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Climate change risk and adaptation costs for stormwater management in California coastal parklands

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ABSTRACT
Extreme precipitation from climate change may strain many existing stormwater systems. While studies have evaluated such effects on stormwater infrastructure, other sources of uncertainty not yet explored should also be considered. This paper presents an analysis of adaptation costs for new stormwater infrastructure to mitigate increases in design storm precipitation depth with climate change, including how economic and managerial uncertainty related to life cycle unit costs and knowledge of existing infrastructure affect costs. For case study areas in California, we quantify adaptation costs for new green infrastructure capacity by evaluating future design storms. Results indicate that design storm depths increase by an average of 28%, but lack of knowledge of the condition of existing infrastructure and life cycle unit costs result in wide cost ranges. The findings illustrate how climate change planning for stormwater should also consider economic and managerial uncertainty when estimating long-term adaptation costs.

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1. Introduction

Cities build stormwater (drainage) infrastructure to reduce the effects of runoff from impervious surface cover. Systems are designed to mitigate the effects of urbanization such as degraded water quality, increased flood risk, hydromodification that erodes channels and deposits sediments, and exposure to contaminants (Debo & Reese, 2003; Hollis, 1975; Schueler, 1994). While designers and operators have always dealt with uncertainty in the expected values of extreme precipitation, likely future increases in the frequency and intensity of such events with climate change may strain current systems and require new investments to protect infrastructure, residents, and environmental systems (Arnbjerg-Nielsen et al., 2013; Willems et al., 2012b). Current stormwater infrastructure sized for the 20th Century built environment will likely need upgrades and improvements (Semadeni-Davies et al., 2008).

Anthropogenic climate change poses unique challenges for infrastructure planning, which must consider adaptation needs as future extreme weather events emerge (Gilrein et al., 2019). For stormwater, changes in the timing and intensity of precipitation will likely exceed sizing guidelines for current infrastructure systems (Brekke et al., 2009; Costa-Cabral et al., 2013; Dettinger et al., 2011; Mallakpour et al., 2019; Musselman et al., 2017). Due to the relatively short time periods during which runoff concentrates in small- and medium-sized urban catchments, stormwater system designs require high-resolution spatial and temporal data, with models supporting detailed depictions of runoff in linked networks of surfaces and pipes, driven by hourly or sub-hourly precipitation values (Arnbjerg-Nielsen et al., 2013; Debo & Reese, 2003). Runoff can take days or weeks to flow through a large watershed, but stormwater systems move water at sub-daily time steps. Existing systems designed based on historic hydrologic records may not perform to design specifications in the future due to both climate change and other factors such as maintenance and design uncertainties. Moreover, the incorporation of new design methods such as smaller, distributed stormwater control measures (SCMs) can further increase uncertainty in future performance (Cook et al., 2019; Montalto et al., 2012). Such devices are referred to by many names, including green infrastructure (green stormwater infrastructure), Low-Impact Development (LID), best management practices, and sustainable urban drainage systems (Dietz, 2007; Fletcher et al., 2015; Low Impact Development Center, 2000; Shuster et al., 2005). They are often not sized to deal with extreme precipitation events (McPhillips et al., 2020).

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Supplemental data for this article can be accessed here.

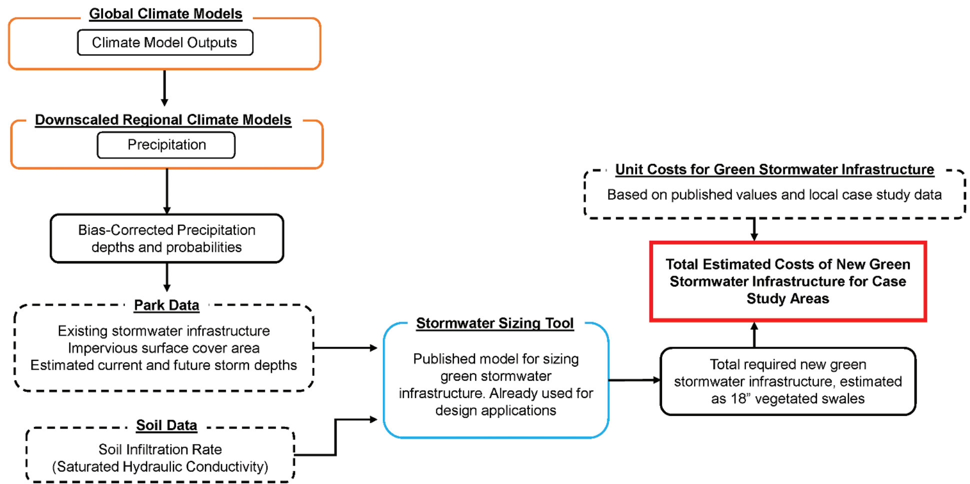

Figure 1. Analysis procedures used to apply estimates of downscaled regional climate model outputs to the case study areas.

While climate change should certainly be considered when sizing future stormwater infrastructure, unfortunately, many available general circulation models (GCMs, also referred to as global climate models) provide outputs that are too coarse for stormwater planning applications (Arnbjerg-Nielsen, 2012; Arnbjerg-Nielsen et al., 2013; Cook et al., 2017; Lenderink & van Meijgaard, 2008; Maraun et al., 2010). Moreover, the choice of GCMs with varying biases and resolutions can significantly influence the results from updating design tools such as Intensity, Duration, and Frequency (IDF) curves (Cook et al., 2020). The certainty and availability of future climate projections are a gap when evaluating failure risks and adaptation options for stormwater planning with climate change (Arnbjerg-Nielsen et al., 2013; Cook et al., 2020; Rosenberg et al., 2010; Willems et al., 2012b).

