems located in areas where storm events become more intense could be overburdened, increasing the frequency of flooding on city streets, buildings and other property, and slowing the transport of people and goods. In cities with combined sewer systems, flooding associated with the overburdening of these systems could also pose risks to human health and aquatic species from water borne pathogens and nutrients.

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Adapting storm water management systems to more intense rainfall events will require significant investment. The assessment of these potential costs on a national scale would provide valuable perspective for policymakers and planners as they consider adaptation investments for the various public assets under their management. Estimation of these investment costs, however, usually occurs on a city-specific basis, as *local* governments have ultimate authority over storm water management investment decisions. In addition, the storm water modeling tools that localities use are not readily scalable to larger geographic areas. For example, the Storm Water Management Model (SWMM) developed by the U.S. Environmental Protection Agency (EPA) and used by multiple cities across the U.S. requires hundreds of data inputs per catchment and often takes hours to solve for a single city. Thus, applying a detailed modeling system such as SWMM to dozens or hundreds of cities across the U.S. would be cost prohibitive, particularly if one is interested in comparing results across different climate change scenarios.

To facilitate nationwide assessments of climate change adaptation costs for urban drainage systems, this paper presents a reduced-form approach for estimating changes in normalized flood depth (the volume of node flooding normalized by the area of the catchment) and the associated costs of flood prevention. This reduced form approach is calibrated to SWMM results for city-wide or neighborhood-level catchments in seven cities across different regions of the U.S.: (1) Haverhill, Massachusetts; (2) Lewiston, Maine; (3) Miami, Florida; (4) Kansas City, Missouri; (5) Louisville, Kentucky; (6) Aurora, Colorado; and (7) Fort Collins, Colorado.¹ Table 1 provides information on the size and degree of imperviousness for each catchment.

The reduced form approach calibrated to the cities in Table 1 is, by design, relatively simple and is intended to be implemented relatively easily so that it may inform assessments of urban drainage adaptation costs on a national scale. Our intention was not to develop a methodology that generates city-specific estimates of climate change adaptation costs with a high degree of accuracy and precision, but instead to develop an approach that generates estimates that perform reasonably well relative to more detailed models such that the city-specific results may be aggregated to generate nation-wide estimates of adaptation costs.

A higher order approach would include developing capacity estimates for future precipitation frequencies for each individual city. Capacity is generally a function of terrain (slope), dimension of conveyance infrastructure (e.g., diameter of pipe), pipe material, and downstream outlet conditions (e.g. backwater). This higher order approach would be akin to performing an individual master plan for each city, which is an extremely resource-intensive undertaking not possible for a national scale assessment.

Existing literature on the effects of climate change for urban drainage systems

Much of the literature examining the effects of climate change on urban drainage systems considers these effects on a local level. Burian (2006) examines the impacts of increased

¹ These cities were chosen in large part because fully populated SWMM models were readily available for each city.

rainfall intensity on a hypothetical, small-scale sewer system in Houston designed according to current engineering standards. The analysis found that increased rainfall intensity for a range of model storm events (e.g., the 10-year storm) would overload much of the system. For example, the authors found that a 40 percent increase in rainfall intensity for the 10-year storm event would force 70 percent of the system's pipes to operate under surcharge conditions, while none of the pipes would operate under surcharge under baseline conditions. Similarly, focusing on the cities of Burlington and Ottawa, Ontario, Watt et al. (2003) estimated that a 15 percent increase in precipitation would cause 25 percent of the storm sewer system's pipes to exceed their capacity. Semadeni-Davies et al. (2008) examine the combined effects of climate change and increased urbanization on a stormwater catchment in Helsingborg, Sweden. Relative to the present level of urbanization and historical climate, combined sewer and pumping station overflow volumes were estimated to increase by 318 percent with increased urbanization under the IPCC A2 scenario.² By comparison, increased urbanization alone is estimated to lead to an 18 percent increase in overflow.

Nie et al. (2009) assess the impacts of increased rainfall intensity according to four metrics of adverse impacts for a 364 hectare catchment in Fredrikstad, Norway: (1) number of flooding manholes and volume of water spilling from flooding manholes, (2) number of surcharging sewer nodes, (3) number of buildings in danger of flooding, and (4) combined sewer overflow volumes. Using a detailed computerized model of the catchment and its stormwater management infrastructure, the authors examined all four metrics under scenarios projecting 20, 30, and 40 percent increases in precipitation. Their analysis found that the volume of spillage from flooded manholes will increase by 40 to 180 percent relative to current climate and that CSO discharges will increase by 35 to 90 percent. The number of buildings at risk from flooding was estimated to increase from 210 under current climate to 574 when precipitation increases by 40 percent.

Examining climate change's impact on urban drainage systems at a regional level, Furlow et al. (2006) assess the impact of low-frequency storm events on the likelihood of combined sewer overflows within the Great Lakes and New England regions. The analysis compares projected storm intensities against the historical benchmark storm event and characterizes the impacts of climate change in terms of (1) the extent to which systems may be "under-designed" and (2) the additional system capacity required to meet the mitigation target in the future. The authors found that for both of the general circulation models (GCMs) they used, additional system capacity would be required in the Great Lakes region, with perhaps significant need for increased capital investment in pipe network capacity. The effect in New England, however, was ambiguous, with results from one GCM showing a need for additional capacity and the second showing no such need.

