Supporting Regional Implementation of Integrated Climate Resilience Consortium for Climate Risk in the Urban Northeast (CCRUN)

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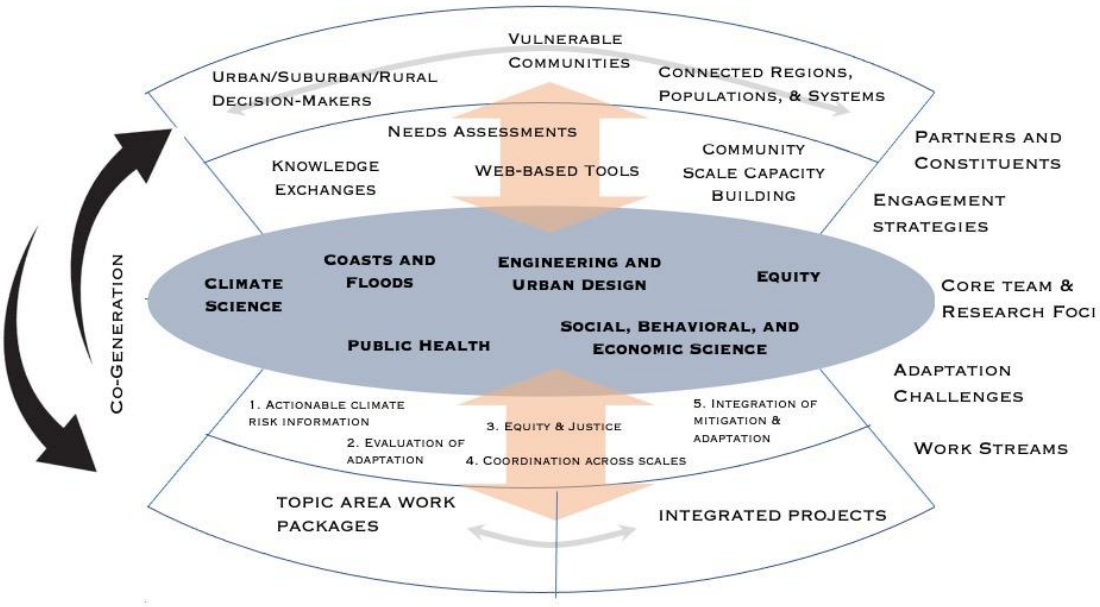
Research Highlights, June 1, 2021 – May 31, 2022

Boston

New York City

Philadelphia



CCRUN Phase III Structure

CCRUN's Mission

CCRUN conducts stakeholder-driven research that reduces climate-related vulnerability and advances opportunities for adaptation in the urban Northeast

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

STEVENS INSTITUTE of TECHNOLOGY THE INNOVATION UNIVERSITY

RUTGERS THE STATE UNIVERSITY OF NEW JERSEY

BOSTON UNIVERSITY

Drexel UNIVERSITY

HUNTER The City University of New York

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* Indicates CCRUN team members supported only by Phase II funding

Stakeholders and Partners**

Camden County Municipal Utilities Authority
City of Camden, New Jersey
Consolidated Edison
Eastwick United
Esperanza
FEMA Region 2
Greenroots
Monmouth, NJ County OEM
Monmouth, NJ County Planning Office
Naval Weapons Station Earle
New Jersey Business and Industry Association
New Jersey Chamber of Commerce
New Jersey Sea Grant
New York City Department of City Planning
New York City Department of Environmental Protection
New York City Department of Parks and Recreation
New York City Mayor's Office of Climate and Environmental Justice
New York Hall of Science
New York Sea Grant
New York State Department of Environmental Conservation
New York State Department of Public Service
New York State Energy Research and Development Authority
NJ Small Business Development Center
Philadelphia Office of Sustainability
Philadelphia Water Department
Port Authority of New York and New Jersey
Rockaway Initiative for Sustainability and Equity
University City District

** This list reflects key CCRUN stakeholders the project team has engaged with over the reporting period.

Key Accomplishments

CCRUN embarked on the first year of research in Phase III, while continuing and completing projects from Phase II. This report includes highlights from both awards. For the key accomplishments, our team presents one activity from each of the awards.

Community Climate Resilience Grant Competition
CCRUN's Equity Team (PI-Leichenko) developed and launched our small grant competition – the CCRUN Community Climate Resilience (CCR) Grant Competition. The CCR competition will award four one-year grants of $25,000 each to non-profit [501(c)(3)] organizations working with socially vulnerable groups on projects that prepare communities in the urban Northeast for hazards related to weather and climate, such as flooding and heat waves. The grant program was designed to incorporate key elements of RISA program theory and will support activities that increase **flexibility** of community partners and the **ability** of partners to **self-organize,** including grant proposal development and network-building. Other activities that the program will support will increase partners' **sense of agency**, enhance use of **assets** and boost **learning outcomes** in the areas of planning, data collection, vulnerability mapping, and advancing nature-based solutions. Proposed projects will aim to reduce risks of climate variability and change in vulnerable communities, identify strategies that improve preparedness and resilience, and enhance equity. The CCRUN research team will work collaboratively with each grantee organization to support implementation of their projects.

During the reporting period, CCRUN released the call for proposals and an informational webinar was held on May 20, 2022. The goal of the webinar was to provide information and answer questions for groups interested in applying for a CCR grant. Approximately 20 individuals attended. At the time this report was prepared, 23 organizations submitted letters of intent with interest in the competition. The CCRUN website has full information about the competition.

Costs and Benefits of Homeowner Actions to Mitigate Future Flood Damages
(NA20OAR4310147A)

Over the reporting period, PI-Madajewicz and PI-Orton, in collaboration with the New York Hall of Science, Rockaway Initiative for Sustainability and Equity, and 10 civic and homeowner associations in Rockaway in New York City, completed workshops designed to improve understanding of the costs and benefits of actions that a homeowner can take to mitigate future flood damages and improve homeowners' planning for flooding. The CCRUN team co-produced the content of the workshops with leaders of community groups. A total of about 50 homeowners attended two series of three workshops each.

In addition, during the past year, the CCRUN Team has also collected follow-up survey data to document how participation in the workshops influenced knowledge, attitudes toward taking action to adapt to flooding, and actions taken. The project team is in the process of analyzing the data. CCRUN researchers have drafted a decision support tool to guide homeowners in making flood adaptation decisions and will disseminate the tool widely once it is finalized.

This project has developed new assets in the form of data that document the change in flood adaptation knowledge, attitudes, and behavior over time among coastal homeowners, and is working on a new decision support tool.