Downscaling of GCMs provides an option to improve the spatial and temporal resolution of model results, which increases their applicability for planning tasks (Barsugli et al., 2013; Hall, 2014). Downscaled climate models offer simulation outputs at finer spatial grid scales (6–50 km) and hourly (or smaller) time intervals. Downscaling techniques use either statistical approaches or dynamic downscaling approaches. Statistical downscaling can address issues in GCM results using observed past weather data, but may inherit assumptions of stationarity since model results are calibrated using historic records. Dynamical downscaling can better represent regional climate patterns, but may maintain or enhance biases of modeling approaches or assumptions (Barsugli et al., 2013). In either case, downscaling GCM parameters to sub-daily values requires assumptions of important atmospheric conditions such as moisture content (Lenderink & van Meijgaard, 2008). While downscaled GCM results have many potential applications for infrastructure planning, fewer downscaled model simulations exist and using them requires significant computational resources and expertise, which creates a barrier for use by practitioner communities.

Anthropogenic climate change quantified by climate modeling is an important source of uncertainty for infrastructure planning, but it is only one of many sources of uncertainty for stormwater management (Heaney & Wright, 1996). Existing research and industry expertise have identified others (OWP, 2018). First, many input parameters for stormwater modeling such as climate, unit costs of construction and maintenance, and land use are not available or known in sufficient detail, especially for site-scale planning. The intensity, duration, and frequency of rainfall vary widely across regions, with no single accepted method to evaluate likely storms (Guo & Urbonas, 2002; Korving et al., 2009, 2003). While stormwater systems are long-lasting, land cover patterns in cities change at a faster rate (Zhu et al., 2007). Land-use changes may introduce equal or greater uncertainty in sizing systems for future decades (Pyke et al., 2011). Integrating key climate drivers with land use change can increase the usefulness of modeling outcomes (Gersonius et al., 2012). Hybridized systems of centralized and distributed stormwater capture devices offer opportunities for additional social benefits, but may also introduce uncertainty in performance (Arnbjerg-Nielsen, 2011; Arnbjerg-Nielsen & Fleischer, 2009; Fratini et al., 2012; Hering et al., 2013; Orsi, 2004; Porse, 2013; Sedlak, 2014). Differences in cost, public acceptance, and maintenance regimes also affect performance of distributed stormwater capture measures (Montalto et al., 2012).

Second, regulatory uncertainty and governance constraints affect planning. Stormwater programs are inconsistently funded through a patchwork of sources (Kea et al., 2016). Most available funding supports activities that achieve compliance with regulatory permits to reduce contaminant loading to watersheds, a task itself subject to significant modeling uncertainty (BASMAA, 2017; EPA Region 9, 2017; Rwqcb, 2014). Designing new or updated stormwater systems to manage future extreme precipitation can exceed the financial capacity of small- and medium-sized cities with legacy drainage systems.

Finally, stormwater managers often have limited information on the sizes and locations of assets in their systems. Municipal stormwater programs are increasingly encouraged to improve system surveys through better asset management (EPA, 2017). Asset management is the process of recording data such as age, size, condition, material, and location for components throughout a system (pipes, gutters, catch basins, and others along with green stormwater infrastructure devices) and using the data to develop repair and replacement plans. The lack of metrics to address uncertainties associated with both limited system knowledge and future climate variability presents a significant knowledge gap for stormwater system planning, especially in small- and medium-sized systems that have previously used straightforward design heuristics.

Thus, when evaluating adaptation needs for stormwater planning with climate change, simultaneously considering how other sources of uncertainty also affect designs is a critical step for better planning outcomes (Gersonius et al., 2012). This paper describes an analysis of climate change risk and adaptation costs for stormwater management. It considers the implications for future stormwater infrastructure from multiple sources of uncertainty, including not only changes in extreme precipitation but also sources of economic and managerial uncertainty. We consider how variability in known construction and maintenance costs, as well as the condition of existing infrastructure, affect total cost estimates. Using case studies from coastal park areas in California managed by the California State Department of Parks and Recreation, the study combines climate modeling, collected field data, and accumulated data on unit costs of green infrastructure to estimate adaptation costs for upgrading systems to mitigate future runoff. It uses downscaled climate modeling to evaluate changes in extreme precipitation. The study addresses two key gaps in research. First, it provides an example of a cost evaluation for upgrading existing smaller stormwater management systems to meet future climate. Second, it demonstrates the need to consider changes in design storm event depths alongside other sources of uncertainty in planning future stormwater systems. The study helps illustrate how climate change adaptation for infrastructure is influenced not only by technical requirements but also by institutional drivers, which may contribute as much or more to future costs.

2. Methods

The sections below describe procedures for 1) investigating the best source(s) of climate change data, 2) evaluating changes in the depth of future and potentially more extreme storms for design standards, 3) assessing resultant increases in drainage capacity to manage runoff, and 4) estimating costs of adaptive upgrades to infrastructure. The process for applying the methods to the case study regions is described. The analysis was part of a broader multi-year effort to evaluate stormwater management practices in California parklands in support of the California State Department of Parks and Recreation, which included field data collection for existing drainage systems. This parallel work was leveraged as part of the analysis for this paper.