The studies summarized above provide interesting insights into the effects of climate change on urban drainage systems at the local, and in one case, regional level. This paper builds on these studies by developing an approach for quantifying climate change impacts and adaptation costs for urban drainage systems that may be applied on a national scale.

².See IPCC (2000) for detailed information on the IPCC emissions scenarios.

Frequency-duration rainfall under alternative climate scenarios

The methodology developed in this paper is applied to three specific climate scenarios described in Paltsev et al. (2013) for the 30-year eras centered on the years 2025, 2050, 2075, and 2100. These scenarios include a reference (REF) case that assumes no changes in greenhouse gas mitigation policies relative to current policy, and two policy scenarios that limit global greenhouse gas emissions such that radiative forcing levels in 2100 are stabilized at 4.5 W/m² (Policy 4.5) or 3.7 W/m² (Policy 3.7). Projections of future climate that reflect these emissions scenarios were derived using the Community Atmospheric Model linked with the Integrated Global Systems Model (IGSM-CAM), as presented in Monier et al. (2014). IGSM-CAM allows for the assessment of changes in climate for multiple climate sensitivities. This analysis assumes a 3°C climate sensitivity, the “most likely sensitivity” reported in the Intergovernmental Panel on Climate Change’s Fourth Assessment Report (IPCC, 2007).

Using the climate projections from IGSM-CAM for each climate scenario, the effects of climate change on urban drainage systems are assessed for three frequency-duration events: the 10-year, 24-hour storm; the 25-year, 24-hour storm; and the 50-year, 24-hour event. This range of storm events is examined due to uncertainty regarding the design capacity of urban drainage systems. Some systems (or even portions of some systems) are designed to accommodate storms with a relatively short return period, while others are designed to manage the runoff from less frequent but more significant rainfall events.

For each frequency-duration event, the rainfall associated with each emission scenario is estimated by scaling city-specific, historical estimates from NOAA Atlas 14 (Bonnin, 2006; Hershfield, 1961; Wilks & Cember, 1993) in proportion to the change in the frequency-duration event implied by projections from IGSM-CAM. Equation (1) summarizes this approach.

$$R_{f,y,s} = H_{FD} \times (1 + C_{f,y,s}) \quad (1)$$

Where $R_{f,y,s}$ = rainfall associated with frequency-duration event f in year y under climate scenario s for each city;

H_{FD} = rainfall associated with the historical frequency-duration event f for each city; and

$C_{f,y,s}$ = proportional change in the rainfall associated with frequency-duration event f in year y for climate scenario s , as derived from historical rainfall data and changes in rainfall projected by IGSM-CAM.

Due to the uncertainty in the daily results generated by IGSM-CAM and other climate models and the relatively coarse spatial resolution of these models, $C_{f,y,s}$ is not estimated for each city directly from IGSM-CAM results. Instead, $C_{f,y,s}$ is derived from a combination of historical climate data and the proportional changes in precipitation implied by IGSM-CAM.

As an initial step in estimating $C_{f,y,s}$, the rainfall associated with each city’s historical frequency-duration events was estimated using data from the Land Surface Hydrology

Research Group at Princeton University. Compiled from weather stations across the country, the Princeton data include daily precipitation measurements at a 1.0-degree resolution for the years 1948–2008; this analysis uses historical data for the 30-year period from 1979 through 2008. Each of the seven cities examined in this study was matched to a specific 1.0-degree grid cell in the Princeton data based on its latitude and longitude.

For each grid cell, the rainfall associated with the 10-year, 25-year, and 50-year 24-hour storms was estimated from the Princeton data using the Gumbel distribution. The Gumbel distribution (Gumbel, 1958) has been extensively used to estimate low frequency precipitation intensities. The distribution has been shown to reasonably fit measured data, and can be defined by estimating only two parameters, making calculation straightforward (Meehl et al., 2000). The Gumbel distribution takes the form:

$$F(x; \mu; \sigma) = e^{-e^{-\frac{(x - \mu)}{\sigma}}} \quad (2)$$

Where $F(x)$ is the limiting cumulative distribution function of the maximum daily values within each time series, μ is the mode, and σ is the shape parameter. A return value, X_T , can be determined using Equation (3). X_T is the expected value that is exceeded once in the amount of time, T . For example, for maximum daily values within the number of years in a dataset, the expected daily value of precipitation has a $1/T$ chance of being exceeded in a given year where T is in years.

$$X_T = \mu - \sigma \ln \left[-\ln \left(1 - \frac{1}{T} \right) \right] \quad (3)$$

The returned value corresponds to the probability in terms of a number of years, T , in which on average, the intensity value is equaled or exceeded. To be statistically accurate, T should not exceed the number of years in a sample; for example, if the sample size is n years, T should be less than or equal to n . However, due to the high consequence of failure of civil systems caused by these low frequency flood events, and the limited timeframes for which measured samples are available, estimates of T are commonly taken to be greater than n in practice.