This project has developed new **assets** in the form of data that document the change in flood adaptation knowledge, attitudes, and behavior over time among coastal homeowners, and is working on a new decision support tool. Preliminary analysis based on transcripts of workshops and meetings indicates several outcomes. One of the messages that emerge most strongly from the workshop and meeting discussions is that the information that CCRUN co-produced with community group leaders has strengthened the **participants' sense of agency** as well as their **flexibility**. Participants gained awareness that a range of adaptation options exist, and different options are appropriate under different conditions. The menu produced the perception among homeowners that there are actions that they can take on their own, and that might make sense for them, whereas prior to the workshops they were only aware that they could raise their home, and almost all were not planning to do so for a variety of reasons.

The workshops also resulted in **learning** for all the partners and for other interested parties, such as the NYC Mayor's Office of Climate and Environmental Justice. Participants had heard repeatedly about growing flood risk but felt that the information was not specific enough for them to make decisions. Levels of water and expected future costs of flood damages at specific addresses, as well as damage costs that could be avoided with specific adaptation actions were all new information that produced an increased sense of urgency regarding the need to act, changing mindsets, and a greater capacity to make decisions. Participants began to consider themselves as responsible for addressing their flood risk in addition to seeing the City of NY as responsible for protecting them against flooding. CCRUN helped connect community groups from across the peninsula, enabling potential new partnerships for planning. Our evidence raises doubts about the value of online information as a decision support tool in the absence of extensive outreach. Our project engaged the more informed and concerned coastal residents and 80% had never heard about the FloodHelpNY online tool that is the premiere source of home-specific guidance about preparing for flooding in NYC.

New Areas of Focus and Partnerships

CCRUN started several new partnerships over the reporting period, which included the opportunity to work with new stakeholders, many at the community level.

Equity in Scientific Co-production Processes: Creation of a Framework
The 'Enabling Urban Residents to Adapt to Coastal Flooding: Evidence from New York City neighborhoods,' project is participating in a NSF-funded project, titled 'Equity in Scientific Co-production Processes: Creation of a Framework,' which is developing a framework for guiding federal investment in research that involves co-production of knowledge toward more equitable processes and outcomes. The project organized a two-day workshop in May 2022, which brought together academics, community members, and federal funders in a unique combination that pushed the frontiers of equity issues being discussed.

PI-Madajewicz and one of the community leaders from the disadvantaged communities in the Rockaways attended the workshop, along with CCRUN Program Manager Bader and representatives from NOAA CPO. The workshop provided a unique opportunity for community members to

communicate their perspectives to academics and funders, gather knowledge, and network. The NSF project is continuing to work on written outputs (working towards a peer-reviewed publication) and will be holding a series of conversations in Year 2.

Mystic River Watershed Association
CCRUN's Health Team (PI-Fabian) started a new partnership with Mystic River Watershed Association, a greater-Boston based environmental organization that works to protect their water, restore important habitat, build climate resilience, transform parks and paths, and inspire youth and community members. Together, a grant was submitted to the Environmental Protection Agency titled Advancing Community Resilience to Cumulative Climate Impacts in the Mystic River Watershed (ACRES). Greater Boston's Mystic River Watershed (Mystic Watershed) is the most highly urbanized watershed in New England, and local low-income BIPOC communities are increasingly at risk of climate-exacerbated urban heat islands, coastal and inland flooding, and numerous sources of active and brownfield chemical exposures. The proposed study partners Boston University (BU) researchers with Mystic River Watershed Association (MyRWA) staff who facilitate the Resilient Mystic Collaborative (RMC). CCRUN will engage a variety of stakeholders in ongoing discussions of priority concerns and proposed climate resilience solutions and will combine stakeholder knowledge with geolocated data to inform communities of climate and chemical hazards and the health benefits of solutions.

New Jersey and New York Sea Grant
CCRUN's Coasts and Floods Team (PI-Orton) established a new partnership with Sea Grant NJ and Sea Grant NY offices where the team collaborated on an App called "FloodHub" that pools citizen science flood observations alongside flood forecast data. The project leveraged a student senior design project and team of six Stevens Computer Science undergraduate students to create the app. A functioning app was developed, during Year 2, the team anticipates improving it and releasing it for public use.

New York State Department of Public Service
Emerging from previous projects with the New York State Energy Research and Development Authority (NYSERDA), this reporting period, the CCRUN climate science team began working with the New York State Department of Public Services. The New York State Public Service Commission is requiring major electric utilities to perform climate vulnerability studies to help prepare for the expected increase in severe weather expected from climate change. The studies must be completed by September 2023.

CCRUN's prior work with Consolidated Edison, the power utility in New York City and environs, on a similar study and recent update of the climate projections of record for New York State with NYSERDA, positioned the team to quickly respond to this urgent task.

In addition to disseminating the climate projections of record for the utilities, CCRUN has initiated a series of stakeholder conversations with utility representatives to present the data, receive critical feedback, and co-generate additional projections where needed, reflective of the diverse baseline climate, and energy needs and mix across the State.

CCRUN is also becoming a partner with the Electrical Power Research Institute (EPRI). As described on its website, EPRI is a national organization that "provides thought leadership, industry expertise, and collaborative value to help the electricity sector identify issues, technology gaps, and broader

needs that can be addressed through effective research and development programs for the benefit of society."

Resilience of Small and Medium Size Businesses
PI-Madajewicz, in partnership with PI-Leichenko and PI-Solecki, and senior team members Kaplan and Herb, has begun new, comparative work and partnerships with organizations who work to support the resilience of small and medium businesses (SMBs) in coastal parts of New York City, especially Rockaway and Long Island City. Leichenko, Kaplan, and Herb are conducting analogous research in three municipalities in coastal NJ, Keansburg, Middletown, and Atlantic Highlands. The project is investigating opportunities to advance resilience of SMBs to climate and other shocks, challenges to improving resilience, and needs that SMBs have for resources to assist them in building resilience. The team has interviewed over 20 individuals at organizations that support the resilience of SMBs and 20 SMB owners, and we are in the process of conducting a survey of 50 SMB owners. The new work is an important complement to the project described above, which is focusing on improving coastal residents' capacity to adapt to flooding. The SMB project is addressing resilience to a broader set of climate and other shocks. The resilience of residents and local businesses is interdependent. Residents need access to goods and services in the wake of climate and other shocks, such as flooding, heat waves, and pandemics; public services rely on the business tax base; and businesses need resilient residents in order to survive shocks. Understanding opportunities, needs, and challenges to improving business resilience will provide a more holistic understanding of pathways to building resilient, well-adapted neighborhoods.