2.1. Investigating sources of climate modeling data

The diversity and complexity of available global and regional climate models, along with the challenges in aligning model outputs with applications for stormwater and drainage planning, can present impediments for their broader use outside of the climate modeling community that should not be underestimated (Barsugli et al., 2013; Cook et al., 2020; Verburg et al., 2016; Wang et al., 2019). The first step is to investigate potential sources of data that would have appropriate spatial and temporal resolution to perform an analysis of future needed stormwater drainage capacity within the small catchment areas of interest in the case study regions, while also being accessible and providing replicable results. To facilitate repeatability of the analysis, simpler approaches that yield results with uncertainty equivalent to more complex ones may be preferable.

Existing research and tools were surveyed from literature, including both the climate planning community in California and stormwater management research more broadly. Two potential sources of climate change model simulation data were identified: 1) the *Cal-Adapt* platform with daily climate parameter values, and 2) the North American Coordinated Regional Downscaling Experiment (*NA-CORDEX*) program (Mearns et al., 2017) with hourly climate parameter values (Table 1). *Cal-Adapt* was developed as a web-based tool that provides access to multiple downscaled GCMs as part of

Table 1. Summary of model parameters for climate model simulations and downscaling procedures.

Source	Scenario	GCM	Downscaling/RCM	Temporal Resolution	Spatial Grid
Cal-Adapt	Historic	CanESM2	*LOCA*	Daily	6-km
	Historic	CIMP5			
	Historic	HadGEM2-ES			
	Historic	MIROC5			
	RCP 4.5	CanESM2			
	RCP 4.5	CIMP5			
	RCP 4.5	HadGEM2-ES			
	RCP 4.5	MIROC5			
	RCP 8.5	CanESM2			
	RCP 8.5	CIMP5			
	RCP 8.5	HadGEM2-ES			
	RCP 8.5	MIROC5			
NA-CORDEX	Historic	CanESM2	CanRCM4	Hourly	44-km
	Historic	HadGEM2-ES	WRF		
	Historic	MPI-ESM-LR	RegCM4		
	Historic	MPI-ESM-LR	WRF		
	RCP 8.5	CanESM2	CanRCM4		
	RCP 8.5	HadGEM2-ES	WRF		
	RCP 8.5	MPI-ESM-LR	RegCM4		
	RCP 8.5	MPI-ESM-LR	WRF		

California's 4th Climate Change Assessment published in 2018 (State of California, 2018). *NA-CORDEX* is a repository of climate models from North American scientists that participate in the World Climate Research Program, which coordinates dynamical downscaling of Regional Climate Models (RCMs) based on simulations using boundary conditions from GCMs. *Cal-Adapt* uses a statistical downscaling procedure applied to GCMs, while the *NA-CORDEX* simulations use regional climate models for downscaling (Figure 1).

Each data source has advantages and drawbacks. Downscaled climate model results from *Cal-Adapt* are easily accessible, especially for users with limited knowledge of GCMs, while the daily time intervals allow for more detailed geographic resolution with manageable data storage requirements. Model results in *Cal-Adapt* are available and well documented for many GCMs. The daily time step in *Cal-Adapt*, however, presents limitations for stormwater planning applications, such as developing return period values or using the data as inputs to continuous simulation models of green infrastructure and drainage planning. Alternatively, the *NA-CORDEX* RCM simulations with hourly temporal resolution can better support local stormwater planning applications, but accessing and using data from the repository requires detailed knowledge of information technology and software engineering, which do not align with typical skills of stormwater management professionals.

Historic and future downscaled climate model simulation results were downloaded from both sources. For *Cal-Adapt*, historic and future gridded (6-km, or 1/16°) daily precipitation data was downloaded. Historic data originated from National Oceanographic and Atmospheric Administration (NOAA) Cooperative Observer Stations and spanned 1950–2006 (Livneh et al., 2013), while data for future scenarios were downloaded for four models spanning 2006–2099. Both RCP 4.5 and RCP 8.5 scenarios were considered. GIS files for identified park boundaries (see discussion in following section) were used to select the appropriate grid cell using the *Cal-Adapt* website's interface. Four simulations were used with the justification that selected GCMs would provide a diverse snapshot of future potential conditions: the Canadian Earth System Model (CanESM2, '*cool/wet*'); Earth System Models from the phase 5 Coupled Model Intercomparison Project, or CIMP5 (CNRM_CM5, '*cool/wet*'); the Met Office Hadley Center Model from the United Kingdom (HadGEM2-ES, '*warm/dry*'); and the Model for Interdisciplinary Research on Climate in Japan (MIROC5, '*most unlike others*'). The data was produced by the *Cal-Adapt* researchers through a statistical downscaling procedure using a Localized Constructed Analog (LOCA) for each model (Pierce et al., 2014).

For *NA-CORDEX*, historic and future (RCP 8.5) gridded hourly precipitation flux data with a 0.44° grid was downloaded for four dynamically downscaled RCMs, each using a GCM for boundary conditions (Mearns et al., 2017). The GCMs and associated RCMs, including the CanESM2, HadGEM2-ES, and the Max-Planck-Institute's Earth Systems Model (MPI-ESM), were selected based on RCM simulations with available hourly data. Table 1 lists the GCM-RCM combinations used from *NA-CORDEX*. The data were loaded and analyzed using the *netcdf4* package for Python 3.3 (Whittaker, 2019). Standardized latitude and longitude coordinates for each case study park were used to extract the relevant grid cells from the hourly RCP 8.5 GCM downscaled model simulations using the *find_nearest* function within the *netcdf4* data extraction package. Table S1 in the Supplemental Data section provides descriptive data for each park, including the latitude and longitude coordinates. *NA-CORDEX* also provides simulations with a 0.22° grid, which can improve results if resources allow for additional time and effort in data processing (Cook et al., 2020).