After estimating rainfall amounts for the historical frequency-duration events, the daily precipitation values in the Princeton data were scaled based on the proportional changes in monthly precipitation projected by IGSM-CAM³ for each climate change scenario relative to the no climate change baseline, as represented in Equation (4). The daily Princeton data were scaled based on the proportional monthly changes projected by IGSM-CAM. This approach maintains days of no precipitation and days of high or low precipitation.

$$P_{d,g,s} = P_{d,g,h} \left(\frac{W_{m,g,IGSM}}{B_{m,g,IGSM}} \right) \quad (4)$$

³.IGSM only provides changes in monthly precipitation. This approach assumes the number of daily storms remain the same but the daily storm intensities change uniformly for every storm at the monthly ratio provided by the IGSM.

Where $P_{d,g,s}$ = scaled estimate of daily precipitation for grid cell g under climate change scenario s ,

$P_{d,g,h}$ = daily precipitation for grid cell g as reported in the historical Princeton data;

$W_{m,g,IGSM}$ = monthly precipitation corresponding to day d and grid cell g under a given climate change scenario, as projected by IGSM-CAM. For each 30-year era examined, this value represents the average for month m across all 30 years.

$B_{m,g,IGSM}$ = monthly precipitation corresponding to day d and grid cell g under a no climate change base case, as projected by IGSM-CAM. This value represents the average for month m over the 30-year base period.

The formula shown in Equation (4) was applied to the entire 30-year time series in the Princeton data for each climate scenario and 30-year era (i.e., 2025, 2050, 2075, and 2100).

The projection of daily precipitation based on monthly results from IGSM-CAM is consistent with other studies in the literature. As shown in Gao et al. (2014), model-based precipitation estimates do not accurately reproduce the frequency and intensity distribution of historical precipitation (i.e., daily precipitation events). Given this uncertainty, a number of researchers have used the monthly climate change signal of precipitation to model daily hydrologic processes (Chiew & McMahon, 2002; Chinowsky et al., 2012, 2013).

Based on the values for $P_{d,g,s}$ derived from Equation (4), the Gumbel distribution (as described above) was applied to estimate frequency-duration rainfall amounts for each climate scenario, year, and grid cell. The ratio of these values to the corresponding values derived directly from the historical Princeton data yields the $C_{f,y,s}$ values for Equation (1) above. Equation (5) summarizes this approach.

$$C_{f,y,s} = \frac{XR_{f,y,s}}{R_{f,h}} \quad (5)$$

Where $C_{f,y,s}$ is as defined above in Equation (1);

$R_{f,h}$ = rainfall associated with frequency-duration event f based on historical data;

$XR_{f,y,s}$ = rainfall associated with frequency-duration event f for year y and climate scenario s , derived from the scaled precipitation values estimated according to Equation (4).

Incorporating the estimated values for $C_{f,y,s}$ into Equation (1) yields frequency-duration rainfall estimates specific to each city. These values reflect the proportional change implied by IGSM-CAM for each climate scenario and historical rainfall data specific to each city.

Figure 1 shows the rainfall for each frequency duration event across all three climate scenarios in 2100 and under the no climate change base case. As shown in the figure, frequency-duration rainfall amounts are highest in Miami and Kansas City among the seven cities analyzed and lowest in Fort Collins and Aurora. The most significant increases in rainfall amounts relative to the historical case are in Kansas City. In addition, frequency-

duration rainfall amounts for the three climate change scenarios (the reference and both policy cases) are higher than the historical amount in every city examined except Miami. This pattern suggests that urban drainage systems in most cities will require at least some adaptation measures, even if aggressive greenhouse gas mitigation policies are implemented. To some extent, this projection of a widespread increase in precipitation is a function of the GCM used for projecting future changes in precipitation patterns. As shown in Monier et al. (2013), IGSM-CAM tends to project more precipitation than other GCMs.

Figure 1 also shows that frequency-duration rainfall amounts for some cities are projected to be *higher* under the mitigation scenarios than under the reference case, though most of the cities included in Figure 1 show lower rainfall amounts for the mitigation scenarios. Thus, based on the IGSM-CAM projections for the scenarios analyzed, greenhouse gas mitigation may, *for some areas*, exacerbate the impacts of climate change as they relate to urban drainage systems.

Uncalibrated reduced form methodology for estimation of capacity exceedence

The reduced form methodology is based on the premise that normalized flood depth (the volume of node flooding normalized by the area of the catchment) for a given drainage system is a function of its capacity and the change in stormwater runoff associated with changes in specific frequency-duration events. Thus, the two key elements of this approach are (1) assumptions regarding system capacity and (2) estimation of changes in stormwater runoff.