The 'RSFO – CCRUN – Resilience of Small and Medium Businesses in Coastal Communities in the New York – New Jersey Metropolitan Region' project is laying the groundwork for future co-production of knowledge and tools that can help build resilience among small and medium businesses in coastal areas. The team is identifying the main needs and challenges among these businesses as well as organizations that support them. In New York City, the project is targeting small and medium businesses in the Rockaways, including businesses in the disadvantaged and underserved neighborhoods on the peninsula, as well as in Long Island City, which has a large immigrant population.

Research Highlights

CCRUN's core research focuses on Topic Areas that span physical, engineering, public health, and social sciences. Presented here are key research findings from each of the teams.

Climate (Horton)

During the past year, climate science research in the region has focused on 1) improving understanding of how coastal land temperature trends in the CCRUN region have differed from areas further inland, and why, 2) understanding the baseline humid heat hazard in the region, and the processes that determine it, and 3) assessing human habitability and migration.

Coastal Land Temperature Trends
Using diverse high spatial resolution datasets, Karmalkar et al. 2021 demonstrated that the highly populated coastal portion of the Northeast US has warmed more than areas further inland, especially during the warm seasons, when extreme heat risk is of course at its greatest. We also linked this

warming trend to patterns in the North Atlantic Ocean, as well as an atmospheric circulation pattern known as the NAO. Importantly, we found that most climate models used for temperature projections are not able to capture the observed warming trends over coastal lands, raising the possibility that the projections used by cities, states, and the National Assessment may underestimate heat dangers in the populous and vulnerable coastal northeast, increasing the risk of maladaptation/insufficient adaptation.

Humid Heat Hazards

In a series of papers, we explored how humid heat extremes are connected to different patterns of interannual variability (e.g., the El Nino Southern Oscillation), how clustering of humid heat events in space and time can compound the hazards/risks, and how extreme precipitation events are linked to extreme humid heat. CCRUN researchers also assessed differences in the trends over time in populations exposed to extreme humid heat vs. extreme dry heat.

Assessing Human Habitability and Migration.

In a review article commissioned in support of the 2021 Managed Retreat Conference, our team investigated the extent to which human habitability can be constrained by climate and other environmental variables, as well as how migration and managed retreat relate to habitability. The study concluded that climate variables like sea level rise and humid heat extremes can lead to non-linear threats to habitability, but that ultimately factors such as the role of adaptive capacity and human agency and ingenuity are critical to estimating where non-linear tipping points may lie. In some instances, non-linear tipping points may be reached before a climate threshold is crossed (e.g., coastal inundation), while in other cases adaptations like air conditioning may enable some portions of communities to persevere even above climate thresholds (e.g. wet bulb temperatures above 35C).

Coasts and Floods (Orton)

Real-Time Attribution

In the past year, a primary effort was real-time attribution modeling of climate and urbanization drivers of increased coastal flooding. Our team demonstrated a coastal flood attribution framework that can be used "real-time" before or soon after a flood, when it has maximal impact, quantifying effects of both estuary urbanization (e.g., dredging, landfill) and climate change on water level distributions. Results showed that floods on Jamaica Bay are worsened by land subsidence, anthropogenic climate change-driven SLR, landfill and dredging. Out of today's Jamaica Bay NWS "minor flood" exceedances, 95% would not occur without 23 cm of climatic (non-subsidence) SLR, and 91% would not occur without estuary urbanization. For an October 2021 king tide flood, real-time attribution showed that, if not for combined human effects of dredging and 13 cm of anthropogenic climate change-driven SLR, 93% fewer buildings would have been exposed to flooding, and no disruptive flooding (> 10 cm depth) of an important roadway would have occurred, in contrast to an estimated actual duration of 4.3 hours. This research was presented in a climate attribution session at the 2021 AGU Fall Meeting.

Quantitative Assessment of Flood Risk Reduction Efforts

During the reporting period, a CCRUN team member completed a PhD dissertation and published previously reported research that quantitatively assessed how flood risk reduction efforts for coastal neighborhoods affect flooding conditions and resulting human mortality (Zhang, 2022; Zhang and Orton, 2022). Climate change and sea level rise are worsening coastal flood risk to property and human health by increasing flood magnitude and frequency.

This research was motivated by a case study that focuses on neighborhoods of Staten Island, NY that had a noteworthy concentration of fatalities during Hurricane Sandy in 2012. Mortality risk and influential factors involving flood water physics and potential socioeconomic and demographic factors are investigated. Then, an idealized modeling approach is used to study physical factors and their influence on the efficacy of different adaptation strategies for mortality risk reduction. Coastal neighborhood morphological and climatological vulnerabilities are examined in terms of fatality reduction benefits for two basic adaptation approaches, protective waterfront berms and retreat. Lastly, mortality risk is compared to the widely adopted metric of economic risk in an evaluation of potential risk reduction adaptation plans for Jamaica Bay, NY.

The Staten Island case study reveals evidence that a waterfront berm may have contributed to mortality by increasing the speed at which seawater rose in the neighborhoods. The idealized modeling results show that, for a berm and a case of managed retreat of an equal cost, retreat becomes more beneficial than the berm in terms of mortality risk reduction for neighborhoods with a larger aspect ratio. It is also found that berms are generally less effective for reducing mortality in regions with storms of a higher intensity. The Jamaica Bay adaptation modeling shows that a cross-inlet storm surge barrier can reduce risk better than waterfront berms because the large embayment serves as a buffering zone for flood waters in the most extreme events.

Overall, these results demonstrate fundamental differences in the efficacy of various flood adaptation measures based on coastal and neighborhood morphology and storm climate. Based on the results, the recommendation is that future adaptation studies consider these local factors and assess a broader spectrum of benefits that includes environmental quality and mortality reduction.

Providing Climate Risk Information and Tools

Through another PhD student dissertation project, our team is providing climate risk information and tools to the Eastwick, PA community and Philadelphia city government. Flooding is becoming more frequent along U.S. coastlines, with drivers from pluvial, fluvial, tidal and storm surge sources and their compound effects. Eastwick is a flood-prone neighborhood in southwestern part of the city of Philadelphia that is susceptible to occasional severe fluvial flooding. Recent tropical storm Isaias (2020) caused severe fluvial flooding overtopping the riverbanks near the confluence of Darby and Cobbs Creeks. Tides and coastal storms are not known to be one of the flood drivers at present, and prior mitigation studies have only looked to solve the fluvial flood problem. To help address Eastwick's needs for mitigation strategies, CCRUN researchers have developed a combined 1D-2D HEC-RAS model to simulate all flood water sources affecting Eastwick.