After investigating the two available sources of data: *Cal-Adapt* and *NA-CORDEX*, we selected RCMs with a 1-hour time interval published by *NA-CORDEX* to use for the analysis, as the simulation outputs most directly aligned with the temporal requirements of urban stormwater and drainage planning for the case study areas (Willems et al., 2012a). The remainder of the paper describes results based on *NA-CORDEX* RCMs. The *Supplemental Data* section reports results from the investigation of potential data sources. Data is reported for changes in extreme precipitation days as part of the *Supplemental Data*, but ultimately the event depths of design storms from the RCMs were used to evaluate upgrade costs.

2.2. Evaluating precipitation changes

The expected change in precipitation is then evaluated to use in stormwater infrastructure sizing. Stormwater models can use: 1) a continuous simulation approach with precipitation events over a given time period of observed or modeled climate, or 2) a return periods approach, where infrastructure is designed to mitigate runoff up to and including a particular return period interval event (Debo & Reese, 2003). While continuous simulation models may better address a range of performance indicators over time, for planning in very small catchments with limited data, the design storm approach can adequately support design requirements.

Precipitation event depths were compared from observed data with RCM outputs for the historic and future periods to assess potential changes in a design storm that would influence stormwater sizing requirements. For both historic and future precipitation data, multiple statistics were calculated to evaluate potential metrics for short- and long-term changes in extreme precipitation events, including moving averages, design storm depths and return periods, and changes in the number of extreme precipitation days based on the number of days with precipitation exceeding the approximately 95th percentile storm in the current and future periods.

The analysis focused on changes in design storm depth and used the Annual Maximum Series (AMS) to estimate precipitation event depths associated with return periods of a storm with 1-hour duration. For the modeled data, the event depth associated with a return period was calculated from the AMS using Weibull Plotting positions (Chow et al., 1988; Weibull, 1939) (see *Supplemental Data*). Precipitation depths of the 1-, 2-, 5-, 10-, 25-, 50-, and 100-year events were estimated for the historic and future time periods using raw outputs for each of the RCM simulations while investigating best available data sources; ultimately, the event depth of 1-hour duration was used for the impact analysis. Summary statistics of model simulations were developed by calculating the median and average values of the estimated future precipitation depth across the four model simulations.

For the observed historic data, point data for event depths were used from the National Oceanic and Atmospheric Administration's Atlas 14 estimates of point precipitation frequency (NOAA-14). NOAA-14 provides spatially explicit tables of return period values across intensity and duration based on both Partial Duration Series (PDS) and AMS procedures. Return periods are calculated from the best fit of several theoretical distributions to empirical frequency distributions, and regional data and L-moments are used to increase accuracy and reduce the influence of outliers (Perica et al., 2014). NOAA-14 data for 1, 2, and 24-hour precipitation event depths across return periods were recorded while investigating best available data sources; ultimately, the event depth of 1-hour duration was used for the impact analysis. Additional information and formulations for return period estimates are provided in the *Supplemental Data* section.

2.3. Bias correction and statistical downscaling

RCM simulations yielded raw outputs. Comparing these outputs with observed NOAA-14 data to estimate design storm changes required a bias correction of the RCM data based on a Model Output Statistics (MOS) technique. GCMs contain errors in simulating global and continental processes. Extreme events may not be well represented in earth system models used to evaluate future climate patterns (Volosciuk et al., 2015). Also, GCMs may poorly represent local climate trends (Hall, 2014). Such error can be translated to RCMs through the dynamical downscaling process (Maraun, 2016). RCMs that are dynamically downscaled from GCMs can also include inherent error in estimating certain climate parameters such as precipitation, which is generated through processes that may not be fully understood or represented in models (Willems et al., 2012a).

Using results from climate models for stormwater and urban drainage planning applications requires temporal and spatial downscaling of GCM outputs and, potentially, further statistical methods for bias correction (Arnbjerg-Nielsen, 2012; Cook et al., 2020, 2019; Willems et al., 2012a). Both temporal downscaling and spatial downscaling to higher resolution gridded model outputs was completed in the analysis using raw outputs from RCMs in *NA-CORDEX* with 1-hour temporal resolution and 50-km spatial resolution. The need for bias correction was then assessed and further spatial downscaling required to match available precipitation data that represented the case study areas was completed. Multiple MOS techniques exist for implementing bias correction to raw downscaled RCM results, including both parametric and non-parametric procedures. They range in complexity from adjusting observed design storms based on the ratio of historic and future modeled data, to fitting the model data to historic results for all events to develop a transfer function.

The case study areas present multiple challenges for implementing a bias correction technique from available methods. Global and regional climate model simulations may not well represent areas with spatial heterogeneity, such as areas with significant changes in topography. Areas of the Pacific Coast of North America experience climatic shifts across small distances due to multiple drivers, including significant elevation changes. Many of the case study areas have microclimates influenced by coastal weather patterns and topography. Additionally, most of the case study areas are remote with limited available historic precipitation event data from gauge stations, many of which had only a single nearby NOAA-14 station. Thus, additional spatial downscaling was needed to compare gridded RCM outputs with point data of historic rainfall.