One option for characterizing system capacity is to obtain detailed capacity data for the urban drainage networks of individual cities. For a broad analysis across dozens or hundreds of cities, however, obtaining capacity data for individual cities is infeasible. In addition, drainage systems in relatively old and established city districts often lack capacity to manage runoff with current climate. This implies that a certain level of capacity exceedence not attributable to climate change occurs in the baseline. To address the lack of capacity data available at the national level and ensure estimation of *incremental* capacity exceedence associated with climate change, the reduced form approach assumes that each system's design capacity is sufficient to manage runoff from the baseline storm event.

The change in a catchment's runoff due to climate change is estimated as a function of changes in rainfall associated with a specific frequency-duration event, the area of each catchment, and each catchment's estimated runoff coefficient. Equation (6) summarizes this approach, which is based on the Rational Method for the assessment of stormwater runoff as described in Maidment (1993) and Brooks et al. (2013).

$$\Delta V_{f,y,s} = \Delta R_{f,y,s} \times A \times F \quad (6)$$

Where $V_{f,y,s}$ = Change in runoff volume associated with frequency-duration event f for year y and climate scenario s relative to a no climate change baseline;

$R_{f,y,s}$ = Change in rainfall associated with frequency-duration event f in year y under climate scenario s relative to a no climate change baseline;

A = Land area of the city; and

F = runoff coefficient.

As shown in Equation (6), the runoff coefficient is necessary for each city to convert the estimated change in rainfall associated with climate change ($R_{f,y,s}$) to a volumetric measurement of runoff.⁴ This analysis estimates a city's runoff coefficient as a function of imperviousness:⁵

$$F_C = 0.05 + 0.9I_C \quad (7)$$

Where F_C = runoff coefficient for city C , and

I_C = imperviousness of city C (measured as a percent of total area).

Imperviousness estimates were obtained from the SWMM models for each city (see below).

Applying the runoff coefficient (F) to the change in rainfall volume for each city, the change in urban runoff associated with climate change was estimated. Under the assumption stated above that each city's urban drainage system has a design capacity capable of managing runoff from the baseline storm event, this analysis assumes that the incremental change in urban drainage system capacity exceedance for each city is equal to the estimated change in runoff associated with a given frequency-duration event.⁶

The estimated change in capacity exceedance is presented in Figure 2, expressed as the change in normalized flood depth (defined above), for each city, scenario, and frequency-duration event in the year 2100. As indicated in the figure, the reduced form approach projects a decrease in normalized flood depth in Miami relative to the historical baseline, consistent with the reduction in frequency-duration rainfall in this city. These negative values for Miami, however, do not indicate that normalized flood depth itself is negative there. Because the values in Figure 2 represent the *change* in normalized flood depth relative to conditions without climate change, the negative values for Miami indicate that normalized flood depth is lower with climate change than without the projected change in climate. The most significant increases in normalized flood depth among the seven cities examined are in Aurora and Kansas City for the reference scenario, Fort Collins for the Policy 4.5 scenario, and Fort Collins and Kansas City for the Policy 3.7 scenario. In addition, across all seven

⁴The runoff coefficient is a commonly used metric representing the portion of rainfall that becomes runoff in a given area (rather than infiltrating into the ground).

⁵This runoff coefficient equation is consistent with guidance published by the New York Department of Environmental Conservation (see Center for Watershed Protection, 2010) and has also been used by the U.S. EPA (see ENSR International, 2005). This equation is also a reasonable approximation of the nonlinear curve linking imperviousness to the runoff coefficient in Maidment (1993).

⁶Because micro-topography and other factors influence whether increased runoff will lead to the failure of a local urban drainage system (see Aronica et al., 2005), not all runoff will necessarily contribute to the exceedance of urban drainage network capacity. Several analytic options were explored in which only a fraction of runoff contributes to capacity exceedance, but the reduced form approach described here performs best relative to SWMM when all runoff is assumed to affect capacity exceedance.

cities examined, the most significant change in normalized flood depth is for the 50-year, 24-hour storm. The climate scenario exhibiting the most significant changes in normalized flood depth is the reference case, except in Fort Collins and Miami.

The data reported in Figure 1 and Figure 2 show that the projected change in normalized flood depth can differ between two storm events with common rainfall amounts. For example, the projected change in normalized flood depth in Louisville in the reference case for the 10-year, 24-hour storm (approximately 1.5 cm) is much greater than the increase for the 50-year, 24-hour storm (approximately 0.7 cm) under the Policy 3.7 scenario, even though the projected rainfall for these two storms is nearly identical (approximately 19 cm). This reflects the fact that the 19 cm of rainfall reflects a relatively large change relative to the historical baseline for the 10-year storm in the reference case, but not as great of an increase for the 50-year storm under the Policy 3.7 scenario. For the 10-year storm in the reference case, the 19 cm of rainfall represents a rainfall increase of 7.8 cm relative to the historical baseline, whereas the 19 cm estimate is an increase of just 3.5 cm for the 50-year storm under the Policy 3.7 scenario relative to historical conditions.