CCRUN research demonstrated validation for a range of events from low-stream flow tides up to the fluvial extreme event tropical storm Isaias. Results show that SLR-induced tidal flooding as severe as present-day extreme rainfall flooding could occur as soon as the 2060s and must be addressed in the adaptation strategies. This research is part of a collaborative study with neighborhood organizations and the Philadelphia Water Department to characterize flood risk from all sources and assess adaptation/mitigation options for the Eastwick area. The flood model, which is expected to be useful to government and community groups (via consultants), is available for download and free use.

Storm Surge Barrier Flood Risk Reduction

Another student on the CCRUN Coasts Team PhD paper project is quantitatively assessing how storm surge barrier flood risk reduction efforts affect estuaries. Gated storm surge barriers have been constructed or proposed in many estuaries worldwide for coastal flood risk reduction. Past studies have shown that, even when open, a barrier system's fixed infrastructure can increase estuary stratification and salt intrusion, potentially affecting water quality and ecological processes. However, surge barrier closures could have a much stronger influence on estuary conditions by temporarily blocking the tidal exchange. In this project, the researcher used an existing regional three-dimensional hydrodynamic, with modifications to simulate surge barrier closure and re-opening, to study the effects on estuarine salt intrusion and stratification of the Hudson River. Across a range of modeled scenarios of gate closure frequencies, durations and river streamflows, the research evaluates the changes caused by gate closures, as well as the recovery time to normal conditions. Our results for the Hudson show long-duration gate closures (three or more days) with low streamflows temporarily lead to salt intrusion and stratification beyond recent historical extremes. Moreover, monthly frequency closures, which could occur as soon as 2070 under realistic scenarios of sea level rise and barrier management, do not allow for recovery under dry streamflow conditions and could lead to durable changes to estuary physical conditions. These changes are also similar to those caused by sea level rise and dredging, potentially leading to aggregate impacts and an increased threat to municipal water supplies. This study demonstrates a framework for understanding the potential impacts of any proposed surge barrier system and can help improve our understanding of corresponding ecological impacts.

Public Health (Fabian)

Benefits of Increasing Greenness on All-Cause Mortality

Across the United States, cities are creating sustainability and climate action plans (CAPs) that call to increase local vegetation. Some locations within the CCRUN region are at the vanguard of these efforts and New York City, Boston, and Philadelphia were included in the regions analyzed in this study. These greening initiatives have the potential to not only benefit the environment but also human health.

CCRUN researchers participated in a study that aimed to assess how an increase in greenness could decrease mortality in the largest urban areas in the United States (Brochu et al., 2022). The team conducted a nationwide quantitative health impact assessment to estimate the predicted reduction in mortality associated with an increase in greenness across two decades (2000, 2010, and 2019). The research estimated that between 34,000 and 38,000 all-cause deaths could have been reduced in 2000, 2010, and 2019 with a local increase in green vegetation by 0.1 unit across the most populated metropolitan areas.

These results can be used to support CAPs by providing a quantitative assessment to the impact local greening initiatives can have on mortality. Urban planners and local governments can use these findings to calculate the co-benefits of local CAPs through a public health lens and support policy development.

Engineering and Urban Design (Montalto)

The research findings of the Engineering and Urban Design Team (PI-Montalto) are summarized here. Much of this research has yet to be published, however, several manuscripts are in preparation. These results have been shared with CCRUN stakeholder partners.

Census Tracts and Flood Risk
In New York City, census tracts corresponding to communities ranked C (declining) or D (hazardous) by the Homeowners Loan Corporation in the 1930s are associated with more extensive pluvial flood risks than census tracts given A (Best) and B (Still Desirable) grades.

Combined Sewer Overflows and Flooding in Camden, NJ
In the Cramer Hill section of Camden, under existing infrastructure conditions, increases in precipitation linearly increase combined sewer overflows (CSOs), whereas sea level rise (SLR) increases flooding. Diverting stormwater out of the combined sewer system can reduce both CSOs and flooding, but with diminishing effectiveness over time, as the climate changes. A master's thesis on this topic has been completeda manuscript is in progress.

Jacob K. Javits Convention Center Green Roof (NA20OAR4310147A)
The impacts of the Jacob K. Javits Convention Center (JJCC) green roof and nearby redevelopment of Hudson Yards (Midtown West, Manhattan, New York City, NY) on the local microclimate were assessed. The analysis was performed using ENVI-met, a grid base three-dimensional (3D) model commonly used to simulate surface-plant-air interactions in urban settings. Using air temperature, relative humidity and wind speed and direction measured onsite on July 22, 2014, a total of six simulations were run at three different stages of the redevelopment process (e.g., in 2014, 2018, and 2021) with and without the JJCC green roof in place. The results show that the greatest impact of the green roof was predicted over the north side of the JJCC, where the air temperature was reduced over the no-green roof scenario by up to 0.75 K, 0.65 K, and 0.64 K in 2014, 2018, and 2021, respectively at 13:00. The diminishing impact of the green roof over time, as the redevelopment projects progressed, was also observed in the diurnal profile simulated at other points in the model domain. For example, on the north green roof, the green roof reduced air temperature by up to 0.45 K, 0.43 K, 0.42 K, for 2014, 2018, 2021 respectively. These results are discussed in the context of efforts to mitigate the impact of urban heat islands.

Trends in Hourly Precipitation
Using 70 years of hourly precipitation data from the international airports of Philadelphia, Boston, and New York City, parsed into rainfall events using a 4 hour no-rain separation period, it was difficult to discern any clear temporal trends in precipitation event characteristics, with the possible exception of a slight increase in event totals over the first two decades of the 21st century.

Urban Heat Island - Hunting Park, Philadelphia, PA (NA20OAR4310147A)
In the Hunting Park neighborhood of North Philadelphia, the median intensity of the urban heat island (UHI) is 2.81 C over the course of the day, whereas at night the UHII of this environmental justice community is 5.31 C. Relative humidity is lower in Hunting Park than in the surrounding suburban and rural communities. Over the course of the day, the median Relative Humidity Intensity (RHI) is -5.83 %, whereas at night it is -18.20% compared to the non-urban reference locations. A manuscript on this topic is in process.

Social, Behavioral, and Economic Science: Socio-Economic Research on Adaptation (Madajewicz)

Future Costs of Flood Damages in the Rockaways, New York City

PI-Madajewicz and PI-Orton have compared expected future costs of flood damages for the Rockaway area of New York City using two different approaches in ongoing research. The research contributes to the broader effort to assess impacts of adaptation efforts. The first approach is based on the widely used FEMA HAZUS model. The second is based on survey data collected by Madajewicz that document the costs of recovery from Hurricane Sandy to households.

The preliminary results identify three points.