Based on these factors, multiple approaches were considered for bias correction and spatial downscaling to compare gridded model outputs with point data. Insufficient historic gauge data was available across the period of interest (1950–2006) to implement a non-parametric approach that compared historic observed and model event data. The location and scale (typically less than 1 square kilometer) of the case study sites meant that local heterogeneity in rainfall patterns and the limited number of gauge stations for interpolating spatial grids equivalent to the RCM simulations made quantile mapping procedures complex and subject to additional error.

It was determined that the change factor method (also known as the delta change or climate change factor) was best able to account for the need for bias correction and spatial downscaling of gridded RCM outputs to sites (Arnbjerg-Nielsen, 2012; Lettenmaier et al., 1999; Willems et al., 2012a). For each case study area, the bias-corrected depth of return period events was estimated through two steps. First, for each RCM, the ratio of increase in a return period event depth was calculated, derived from the AMS, between the historic and future period from the RCM simulations. Next, an estimated median and average change factor was calculated across all four available models. Finally, the value of the return period event depth is estimated for the future period at the associated NOAA-14 station, calculated as the product of the change factor and NOAA-14 AMS-derived historic event depth. Neither variance nor confidence intervals are reported for the future period based on the MOS technique (Arnbjerg-Nielsen, 2012). A single design storm was used with an event depth associated with the 25-year return period interval and 1-hour duration for the stormwater SCM sizing calculation to align with design practice in the region, as described in the next section.

2.4. Evaluating existing and future drainage capacity for design storm events

Stormwater infrastructure upgrade needs were estimated for each of the 21 case study areas of coastal parklands managed by the California Department of Parks and Recreation based on the bias-corrected future precipitation depths from RCM simulations (Figure 2). The park areas span diverse climate areas, from wetter and cooler parks along the northern coast to drier and warmer parks in the central and southern coasts. Across the state, coastal areas have temperate climates with seasonal precipitation, but temperature and precipitation can change significantly just a few miles inland.

To evaluate existing drainage capacity in each of the case study areas, stormwater systems were surveyed through field visits and mapped using GIS. Existing system components were identified to include subsurface pipes, gutters, low-impact development devices, manholes, and lined and unlined drainage ditches. The drainage infrastructure GIS representations (vectors)

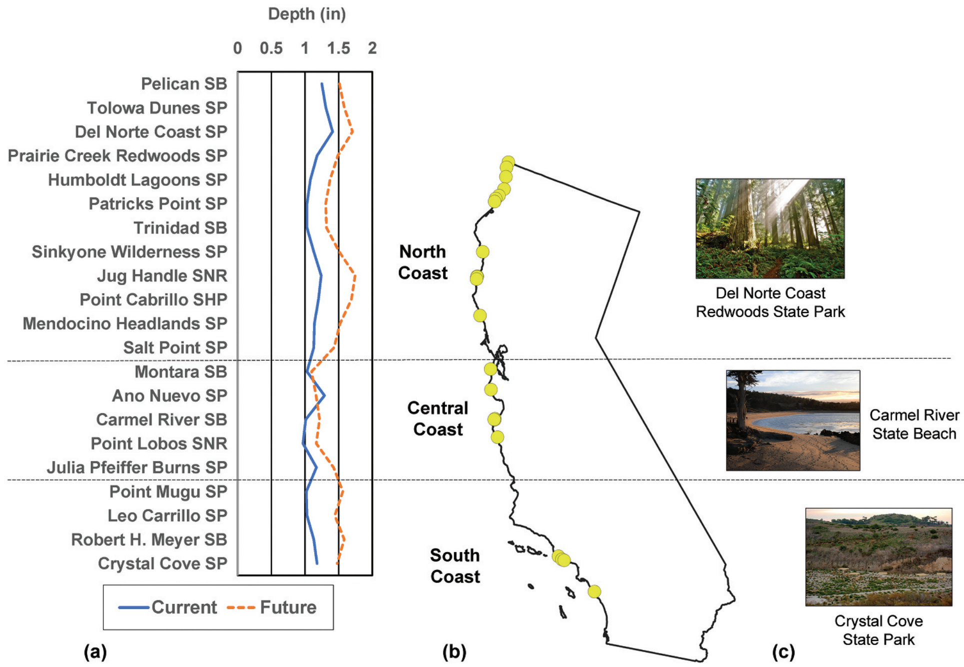

Figure 2. Case study areas used in the analysis and associated event depths for the design storm of interest (SP = State Park, SB = State Beach, SNR = State Natural Reserve, SHP = State Historic Park). (a) Current and future bias-corrected values of the design storm precipitation depth (25-year, 1-hour event); (b) Geographic locations across the North, Central, and South Coast regions of California; and (c) Example landscapes from parks in each region (Image sources: California State Parks and Recreation).

were overlaid with derived polygons for parking lots and other key assets that were identified through imagery. The area of impervious surface cover connected to drainage systems was estimated from imagery and survey data to be approximately 56 acres total across the 21 case study parks. Calculations were performed for each park individually.