SWMM analysis

For each of the cities analyzed with the reduced form methodology, changes in normalized flood depth for each climate scenario were also examined using the U.S. EPA's SWMM model. Focusing on drainage at the local level, SWMM uses detailed information entered by the user on drainage system design and capacity, topography, imperviousness, and several other site-specific factors to simulate runoff flows to individual drainage areas within urban areas. Existing, city-specific configurations of SWMM developed for planning, academic, and educational purposes were obtained from government and academic sources.⁷ These models were applied as they were provided, with little or no modification to the physical representation of the system, including capacity. The SCS type II and Type III 24-hour design hyetographs were incorporated into SWMM for the cities to which they correspond. These unit hyetographs were used with the storm depth totals to generate a time series of rainfall depths in 6-minute increments for each city, climate scenario, and recurrence interval. In addition, both catchment runoff routing and pipe conveyance routing were modeled in SWMM. For runoff routing, a nonlinear reservoir approximation for catchment runoff was used, and for hydraulics the full one-dimensional St. Venant equations were approximated with the dynamic wave computation for pipe routing.

SWMM was used to estimate normalized flood depth (volume of node flooding normalized by catchment area) as a metric of system performance under each scenario. These values represent a clear failure of a system, as they implicitly reflect the capacity of a system's drainage infrastructure and water surface elevations greater than the ground surface elevations that typically coincide with street flooding. As a metric, normalized flood depth also avoids conflicting measures between combined and separate systems. In particular, what constitutes a capacity failure in combined systems can be site-specific and subject to

⁷The Louisville, Kansas City, and Fort Collins SWMM models were provided by the U.S. EPA; the Aurora SWMM model was provided by the University of Colorado; the Haverhill and Lewiston models were provided by each city; and the Miami SWMM model was provided by Wayne Huber of Oregon State University.

regulatory interpretation. Node flooding however, is not hampered by these conflicts. It is a clear and unambiguous indication of capacity failure.

To isolate the change in normalized flood depth associated with climate change, the values for the historical baseline were subtracted from the corresponding values for each climate scenario. Figure 3 summarizes the results for the year 2100. Similar to the reduced form results, the SWMM results show a reduction in normalized flood depth in Miami and increases in Kansas City, Haverhill, Louisville, and Lewiston. The magnitude of the changes projected by SWMM, however, differs significantly from the changes projected by the reduced form approach in many cases. For example, the SWMM results for Louisville show an increase in normalized flood depth of at least two centimeters for several policy scenarios and frequency-duration events, whereas most of the results derived from the reduced form approach show an increase of less than one centimeter.

To provide a more detailed comparison between the reduced form and SWMM results, the change in normalized flood depth projected by the reduced form approach for each city, climate scenario, and year, is presented in Figure 4, mapped against the corresponding values from SWMM. These values are presented separately for each frequency-duration event. Points along the diagonal in Figure 4 represent instances where the reduced form and SWMM results closely match one another. In the upper right hand quadrant of the graphs, points below the diagonal represent instances where the change in normalized flood depth projected by the reduced form approach is less than the corresponding change projected by SWMM. Above the diagonal, the reduced form approach projections are greater than the SWMM estimates. In the lower left hand quadrant, the opposite applies. Overall, the graphs suggest that the reduced form approach is not systematically biased in any one direction and that it tracks reasonably well with SWMM results.⁸ In particular, for Kansas City, Louisville, and Lewiston, changes in the SWMM results correspond with similar changes in results for the reduced form approach (i.e., the points for these cities follow a path that is somewhat parallel with the diagonal). The points for some of these cities, however, are a consistent distance from the diagonal, suggesting that some characteristics specific to the city cause results from the reduced form approach to diverge from the SWMM results. In addition, Figure 4 shows that SWMM projects no change in normalized flood depth for both Colorado cities (Aurora and Fort Collins), whereas the reduced form approach shows an increase across all three storm events for these cities.

Calibration of reduced form methodology

While the reduced form approach presented above is fairly consistent with SWMM, the comparison in Figure 4 shows that each city included in the reduced form model exhibits a unique error trend in comparison to the SWMM model. In other words, the differences between the corresponding estimates appear to be caused by site-specific factors not reflected within the reduced form model. To minimize these systematic differences, a regression analysis was performed estimating the difference between the SWMM and

⁸The signs of the reduced form and SWMM results are always consistent because both are based on the same projected changes in rainfall for a given frequency duration event.

reduced form results (SWMM – reduced form) as a function of various site-specific characteristics. Appended to the reduced form model, the resulting regression equations, in effect, act as calibration factors to yield normalized flood depth estimates more closely aligned with those produced by the SWMM model. This regression analysis is based on the estimated difference between SWMM and the uncalibrated reduced form approach by year (2025, 2050, 2075, and 2100), climate scenario, and frequency-duration event.

An important shortcoming of the (uncalibrated) reduced form approach that the calibration procedure addresses is the extent of flooding when systems are loaded at full capacity. As noted above, the uncalibrated reduced form approach assumes that the capacity of a system is sufficient for the baseline storm event but floods during heavier events. In reality, however, systems that are loaded at design capacity may not be completely filled. Thus, while additional runoff will lead to flooding in the most critical locations, some runoff can still be stored in other parts of the system, limiting normalized flood depth. Because this effect is reflected in the SWMM-based results used for the calibration procedure described in this section, the calibrated version of the reduced form approach also reflects this effect.