(1) The expected future costs of flood damages based on recovery costs documented through the survey are substantially higher than costs produced by HAZUS and the difference grows over time. The difference highlights the urgent need for better data on costs of flood damages in order to guide investments in adaptation.
(2) Both approaches show that over the next 30 years, the bulk of the cost distribution will shift from the 50 to 100 – year return period floods to 5 to 10 – year return period floods. More frequent events will increasingly be responsible for the great majority of the damages. The finding has important implications for planning adaptation measures. For example, the major infrastructure being planned to protect much of the NYC coastline consists of barriers that would be closed for low-frequency, high impact events. Such protections alone will not prevent the majority of damages. Furthermore, residents are mainly concerned about low-frequency high-impact events based on historical experience. Preparing for the events that will increasingly cause most damages will require a change in mindsets.
(3) Expected damages over a 15 to 30 - year time horizon that can be avoided with individual home-level adaptation measures, even relatively lower-cost measures such as flood-proofing basements, are one to two orders of magnitude larger than are the costs of those measures for homes whose lowest floors, the basement or the first floor, are located at or below 3 feet of elevation. The great majority of homes in low-lying coastal areas such as the Rockaways are in this category.

Such a cost-benefit analysis is unique to our research, to the best of our knowledge. Coastal residents were seeing such analyses for the first time in our workshops. Delays in considering the mounting costs in the absence of adaptation can result in significant shocks to livelihoods and sharp increases in homelessness and poverty in urban, coastal areas. These findings are likely to apply to coastal, urban areas outside of the Rockaways, though further research should investigate the difference between costs incurred by residents and HAZUS estimates in diverse contexts. A manuscript summarizing the results is in progress.

Co-Production of Information about Benefits and Costs of Home-Level Flood Adaptation
(NA20OAR4310147A)

PI-Madajewicz is investigating how effectively co-producing information about benefits and costs of home-level flood adaptations influences knowledge, attitudes, and adaptation behavior among different socio-economic groups. The study compares the change in outcomes over time among members of five community groups, which participated in the co-production workshops, and five community groups that did not participate. The research design enables us to investigate the causal effect of participating in the workshops on adaptation outcomes under certain assumptions. The surveys document the change over time in these outcomes for the same individuals, mitigating the selection bias that is present in a comparison of outcomes at a single point in time between participants and non-participants. Both participant and non-participant groups have had access to other outreach efforts that have taken place in New York City, allowing us to compare the change that results from the co-production process combined with the other outreach efforts to the change that occurred as a

result of the other outreach alone. Both participating and control community groups represent a range of socio-economic conditions across the Rockaways, from the middle-class, mostly white neighborhoods in the west to the low-income, underserved, and mostly African American and Hispanic neighborhoods in the east. We are in the process of analyzing the data. The team discussed the preliminary results based on qualitative evidence from workshop and meeting transcripts. The evidence about the effectiveness of the co-production approach is likely to be applicable to other urban, coastal environments.

Social, Behavioral, and Economic Science: Socio-Spatial Research on Adaptation (Solecki)

Climate Resilient Decision-Making Support Tool Kit Development
(NA20OAR4310147A)
The Hunter College team (PI-Solecki) has been focused on developing an integrated set of decision-making support tool kits. Each tool kit is focused on a different aspect of the climate risk management decision making process.

Macro Adaptation Resilience Took Kit (MART) – this tool kit was developed and tested in late 2019. In the past year, we have been able to formally develop the results of the application into a peer reviewed journal article for Climate Risk Management. The manuscript describes the process of application, success and caveats, and conditions under which it can be applied to other contexts. The MART approach has been successfully integrated into several research proposals that have been funded, and others that are out for review. Additional applications of the approach are pending.

Post Extreme Event Learning Tool Kit (PELT) – this tool kit was initially developed in 2019 and was substantially revised and restructured to work online via COVID restrictions. During the past year we developed an extensive workbook on the PELT application. During the half year we executed a full web-based application of PELT with a client group in NYC – Community Board 8 with respect to the impact of Hurricane Ida. The beta-application was successful, and we have developed a client report. The application illustrated the vastly different understanding of the impact of Hurricane Ida on the immediate neighborhood and differences among the respondents with respect to the drivers (causes) of the impacts and potential policy responses. We are currently looking to apply the tool kit with another community and do a formal write up as a case study.

Effective Coastal Resilience Planning and Programming
The social science team in 2019 began a comprehensive climate coast program examining how climate change risk is intersecting with everyday lived experience of at-risk coastal households. The key questions are how households perceive climate risk, how they are acting or responding to local resilience programs, and how they expect climate change to impact their plans for the future. The work also involved two workshops with Long Island and New Jersey coastal resilience stakeholders to assess their data and information needs regarding the effectiveness of the coastal resilience plans. Their input was utilized for the development of survey instruments.

COVID forced a dramatic restructuring of the survey and the survey process. During the past year the survey process was completed, and the team began the analysis of the results. The results indicate significant variation in risk perception but also a widespread lack of knowledge and appreciation of many resilience efforts available to residents and as well as a lack of trust of many sources of information about flood risk. Furthermore, overall, many residents felt that their climate risk exposure

and vulnerability will increase in the future and that government programs will have limited ability to reduce the risk. The results are being developed into most likely two different manuscripts.

Legacy of Hurricane Sandy
The CCRUN social science team (PI-Solecki) is in the final stages of completing a manuscript focused on survey results and discourse analysis analyzing Hurricane Sandy resilience legacy in the Northeast US. The research and resulting paper directly examine to what extent did Hurricane Sandy and its aftermath influence policy development in communities not extensively affected by its impacts. Anecdotal evidence indicated that cities distant from New Jersey-New York took on a series of new resilience policies post Sandy. The analysis found that the storm and its impact were significant catalysts for action, and which were often fostered by local policy entrepreneurs that coupled climate adaptation with goals of long-term economic development. The manuscript is about to be submitted to the Journal of Extreme Events.

Outreach and Engagement Activities

2021 Managed Retreat Conference
Towards the end of Phase II, in June of 2021, CCRUN again helped co-organize the 2nd Managed Retreat Conference. The conference featured multiple panels and sessions related to sustained assessment. One panel, titled Regional Perspectives on US Relocation and Migration: A NOAA RISA Panel included presentations from CCRUN, GLISA, Pacific RISA, and ACCAP. A second panel featured CCRUN's Sustained Assessment Specialist with several individuals from NYC Mayor's Office of Resilience and local community-based organizations to discuss the Climate Knowledge Exchange and the value of sustained assessment processes in planning for coastal adaptation and relocation. Close to 950 attended the conference and approximately 300 people presented across over 50 sessions.

Community Workshops
Through the reporting period, CCRUN team members have participated in numerous community workshops and events, which are highlighted here by location.