Using data for existing drainage systems, aerial imagery, and estimated design storm event depths from the 1-hour RCM simulations, we calculated the volume of new stormwater infrastructure needed to manage future precipitation events based on a multi-step procedure:

(1) Estimate the historic and future bias-corrected RCM precipitation event depths for design storms based on the *NA-CORDEX* RCM simulations as previously described.
(2) Quantify the expected change in the precipitation depth of a design storm – the 25-year, 1-hour event-based on bias-corrected RCM simulations. The design storm parameters were chosen based on standard design practice for distributed stormwater devices in non-urban areas used by some state agencies in California. For instance, the California Department of Transportation designs stormwater devices to capture volume up to a 25-year, 1-hour storm event depth for parking lots and non-roadway impervious surface cover.
(3) Estimate sizes of contributing catchment areas for directly connected impervious areas (DCIA) using field data, imagery, and GIS in each case study area.
(4) Evaluate new green infrastructure capacity that would mitigate the additional runoff in each case study area. The example of swales and rain gardens with subsurface drainage were considered with a depth of 18 inches and a saturated hydraulic conductivity derived from GIS.

To estimate SCM sizing, an existing industry tool was used, the *California Phase II LID Sizing Tool* (the 'tool') that uses inputs for saturated hydraulic conductivity of soil, precipitation from nearby NOAA-14 stations, and catchment area data to evaluate the size of a green stormwater infrastructure device needed to mitigate runoff from design storms (OWP at Sacramento State, 2017). The tool is widely used for drainage planning in small catchments throughout California. It uses standard engineering calculations to estimate the area of green infrastructure needed to mitigate runoff based on SCM design specifications. Full documentation with methods is available online (https://www.owp.csus.edu/LIDTool/).

Sizing calculations included uncertainty associated with managerial practices. Like many other stormwater systems throughout the U.S., the condition and design parameters of existing grey stormwater infrastructure in the case study areas were not known. As a result, for each parkland area, an estimated acreage of new vegetated swales (18” in depth) needed to manage runoff associated with the DCIA (in square-feet) was calculated based on two assumptions: new vegetated swales must mitigate runoff from the entire event assuming that existing infrastructure is inadequate; or new swales must mitigate only the additional (marginal) runoff from predicted larger future extreme events. The assumptions are described further below as part of scenarios considered to evaluate uncertainty.

2.5. Estimating costs for infrastructure upgrades

The final step of the analysis estimated ranges of costs for new green stormwater infrastructure needed to mitigate future precipitation events across all of the case study areas. Unit costs for green stormwater infrastructure vary widely and present an additional source of uncertainty to be considered. The annualized life cycle cost of vegetated swales or rain gardens, including costs for both construction and operations and maintenance (O&M), was derived from several existing sources. First, existing literature has summary ranges of unit costs. In California, reported construction costs for vegetated swales in California were estimated to be $1-$9/sq-ft (CASQA, 2003; EPA, 2019). This value would not include additional costs for planning and contingencies that could be as much as 80% of the unit costs based on reported practices (EFC at Sacramento State, 2019; LADWP, 2015). A nationwide compilation of reported costs for rain gardens ranged from $10-$40/sq-ft for construction and $0.06-$1.45/sq-ft for maintenance costs. More complex projects were at the upper end of the ranges based on site conditions or locational characteristics (CASQA, 2003; EFC at Sacramento State, 2019; Gold et al., 2015; LADWP, 2015; RTI International & Geosyntec Consultants, 2015). Life cycle unit costs, evaluated as the cost per area (square-foot), were considered over a 20-year period using a discount rate of 0.05. Incorporating long-term O&M costs for cleaning, dredging, weeding, and other activities is essential for proper management of green stormwater infrastructure devices.

Second, unit cost data from a small-scale retrofit project was used as an indicator of potential SCM costs in areas with site design characteristics similar to the case study areas. Small-scale retrofit projects may cost substantially more than the average costs reported in literature, especially for sites with particular design challenges. We used unit costs for installing vegetated, irrigated green stormwater infrastructure features such as bioretention basins and swales on a college campus as a second set of more conservative (larger) unit costs. Unit costs for planning, constructing, and maintaining a device ranged from $51-$108/sq-ft across 20 distinct devices (Johnston & Kerner, 2016; OWP at Sacramento State, 2017). The *Supplemental Data* section has further information on data sources used in estimating the range of potential unit costs.

The uncertainty in appropriate unit costs results in ranges of estimated totals total costs for new adaptive infrastructure and requires judgment and assumptions. Key drivers of the size for such ranges include accessibility of sites in remote locations, permitting requirements, and the relatively small size of the projects across the California Coastal park areas mean that higher cost estimate ranges are more likely to be representative of final unit costs.

2.6. Analysis of uncertainty

Estimated costs for needed new stormwater infrastructure can vary based on assumptions for and uncertainty in climatic, economic, and managerial factors. The percent increase in the future design storm based on the MOS was estimated and compared with the influence of the two additional sources of uncertainty described in previous sections: 1) economic uncertainty in unit costs of new green stormwater infrastructure devices, and 2) managerial uncertainty in the condition and design parameters of existing infrastructure. Economic uncertainty results from the site-specific parameters that influence ultimate costs for new green stormwater infrastructure projects, including remoteness, soil conditions, terrain, and economic trends. Managerial uncertainty results from past institutional practices regarding asset management, which, if not practiced, can result in limited knowledge of the condition or adequacy of existing systems. Other sources of uncertainty that influence planning and costs were not directly considered, including regulatory requirements such as water quality requirements or SCM performance.