The specific variables considered in the regression analyses performed for the calibration procedure include the following:

- *Ratio of 24-hour to 6-hour storm rainfall amounts, for each storm frequency:* This variable helps capture differences in design capacity across cities. In areas where the 24-hour storm is more concentrated during a 24-hour period, design capacity is likely to be higher, reducing the potential for flooding. These values were estimated based on frequency-duration values from NOAA Atlas 14 (Bonnin et al., 2006; Hershfield, 1961; Wilks & Cember, 1993).
- *Combined sewer:* Also related to system capacity, a dummy variable was included in the regression to indicate whether each city has a combined sewer system. Combined sewer locations include Kansas City, Louisville, Lewiston and Haverhill.
- *Imperviousness:* Imperviousness was incorporated into the regression analysis to account for any systematic differences in the relationship between imperviousness and runoff in SWMM and the same relationship as estimated by the reduced form approach. Imperviousness values were obtained from the SWMM model for each catchment.
- *Proportional change in frequency-duration rainfall amounts:* Although this is incorporated into both the SWMM and reduced form approaches, this variable was included to capture model bias correlated with the magnitude of rainfall change. These values were estimated using the approach outlined above.
- *Magnitude of 6-hour storm event for each storm frequency:* Similar to the ratio for the 24-hour to 6-hour storm, rainfall associated with the 6-hour storm event was incorporated into the regression analysis to capture the design capacity of systems located in areas where rainfall is concentrated over relatively short

periods. These values were obtained from NOAA Atlas 14 (Bonnin et al., 2006; Hershfield, 1961; Wilks & Cember, 1993).

Table 2 displays the regression results of several different model specifications, each chosen to represent different variables that may account for some of the variation in the difference between the SWMM and reduced form results.⁹ Model 1 represents an initial specification with three independent variables—CSO dummy, 24/6 storm ratio, and magnitude of the six-hour storm event—that reflect differences in capacity for each system. Models 2 through 7 introduce various combinations of the other variables considered. As indicated in the table, each of the independent variables was found to be statistically significant, though the proportional change in the frequency-duration event is not significant in one of the four specifications in which it is included. Overall, the model that includes all of the variables described above accounts for approximately 60 percent of the variation in the estimated difference between SWMM and the reduced form approach.

Possible collinearity among the regressors included in the regression models (indicated by asterisks) is given in Table 3. Many of these correlations, however, are likely to be spurious, and may subside with the addition of new locations into the model. In addition, although multi-collinearity may bias the individual coefficients estimated by each model, it does not bias any of the regression models as a whole. Thus, the models shown in Table 2 may serve as a basis for calibrating the reduced form approach.

For the purposes of calibrating the reduced form approach, we use Model 7 from Table 2. Of the models for which all of the independent variables are statistically significant, this model has the highest explanatory power with an R^2 of 0.590. Incorporating Model 7 into the reduced form approach, adjusted estimates of normalized flood depth were developed. Figure 5 shows the performance of the calibrated reduced form approach relative to SWMM. Compared to Figure 4, the results in Figure 5 show that the calibrated reduced form estimates more closely match the estimates generated by SWMM. As additional insight into the performance of the calibrated reduced form methodology relative to the uncalibrated approach, Table 4 summarizes the sum of squared differences between the SWMM estimates of normalized flood depth and the reduced form estimates, with and without the regression-based calibration. The data in the table clearly show that the calibration procedure reduces the difference between the SWMM and reduced form estimates of normalized flood depth.

Cost implications

Based on the changes in normalized flood depth projected by the calibrated reduced form methodology (using Model 7 in Table 2), it is possible to estimate climate change adaptation costs for urban drainage systems. To estimate these costs, it is assumed that urban areas will utilize a range of storm water management practices that focus on limiting the quantity of runoff instead of expanding formal drainage networks of catch basins and conveyance systems. These best management practices (BMPs) are widely used in the U.S. and throughout the industrialized world. The use of BMPs is consistent with the

⁹Other model specifications that included regional dummy variables and dummy variables for individual years were also considered. These were excluded from the analysis due to collinearity with the CSO dummy variable, which has a stronger explanatory basis.

globally recognized approach that development of robust adaptation options is a viable adaptation strategy (Lempert & Groves, 2010; Stakhiv, 2010). Flexibility is a hallmark of such measures, as the installation of BMPs as needed affords local drainage network managers more flexibility than reconfiguring underground drainage conveyance systems as climate conditions change (Arisz & Burrell, 2006).

BMP volume management techniques generally include temporary storage above or below ground or infiltration. U.S. EPA (1999) reports that base construction costs for these measures are approximately \$46.22/m³ of storage or management (converted to year 2010 dollars) plus an additional 30 percent for design and contingencies.¹⁰ These capital costs are annualized over the 35-year design life of BMPs.¹¹ Annual maintenance costs are approximately five percent of upfront construction costs.¹² To apply these unit cost values, normalized flood depth estimates were converted to volumes of node flooding by calculating the product of normalized flood depth and the area of each catchment. To facilitate comparison across cities, costs are presented per square kilometer of catchment area.