Boston - CCRUN's Public Health Team (PI-Fabian) has co-organized and participated in multiple C-HEAT community engagement activities related to heat exposure and adaptation in Chelsea and East Boston. All neighborhoods in these communities are designated environmental justice according to Massachusetts criteria. These included two events organized with GreenRoots and open to the general public to get community input on park design, heat and health education, and climate adaptation. Partnered with Museum of Science Boston on their New England Climate Stories exhibit. Through Iseechange collected data from communities on impacts of climate.

New York City - PI-Madajewicz and PI-Orton, in collaboration with other partners, completed workshops, which built capacity to plan for and adapt to coastal flooding among urban, coastal homeowners, as discussed above. The participating communities are in the historically underserved area of the Rockaways, which is poorly connected to the remainder of New York City and extremely exposed to flooding.

Participating communities range from middle-income and mostly white in the western part of the peninsula to low-income, historically disadvantaged, mostly African American and Hispanic, and

with a high proportion of immigrants from Central and South America in the east. CCRUN co-produced the material for the workshops with community group leaders and other project partners mentioned above. The team conducted the workshops themselves in the mode of co-production, with participants identifying knowledge and information that helps them to make decisions. Our researchers are now in the process of integrating the salient knowledge and information that emerged in the workshops into a decision support tool that can help guide homeowners' flood adaptation decisions in coastal communities beyond those individuals who participated in the workshops.

Philadelphia - CCRUN hosted the October 16, 2021, event, Academy Town Square: Grassroots Change in Eastwick. To serve the Eastwick Community of Philadelphia. The CCRUN Team (PI-Montalto) also hosted residents of the Eastwick Community at the Academy of Natural Sciences of Drexel University, specifically as part of a photography exhibit entitled Drowning World. CCRUN conducted two workshops with youth engaged in a Violence Prevention Program hosted by our partner, Esperanza, located in North Philadelphia. In these workshops, participants discussed heat risks and climate change and different strategies for reducing risks. There was also the opportunity for students to use thermal temperature guns to explore the variable surface temperatures associated with different spaces.

Green Infrastructure, Climate and Cities Seminar Series (NA20OAR4310147A)
CCRUN's longstanding Green Infrastructure, Climate, and Cities and seminar series continued in the first year of Phase III. A broad array of topics has been covered through the series, where for each event, invited speakers present on general themes related to climate science, climate impacts, adaptation and resilience, and mitigation. The series has hosted subject matter experts, allowed for cross-RISA collaboration, and engaged a number of local partners and community groups. Over this reporting period, 6 seminars were held, topping approximately 300 attendees (an average of 50 attendees per session). More information about the seminar series can be found on the CCRUN website, including links to our Youtube page which archives the videos of prior seminars.

Lectures in Climate Change
CCRUN hosted presentations in a bi-weekly series that were drawn from the recent book, Our Warming Planet: Climate Change Impacts and Adaptation. The series presents key adaptation topics including methods for impacts and adaptation assessment, impacts on sectors, effects on different regions and countries, and adaptation policy and practice. The lecture series is for students, teachers, and interested researchers and colleagues around the world to be better able to understand various aspects of climate change.

The lecture series features presentations on various topics on climate change by their authors and allows for a dialogue between experts in the field and people interested in gaining deeper knowledge in a broad array of topics in climate change impacts and adaptation. All of the webinars are posted on the CCRUN website and Youtube page for viewing. Our stakeholders can access these as they are a terrific resource for general information on key topics related to weather and climate. Average attendance for each webinar has been approximately 75 attendees.

Planned Activities

2023 Managed Retreat Conference

In June 2023, Columbia will for the 3rd time host a global conference on Managed Retreat. CCRUN will be a primary sponsor. We currently anticipate a primarily in person conference over 4 days, however with individual sessions intentionally being remote to facilitate participation from those unable to travel to New York City for a variety of reasons. Given the growth in research and decision-maker interest in this topic, we anticipate that we may exceed the ~900 attendees of the 2021 (virtual) Managed Retreat conference.

We anticipate a greater focus on migration in 2023 than in prior conference iterations. Key themes and goals likely to carry over from the 2021 conference include:

- Deep engagement by the public, private and nonprofit sectors, together with academics, scientists, and community representatives
- A major emphasis on issues of environmental justice

The goals form the 2023 Conference are:

- Advancing the research agenda around managed retreat in an Interdisciplinary, solutions-oriented way;
- Facilitating networking and discussion among many types of stakeholders, and bridge the information gap between academics, practitioners, and affected communities; and
- Developing concrete solutions and best practices around a complex climate adaptation issue.

Community Climate Resilience Grant Competition

In Year 2, CCRUN's CCR competition will begin. Once the grants are awarded, the team is planning to develop a Community of Practice with grantees. CCRUN is also planning to host a webinar for all applicants on online climate data tools and resources, which will give our researchers the opportunity to highlight products developed by CCRUN and also tools from NOAA.

New York City Climate Vulnerability, Impacts, and Adaptation Analysis

Several CCRUN researchers (Horton, Montalto, Madajewicz, Orton) will be starting a recently awarded project through the New York City Town and Gown Funding Program. The primary task for the project team, which is multi-institutional and includes non-RISA team members, is to complete a Climate Vulnerability, Impacts, and Adaptation Analysis (VIA), with the primary stakeholder being the New York City Mayor's Office of Climate and Environmental Justice. This work will also interact with ongoing efforts of the Fourth New York City Panel on Climate Change (NPCC), an advisory body to the Mayor's Office in which CCRUN team members played a foundational role and continue to participate in.

Specific contributions to this project by the CCRUN team include:

Horton - The CCRUN climate science team will develop climate projections for the New York City region, drawing upon ongoing work for New York State. More novel and in-depth components will focus on projections of heat plus humidity, sequential extreme events like heat waves after floods, all climate hazards of critical interest to city stakeholders.

Madajewicz - Our plan is to advance research toward a social vulnerability index of flooding in response to demand from the NYC Mayor's Office of Climate and Environmental Justice. The work will make two contributions. First, we will investigate vulnerability to nuisance/tidal and pluvial flooding, which is not well understood, in diverse populations based on primary interview and survey data. We will integrate indicators of vulnerability to these types of flooding with indicators of

vulnerability to coastal storm flooding, established in prior CCRUN-funded research (Madajewicz 2020). Second, we will develop a social vulnerability to flooding index using a new approach that clarifies the relationship between the index and its components and its policy implications.

Montalto - Through this project, Drexel CCRUN researchers will work with the City of New York to develop new IDF curves and study other precipitation trends throughout the region. The team will also look at weather radar to understand spatial patterns of precipitation in New York City. There will be a large component of stakeholder engagement with stakeholders to discuss these topics. This research will also compare two methods of analyzing precipitation trends, using individual events (typically used by engineers) and using statistical techniques (typically used by climate scientists).