The extent of economic and managerial sources of uncertainty were quantified to determine how they influenced total estimated adaptation costs based on a scenario approach. For economic uncertainty, the ranges were calculated for the costs based on the two sources of unit cost data (min, median, and max). The resulting cost ranges based on unit costs were compared to the estimated increase in costs to meet future design storm standards as a measure of the magnitude of economic uncertainty. For managerial uncertainty, an estimate of the range of costs related to assumptions of existing infrastructure condition were calculated, where: the minimum value assumes that existing infrastructure is adequate and only future increased runoff must be mitigated through new SCM devices; and the maximum values assumes that all existing infrastructure is inadequate and new SCM devices must mitigate all future runoff. The percent difference between the two managerial uncertainty scenarios could be compared to the percent increase to meet future design storm standards as a measure of how these sources of uncertainty influence planning assumptions and adaptation costs.

3. Results

Results are reported that describe expected precipitation changes across case study areas, the associated increases in needed drainage capacity, the cost ranges for total and marginal infrastructure upgrades to meet design storm requirements, and the cost ranges related to economic and managerial uncertainty compared to the overall increase needed to update stormwater infrastructure to meet future expected design storm values.

3.1. Expected precipitation changes

The estimated climate change factor (CF), calculated as the median of the CF derived from the historic and future periods from RCM simulations, ranged from 0.9 to 1.53, with a median value across case study areas of 1.26. The CF values indicate that in all but one of the case study areas, the future design storm is predicted to change substantially. The expected change in the future design storm value is predicted to be greatest in the Southern California regions, followed by the Northern California and Central California regions (Table 2). The change factors correspond to the expected percent increase in the future design storm, which across all case study areas in the state had median and average values of 27% and 28%. (Figure 2(a)) shows the geographic distribution of current and future design storm values across the case study areas.

Table 2. Values by region of design storm precipitation depths (25-yr, 1-hour) and climate change factors associated with observed and modeled data using the Annual Maximum Series. Historic observed values are based on the nearest NOAA-14 rain gauge station. Historic and future modeled results are the average of design storms across RCM simulations. Change factor values (MOS technique) are used to estimate the bias-corrected future design storm event.

Region	NOAA-14 Historic Observed (in)	Modeled Historic: Median of 4 RCMs (in)	Modeled Future: Median of 4 RCMs (in)	Change Factor	Bias-Corrected Future Design Storm (in)
North Coast	1.52	1.18	1.17	1.46	1.29
Central Coast	1.21	1.09	1.24	1.39	1.12
South Coast	1.52	1.09	0.84	1.23	1.40

3.2. Drainage capacity assessment

From analysis of collected field data, distinct areas of directly connected impervious surface cover associated with identified stormwater system assets in the parklands ranged from 400 to 85,700 square feet (sq-ft). The average value of a single impervious surface cover feature across parks was 13,500 sq-ft (median of 8,650 sq-ft). The total (sum) of DCIA in a park ranged from 2,300 to 570,000 sq-ft across the case study areas. Thus, for both individual areas and total lumped areas in a park, the DCIA was considered to be small, with infrastructure that collects runoff to be drained directly offshore as runoff collects and conveys to drainage features quickly at sub-daily time intervals. Five parks contained a majority (54%) of features, corresponding to parks with large areas of managed hardscape.

Across all case study areas, a total sum of 221,000 square-feet (5 acres) of additional green infrastructure (new vegetated swales of 18” in depth) is needed to manage runoff from a future design storm (precipitation depth for the 25-year, 1-hour event) if assuming that existing systems adequately manage runoff up to the current design storm depth. This is equivalent to 27% of the existing impervious surface cover. The land area need could potentially be reduced if using a different

Table 3. Summarizing estimated cost ranges for marginal or full capacity improvements. Cost ranges depend on decisions to apply reported unit cost values, as well as assumptions regarding the adequacy of current infrastructure that is captured by the considered scenarios.

		Total Costs for Updating Stormwater Infrastructure based on the Future Design Storm ($), by Scenario	
	Life Cycle Unit Costs ($/sq-ft)	Marginal Improvements	Full Capacity Needed
Estimates based on existing stormwater planning tools			
Minimum	11	$2,487,397	$8,757,617
Median	34	$7,688,318	$27,068,998
Maximum	69	$15,376,636	$54,934,143
Estimates based on relevant extensive case study			
Minimum	51	$11,532,477	$40,603,497
Median	107	$24,195,589	$85,187,729
Maximum	156	$35,275,812	$124,198,932

SCM or multi-purpose site design. However, if new devices are required to manage all runoff because of inadequate existing infrastructure, the total area needed would be 796,000 sq-ft (18 acres). The average area of swales in a park was approximately 10,000 sq-ft (0.2 acres). The *Supplemental Data* section details the breakdown of needed drainage area increases across case study areas.

3.3. Adaptation costs

The cost of using vegetated swales to mitigate runoff from the 25-year, 1-hour event varies based on both the economic uncertainty via assumptions of unit costs and managerial uncertainty via assumptions of knowledge of existing infrastructure conditions (Table 3). Below results are described based on evaluating scenarios where there is: significant economic uncertainty but limited managerial uncertainty; and significant economic uncertainty and significant managerial uncertainty.