Figure 6 presents the estimated adaptation cost per square kilometer by city, scenario, and frequency-duration event for the years 2050 and 2100. The results in Figure 6 show that adaptation costs vary significantly by city; costs are relatively small in Miami and Fort Collins but much more significant in Kansas City and Louisville. This is consistent with the changes in rainfall relative to the historical case shown above in Figure 1. Figure 6 also shows that cost savings are not estimated for any cities projected to experience a reduction in normalized flood depth, as it is unlikely that municipalities would be able to cost-effectively reduce the capacity of their urban drainage systems to realize these savings. In those cities expected to experience an increase in costs, the pattern of these increases is not consistent across climate scenarios. In some cities, costs are highest under the reference case, but in other areas costs are highest under one of the greenhouse gas mitigation scenarios. This pattern is consistent with the projected changes in the frequency-duration rainfall events, as shown above in Figure 1.

Discussion and conclusions

This paper presents a systematic approach for assessing climate change adaptation costs for urban drainage systems that may be applied on a national scale using readily available data from existing sources. This approach yields results comparable to those generated by the more detailed SWMM model, which has been applied extensively across many cities in the U.S. This paper has also shown that calibrating the reduced form approach can improve its accuracy and, based on the cities and scenarios analyzed here, accounts for approximately 60 percent of the variation between the uncalibrated reduced form approach and the SWMM results. As illustrated above, projections of normalized flood depth derived from the calibrated reduced form approach are not systematically biased in one direction or another and provide a reasonable approximation of the magnitude of adaptation costs associated with stormwater management.

¹⁰This value is based on contingency values that U.S. EPA (1999) cites from Wiegand et al. (1986) and Brown and Schueler (1997).

¹¹For design life information, see Olson et al. (2010).

¹²The cost of land not already owned by a municipality is not included in these estimates.

Application of the reduced form approach for a nation-wide analysis would be feasible with data for a limited number of variables for each city. These variables include imperviousness, surface area, rainfall associated with the baseline frequency-duration event, and the climate change induced change in this event. While the reduced form approach lacks the city-specific detail of a model such as SWMM, the capability to assess adaptation costs on a broad geographic scale represents a significant advance as it will help planners, policymakers, and other interested stakeholders better understand the national implications of climate change for the country's urban drainage systems. Applying the reduced form approach to every municipality in the U.S. that has a storm water drainage system may not be feasible, but a national analysis could be tailored to include cities that account for a significant portion of the population or that are projected to experience the most significant increases in storm intensity.

Planners may also find the reduced form approach useful for screening assessments examining the range of potential futures that may occur with climate change. For a specific policy scenario, projected changes in frequency-duration events will vary by GCM, and, for a given GCM, will depend on the assumed climate sensitivity. Because the reduced form approach presented here can be implemented with minimal data collection effort, it would enable planners to quickly assess the potential magnitude of adaptation costs under multiple scenarios using several GCMs.

The results summarized above for the seven cities included in this study show that climate change may lead to an increase in normalized flood depth in many areas but a decrease in others. This finding is consistent with the precipitation projections generated by IGSM-CAM and highlights that changes in the intensity of rainfall events, in terms of both magnitude and sign, vary spatially. Thus, while climate change may pose a significant threat to some urban drainage systems, others will continue to provide a consistent level of service and may even experience fewer or less severe instances of exceeded capacity as the climate changes. Cities where frequency-duration events become less intense, however, are unlikely to realize a substantial cost savings. As noted above, it is unlikely that such cities would be able to cost-effectively reduce the capacity of conveyance and storage systems to realize these savings.

The reduced form method may also help inform assessment of the nation-wide benefits associated with greenhouse gas mitigation. While other sectors (e.g., agriculture, coastal property affected by sea level rise, etc.) may account for a greater portion of mitigation benefits, policies that reduce the need for adaptive measures for urban drainage systems and other infrastructure will yield cost savings across much of the U.S. Not all areas will *necessarily* realize a cost savings as a result of mitigation efforts, however. As indicated above, the adaptation costs associated with a given frequency duration event *increase* under the mitigation scenarios analyzed here relative to the reference case for some cities. Our projection of the specific cities where this will occur reflects outputs from IGSM-CAM; results from other GCMs may suggest a different spatial distribution of costs. This uncertainty in climate model outputs is a major source of uncertainty for any assessment of climate change adaptation costs.

Due to the reduced form design of the approach presented in this paper, results derived from this approach are subject to a number of uncertainties, in addition to the significant uncertainties associated with projected changes in climate. For example, the reduced form approach assumes that the cities for which existing SWMM models were available are sufficiently representative to serve as the basis for calibration of the reduced form methodology. While these cities provide broad geographic coverage of the Northeast, the Southeast, the Midwest, and the Rocky Mountains, no cities on the West Coast were included in the sample. Thus, to the extent that storm water management systems on the West Coast are different than those in other regions, the calibrated reduced form approach may not perform well for cities in this region. For an assessment of nation-wide urban drainage adaptation costs, however, the reduced form approach would be representative of most regions.