Orton - Our research will be focused on three major task areas – climate projections, future rainfall, and coastal flood vulnerability. Specifically, Orton will perform new separate probabilistic hazard assessments that only include tropical cyclone events for rain, wind, and surge, given the important role of hurricanes in recent disasters. Orton will work with the climate science team to assess compound extreme events, and co-lead sensitivity studies of rain effects on 100-year coastal flood zones. Lastly, Orton will assist Madajewicz in assessing and mapping social vulnerability to flooding.

Program Impacts Evaluation

The CCRUN program evaluation is assessing progress toward the program goal of improving adaptation to climate risks in the urban Northeast. The three components of the evaluation are the program theory, monitoring, and evaluation.

The program theory describes what actions and inputs can bring about the improvement in adaptation that CCRUN intends to achieve, through what causal mechanisms, and what are outputs, outcomes, and impacts that the team should be measuring. The program theory has four broad components that articulate how CCRUN may achieve interim objectives on the path to achieving the goal of improved adaptation: (1) producing science that is useful for decision-making, (2) supporting the process of putting that science to use, (3) designing and implementing uses that advance adaptation, (4) learning through evaluation to improve the work in each of the other three components. CCRUN work is focusing on the first two components though at least one current project includes the third component. We aim to make the learning process, which has been occurring since the beginning of CCRUN, more systematic during this 5-year phase.

CCRUN intends to achieve improvements in producing usable science and supporting decisions based on that science by directly engaging policymakers in the co-production of climate science. Co-production spans a very broad range of types and intensities of engagement with different types of stakeholders. The specific inputs, actions, participants, and causal mechanisms that compose effective engagement are likely to differ across decision problems and contexts. The team is working to develop specific program theories for different decision problems and contexts that can support the design of evaluations of specific engagements. In the meantime, this report features numerous examples of stakeholder engagements and the results.

The monitoring system has been tracking a consistent set of process indicators since the early years of CCRUN. The indicators inform the team whether the CCRUN process is advancing toward the

objectives of useful science and support for decisions based on that science. The process indicators fall into the following categories.

- The decision makers with whom CCRUN researchers are working, including the length of the relationship and decision problems addressed. Decision makers include practitioners and policymakers from public, private non-profit, and private for-profit sectors, and representatives of community groups.
    - Activities undertaken with decision makers, for example design and implementation of approaches to adaptation.
- Climate information/decision support tools co-developed with the decision makers
- Publications in outlets read by decision makers
    - Decision maker testimonials
- Outreach to communicate research results and experience with using the research results to decision makers.
- Engagement with scientists
- Presentations of results in various research venues;
- Peer-reviewed publications/citations of peer-reviewed publications
- Broad communications
- Contacts with the media
- Number of views of various parts of the CCRUN website
- Number of social media posts

As part of the monitoring process, CCRUN is collecting data on outcomes of engagement, such as how information was used or what new planning and/or policy processes resulted, and impacts, such as reduced damages from flooding, in the context of engagements. Importantly, the team has baseline data on vulnerability and resilience to coastal flooding among urban residents in two areas of NYC, Rockaway and South Shore of Staten Island, collected after Hurricane Sandy. A current project has updated these data in Rockaway with additional information about residents' awareness of flood risks and adaptation options, sources of information, actions taken to adapt to flooding, and obstacles to adaptation. Collecting similar data after future storms will allow the team to document how adaptation, vulnerability, and resilience are evolving over time given the use of flood projections to improve adaptation since Hurricane Sandy.

Another type of baseline data that the team has collected documents current decision processes and needs among decision makers in municipalities in New Jersey and on Long Island. The data will enable the team to assess how the adaptation process evolves over time in response to future engagements in those municipalities.

The team has collected baseline data through a small pilot survey on shocks experienced, and adaptation actions taken by 50 small and medium business owners and operators in coastal areas of NYC and four northern NJ towns. We aim to expand the data set in the future. The data will enable the team to track changes in qualitative severity of shocks and in adaptation behavior over time as new climate events occur and new adaptation initiatives are implemented, comparing the large urban metropolis of NYC to evolution of adaptation in smaller municipalities.

The team also has been continuing its work with local New Jersey and Long Island shore practitioners and policymakers regarding their information and data needs on how households are utilizing the resilience planning programs developed for their use.

CCRUN current and future evaluation efforts rely on a number of approaches, depending on the particular evaluation problem, including ex-ante evaluation and the following approaches to ex-post evaluation: theory-based evaluation, contribution analysis, non-experimental econometric methods, and field experiments when appropriate. Ex ante evaluation assesses the potential outcomes and impacts that may result from the use of climate information or an investment in adaptation in the future, based mainly on models. Ex post evaluation assesses outcomes and impacts that actually occurred as a result of a particular engagement with information and/or investment in adaptation, based on data. The outcome and impact indicators are specific to decision problems and contexts. Outcome indicators may include changes in policies, codes, standards, regulations, management decisions, capital investments, allocation of administrative resources, and individual adaptation actions by urban residents. Impact indicators may include losses due to extreme events, economic outcomes such as the value of infrastructure, economic outcomes, incomes, and other measures of livelihoods. Important outcome and impact indicators are ones that measure the distribution of various outcomes and impacts in the population to capture the equity of progress on adaptation, for example gentrification of neighborhoods, adaptation in historically disadvantaged communities, access to housing, performance of small businesses, changes in employment patterns, etc.

The team has completed an ex-ante evaluation and a benefit cost analysis, which informs coastal residents about the benefits of taking a range of possible adaptation actions to protect their homes from flooding, quantified as avoided future flood recovery costs, compared to costs of implementing those actions. This kind of analysis is unique to our project to the best of our knowledge. The benefit estimates are based on flood recovery costs reported to us by residents in a prior household survey, carried out as part of CCRUN research, that documented recovery from Hurricane Sandy. The benefit estimates also constitute the potential socio-economic value of coastal flood risk predictions produced by CCRUN for coastal residents. We have drafted a decision support tool for coastal homeowners that will communicate this information broadly to coastal residents. The team has presented the results at several conferences and the paper for submission to a peer-reviewed journal is in progress.

A current project is investigating the impacts of co-producing information about local flood risks and costs and benefits of adaptation options on adaptation behavior among coastal residents in NYC. It is comparing adaptation behavior that results from engaging community group members in co-producing the information and discussing it through in-person workshops with behavior that results when information is available through workshops designed without co-production and online. It also investigates whether the effectiveness of the co-production approach differs for populations with different socio-economic characteristics. The evaluation is using a mixed method approach, integrating qualitative information from workshop and meeting transcripts with a quantitative, quasi-experimental approach known in econometrics as a difference-in-difference analysis. The econometric approach is widely used to evaluate social programs but has rarely been applied to understand the impacts of climate-related initiatives. We have just completed the follow-up survey and are in the process of analyzing data. We discuss preliminary evidence based on workshop and meeting transcripts in response to Question 8.