For the first case of significant economic uncertainty but limited managerial uncertainty, the main driver of wide cost ranges is estimated life cycle unit costs. Managerial uncertainty is limited by assuming that existing infrastructure conditions are known and deemed adequate. Using existing published estimates of unit construction costs, we estimated life cycle costs for vegetated swales and rain gardens ranging from \$11-\$69/sq-ft, which includes the unit costs of construction noted from existing sources as well as costs for planning, permitting, contingency, and maintenance typically included in engineering estimates (CASQA, 2003; EFC at Sacramento State, 2019; Gold et al., 2015; LADWP, 2015; RTI International, & Geosyntec Consultants, 2015). The total cost for marginal infrastructure improvements to manage just additional runoff from climate change across the case study areas ranges from \$2.4-\$15 million to mitigate runoff from approximately 56 acres of DCIA. In the lower range of life cycle unit costs (\$11/sq-ft), infrastructure improvements are as little as \$1,900 in a park to as much as \$570,000 in larger parks with more DCIA. The upgrade costs in a single park at the higher end of the unit cost range (\$69/sq-ft) span from \$11,000 to \$3.5 million. Using the local retrofit project costs to evaluate life cycle unit costs (\$51-\$156/sq-ft), the resultant range of total costs for marginal improvements across all parks ranges from \$12-\$35 million.

For the second case where there is significant economic and managerial uncertainty, wide total cost ranges are driven by both life cycle unit costs and the assumed poor condition of existing infrastructure in the absence of asset management. Using life cycle costs derived from literature, the total cost of upgrades across parks ranges from \$8.7 million to \$55 million, while total costs based on the local retrofit project range from \$41 to \$120 million.

Comparing the cost ranges generated by the assumptions of economic and managerial uncertainty to the increase associated with the future design storm offered a way to gauge the impact of these sources of uncertainty that are often overlooked in assessment of climate change adaptation. The percent increase in the design storm across parks averages about 28%. The high end of life cycle unit cost estimates increases the estimated total costs by as much as 100%. In other words, while the estimated increase in the design storm with climate change (median value) could result in investment needs of \$7 million (\$34/sq-ft) based on unit costs associated with nationwide data, uncertainty in the unit costs could more than double the total costs to over \$15 million. Similarly, assuming poor condition of existing infrastructure due to lack of knowledge, managerial uncertainty has an even greater effect, increasing total costs by over 250% for the most extreme case.

4. Discussion

Changes in extreme precipitation will affect performance of existing stormwater systems and future design assumptions, but the analysis demonstrated that economic and managerial factors also significant influence uncertainty in estimating adaptation costs. While uncertain knowledge of future climate trends may persist, economic and managerial uncertainty can be reduced through utility actions and planning. Municipalities that conduct asset management can significantly reduce the uncertainty associated with the condition of existing infrastructure. Without information on existing stormwater system design and operations, understanding the need for entirely new or marginal improvements becomes a judgment call. In the absence of a robust asset inventory or monitoring program, managers may not have a full understanding of the adequacy of current infrastructure. To reduce economic uncertainty associated with unit costs for project planning, collecting better local data on existing projects or site conditions can better hone estimates in the design stage. For the case study areas, given mobilization, planning, and permitting costs in the case study areas, unit costs would likely resemble lower and mid-range values from local small-scale retrofit project than national estimates reported through existing literature. In the case that high cost ranges are most accurate, creative designs such as integrating green stormwater infrastructure devices into multi-functional recreational facilities such as sports fields could help defray some future costs for adaptation.

The mismatch in temporal resolution from many downscaled climate models presents a significant source of uncertainty when trying to use empirical modeling for stormwater planning applications. While downscaling methods can provide sub-daily estimates of climate parameters, using results from RCMs can be labor-intensive and likely prohibitive for many urban stormwater programs to undertake. Moreover, in very small catchments, a very short time of concentration (less than one hour) may result in more flow arriving to a stormwater capture device at a single time. A shorter duration storm of 5–15 minutes in duration is more appropriate for such planning applications, but downscaled climate model precipitation data at temporal resolutions less than one hour are not typical.

5. Conclusions

The analysis presented a risk assessment procedure to evaluate climate change adaptation needs and costs for urban stormwater management. Using downscaled climate modeling and field data from 21 case study areas in California Coastal parklands, the analysis demonstrated methods to deal with uncertainties in estimating changes in precipitation event depth and associated runoff volume.

Results showed how economic and managerial uncertainties can affect adaptation needs as much or more than modeled increases in future precipitation events. For approximately 56 acres of total DCIA across case study areas, long-term adaptation costs would likely range from $2.4-$35 million if using green infrastructure to mitigate additional runoff from storms, while costs are higher, $8.7-$120 million, if new green infrastructure is required to mitigate all runoff. This second case could also occur if regulatory requirements necessitated green infrastructure improvements for all runoff to improve water quality or existing drainage infrastructure is found to be old and inadequate. The wide ranges result from key uncertainties in site-specific knowledge and unit costs, which could be refined through more detailed engineering assessments. The ranges represent the potential value of additional studies that perform asset management to understand the state of current infrastructure.

The paper provides a template for using climate change modeling to evaluate future flood risk in small- and medium-sized urban stormwater catchments, and offers lessons regarding the level of certainty that climate modeling may contribute for future planning and operations. Future work can directly compare the relative quantitative contribution of various sources of uncertainty to cost outcomes.

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Data availability statement

Climate change model simulation data is publicly available-from the Cal-Adapt (https://cal-adapt.org/) and NA-CORDEX (https://na-cordex.org/) websites. Software used to perform the analysis is included with the submission as a supplementary file. Detailed calculation spreadsheets are available from the authors by request.

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