The reduced form model's lack of system-specific details also introduces uncertainty into model results. As noted above, the model assumes that systems are designed to manage the runoff associated with a 24-hour storm event, but in reality some systems may be designed for other storm events. The reduced form approach also includes no explicit representation of soil characteristics or vegetation, both of which affect runoff volumes. It is unclear, however, whether this lack of detail with respect to system capacity and other system-specific characteristics would bias the results of the reduced form model in analyses where it is used to estimate adaptation costs in aggregate for dozens of cities. In addition, the calibration approach outlined above is intended to account for these factors to the extent practicable, based upon a widely accepted stormwater model.

Considering these assumptions and the associated uncertainties, estimates of urban drainage adaptation costs based on the reduced form approach developed in this paper represent a first-order approximation of these costs, as the reduced form methodology is the first that we are aware of that addresses urban drainage adaptation costs on a national scale. Future research will likely build and improve upon this approach. Potential improvements include refining the calibration with SWMM to reflect additional cities and expanding the regression-based calibration to account for variables such as soil type, saturation of soil at the time of the storm event, and the age of a storm water management system. In addition, future research may consider changes in key variables over time, such as imperviousness and ongoing transitions from combined to separated sewer systems.

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Figure 1.
Projected rainfall in 2100.

Figure 2.
Projected changes in normalized flood depth in 2100 based on the uncalibrated reduced form approach.

Figure 3.
Projected changes in normalized flood depth in 2100 based on SWMM.

Figure 4.
Comparison of uncalibrated reduced form and SWMM normalized flood depth projections.

Figure 5.
Comparison of calibrated reduced form and SWMM normalized flood depth projections.

Figure 6.
Calibrated reduced form cost per square kilometer.

Table 1.

Summary of catchments used for calibration.

Catchment city	Catchment area (square kilometers)	Imperviousness (%)
Haverhill, MA	6.89	56.0
Lewiston, ME	19.11	31.9
Miami, FL	0.05	43.9
Kansas City, MO	0.73	18.1
Louisville, KY	4.22	15.5
Aurora, CO	3.52	53.0
Fort Collins, CO	0.13	57.1

Table 2.

Regression models for calibration of reduced form approach.

Variables	Model 1 Coefficient	Model 2 Coefficient	Model 3 Coefficient	Model 4 Coefficient	Model 5 Coefficient	Model 6 Coefficient	Model 7 Coefficient
CSO Dummy	1.2414 *** (0.1672)	1.0894 *** (0.1201)	0.3482 *** (0.1113)	0.3418 *** (0.1096)	1.1090 *** (0.1324)	0.4868 *** (0.0949)	0.5276 *** (0.1111)
24/6 Precip Ratio	5.1843 *** (1.5940)	9.2847 *** (1.1668)	6.9895 *** (0.8465)	7.1146 *** (1.1190)	4.5899 *** (1.4053)	4.0954 *** (0.9938)	3.8585 *** (0.9955)
6-hour Precip (cm)	0.1171 *** (0.0277)				0.1519 *** (0.0333)	0.0939 *** (0.0125)	0.1213 *** (0.0242)
Frequency Duration Factor		0.8877 * (0.4982)		0.4264 (0.5156)	1.4240 *** (0.4803)		0.9598 * (0.5273)
Imperviousness			-0.0395 *** (0.0091)	-0.0376 *** (0.0077)		-0.0351 *** (0.0070)	-0.0291 *** (0.0049)
Constant	-8.7765 *** (1.8398)	-14.0963 *** (2.0038)	-7.9422 *** (1.0061)	-8.7050 *** (1.8618)	-10.0150 *** (1.6671)	-5.2640 *** (1.1854)	-6.6723 *** (1.5625)
Observations	252	252	252	252	252	252	252
Number of Clusters	9	9	9	9	9	9	9
R-squared (overall)	0.475	0.431	0.522	0.527	0.536	0.564	0.590

Note: Dependent variable is SWMM normalized flood depth (in centimeters), less reduced form normalized flood depth (in centimeters). Robust standard errors in parentheses

p < 0.01**
p < 0.05*
p < 0.1

Table 3.

Correlation among independent variables.

	CSO dummy	24/6 precip ratio	Climate change factor	6-hour precip (cm)	Imperviousness
CSO dummy	1				
24/6 precip ratio	-0.0234	1			
Climate change factor	0.1976*	-0.2009*	1		
6-hour precip (cm)	-0.0746	0.6444*	-0.352*	1	
Imperviousness	-0.6337*	-0.2268*	-0.2623*	-0.2069*	1

Table 4.

Sum of squared differences between SWMM and reduced form normalized flood depth estimates.

Version of reduced form model	10-year, 24-hour	25-year, 24-hour	50-year, 24-hour
Uncalibrated reduced form	67.41	153.98	280.90
Calibrated reduced form	38.38	54.65	112.36