In another planned approach, data collected through monitoring will help to identify case studies in which the team will investigate how science that CCRUN has co-produced with policymakers is being used by practitioners in the urban northeast region and beyond, what outcomes are emerging from that use, and what are the likely impacts. Case studies will be designed based on detailed program theories.

An evaluation challenge is that outcomes and impacts can be observed only in specific contexts. The team is continuing to investigate how to select evaluation cases strategically and what methods to apply in order to provide evidence that can be aggregated to measure broader program impacts.

Evidence of Societal Impact

Adapting to Coastal Flooding in New York City (NA20OAR4310147A)
The work on adaptation to coastal flooding in New York City has improved adaptive capacity in several coastal neighborhoods, including disadvantaged neighborhoods that have been historically underserved by the City of New York and whose populations are majority African American and Hispanic, low-income, and house large immigrant populations. The work has developed new assets: data that document changes in flood adaptation knowledge, attitudes, and behavior among coastal homeowners; quantitative analyses of the expected future flood damages for homes and the portion of those damages that could be avoided with several different adaptation actions, which were shared with homeowners to guide their decisions; a new decision support tool, which is under development. Preliminary analysis based on transcripts of workshops and meetings indicates several outcomes. One of the messages that emerge most strongly from the workshop and meeting discussions is that the information that was co-produced with community group leaders has strengthened the participants' **sense of agency** as well as their **flexibility**. Participants gained awareness that a range of adaptation options exist and different options are appropriate under different conditions. The menu produced the perception among homeowners that there are actions that they can take on their own, and that might make sense for them, whereas prior to the workshops they were only aware that they could raise their home, and almost all were not planning to do so for a variety of reasons. The workshops resulted in **learning** for all the partners and for other interested parties, such as the NYC Mayor's Office of Climate and Environmental Justice. Participants had heard repeatedly about growing flood risk but felt that the information was not specific enough for them to make decisions. Levels of water and expected future costs of flood damages at specific addresses, as well as damage costs that could be avoided with specific adaptation actions were all new information that produced an increased **sense of urgency**, **changing mindsets**, and a **greater capacity to make decisions**. Participants began to consider themselves as responsible for addressing their flood risk in addition to seeing the City of NY as responsible for protecting them against flooding. The team also connected community groups from across the peninsula, enabling potential **new partnerships** for planning. The evidence about the effectiveness of the approach is likely to be applicable to other urban, coastal environments.

New York City and New York State Climate Workshop
CCRUN team members have had a long-standing relationship with stakeholders in New York State and New York City. The foundation of adaptation and resilience efforts at both levels of governance are grounded in CCRUN climate science, in some cases where it is codified. CCRUNs expertise has contributed greatly to the decision-making process on how to better prepare for weather and climate extremes.

In addition to providing data, there existed an opportunity for CCRUN also to play a larger role in the organization and coordination of efforts between the various efforts taking place. The 2019 NPCC report featured a recommendation that stated:

"The City should task the NPCC to coordinate with other regional organizations, such as the Consortium for Climate Risk in the Urban Northeast (CCRUN), to conduct integrated climate assessments for the New York metropolitan region on a regular basis. These assessments should encourage the participation of a wide range of city and regional agencies and communities, and a full range of systems and sectors."

During the reporting period, working with the Mayor's Office in New York City and other stakeholders, plans were made for an early-June 2022 workshop. This event will be an opportunity for stakeholders to learn about the latest climate science information based on observed data and the latest climate models, from CCRUN and other scientists. It will also be a chance for coordination between state and city entities.

CCRUN's program manager is on the workshop planning committee, and other team members are scheduled to participate through their roles on the NPCC.

Case Study

Flood Modeling in Camden and Philadelphia

Over the reporting period, CCRUN (PI-Montalto and PI-Orton) has become a trusted technical partner to stakeholders in two flood-prone communities of the Philadelphia region (the Eastwick community of Philadelphia, PA and the Cramer Hill community of Camden, NJ). In both cases, the researchers built/continue to build hydrologic and hydraulic (H&H) models using PCSWMM that can be used to assess current compound flood risks and the ability of various stakeholder-derived adaptation strategies to reduce risks now and in the future.

In Camden, CCRUN's modeling tools helped the Camden County Municipal Utilities Authority (CCMUA) understand the impacts of extreme precipitation and river rise on both combined sewer overflows and urban flooding. The team also used the model to evaluate the potential mitigatory role of the "Pennsauken Disconnect" project. If constructed, this project will divert stormwater generated in the upstream township of Pennsauken away from the Cramer Hill sewer system, preserving a greater fraction of its conveyance capacity for management of stormwater and wastewater originating in Camden. Our modeling results were incorporated into a proposal that CCMUA submitted to the Hazard Mitigation Unity of the New Jersey State Police to access Justice 40 funds for implementation (proposal still pending). This work was also supported by cross-RISA supplemental funds.

The Eastwick work is also supported by a NOAA COCA-SARP grant (PI Orton) and NOAA AdSci grant led by Drexel (PI Montalto). CCRUN's H&H modeling is being used to evaluate compound flood risks at the downstream end of the Darby-Cobbs watershed and the ability of upstream green infrastructure and floodplain restoration initiatives to reduce downstream flooding. While most of the modeling has been supported by the COCA-SARP and AdSci grant, the core CCRUN funds have been used to work with the community to create a larger regional conversation about the flooding problems in Eastwick and what can be done about them. CCRUN is helping the Eastwick community think through the feasibility of a landswap which would enable residents of low-lying properties swap title with the city to be moved to a higher elevation section of vacant city-owned land.

The CCRUN team (PI-Montalto) organized a Town Square meeting about this idea, an April 2022 CCRUN seminar on land swaps and other options for communities seeking to adapt in place and have been planning an all-day workshop for June 2022 in Eastwick featuring residents and a wide range of governmental stakeholders.

Appendix A. CCRUN Publication List

Peer-Reviewed Publications

Birkmann, J., Feldmeyer, D., McMillan, J. M., Solecki, W., Totin, E., Roberts, D., Trisos, C., Jamshed, A., Boyd, E., & Wrathall, D. (2021). Regional clusters of vulnerability show the need for transboundary cooperation. *Environmental Research Letters*, *16*(9), 094052. https://doi.org/10.1088/1748-9326/ac1f43

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