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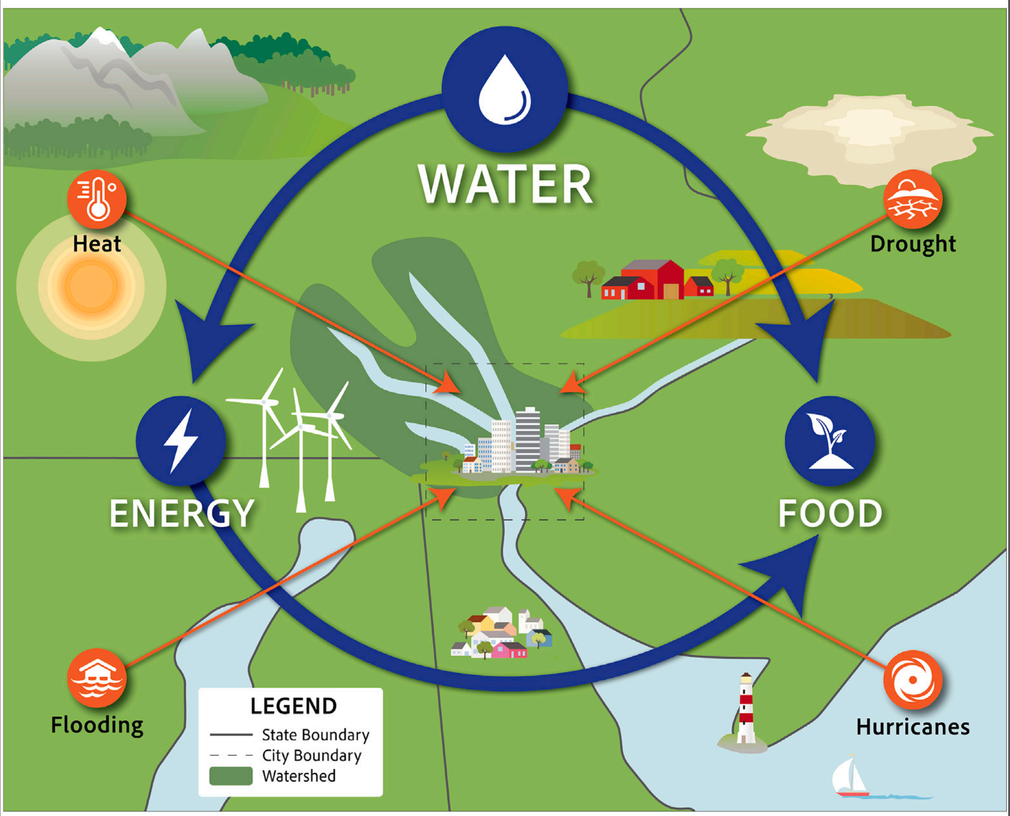

Mari R. Tye, Olga Wilhelmi, Jennifer Boehnert, Emily Faye, Rebecka Milestad, Andrea L. Pierce, Pia Laborgne

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Highlights

Climate change will decrease urban resilience

Nexus systems, governance, resilience, and climate change are multi-scalar

Cascading effects from multiple scales can exacerbate urban system weaknesses

Resilience needs to be examined from multiple spatial and governance angles

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Examining urban resilience through a food-water-energy nexus lens to understand the effects of climate change

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SUMMARY

Urban centers located on the coast expose some of the most vulnerable populations to the effects of climate change. In addition to the challenges faced by high population densities and interdependent social-ecological systems, there is an increasing demand for resources. Exposing the pinch points that are already sensitive to extreme weather, highlights the urban systems that will be least resilient in the face of climate change. We map the projected changes in water availability onto the components of the food-water-energy Nexus at several spatial scales. Resilience thinking acknowledges the different spatial scales at which governance operates, resilience occurs, and Nexus systems function. We use a case study to illustrate how the effects of climate change at locations remote from the city could impact resilience of urban communities in multiple ways through cascading effects from the Nexus. This article underscores the need to examine resilience from multiple spatial and governance angles.

INTRODUCTION

With approximately 4 billion people living in urban areas,[1] there has been a transition in demand for resources, such as food, water, and energy, to these high population centers. Many urban centers are also located near the coast and are highly exposed to natural hazards and climate-related challenges, in addition to having high system fragility due to their high population densities and aging infrastructure. Fragility is the absence of system resilience, stemming from a combination of high exposure, high sensitivity, highly interdependent systems, and a lack of adaptive capacity.[2,3]

Traditional approaches to enable cities to withstand hazardous events have a misplaced focus on controlling and resisting shocks or disturbances. Resistance aims at system stability and maintaining functionality in the face of the disturbance.[4,5] However, resistance to natural hazards does not necessarily achieve a resilient response and can amplify the negative consequences when a failure occurs.[6] As anthropogenic changes have continued to put pressure on natural and built environments, there has been increasing recognition of the need for greater system flexibility and the ability to absorb shocks and disturbances, while also presenting the opportunity to transform and adapt to new conditions following a shock.[5,7] For clarity, we define urban resilience to be the capacity of individual and combined system components of the urban environment to maintain their essential function while absorbing or buffering against a shock or disturbance and having sufficient adaptive and transformative capacity and redundancy within the system to withstand one or more disturbances.[3–5,8]

We consider that urban resilience, in particular, benefits from the dynamism of "resilience thinking" that recognizes the multiple scales of governance in the urban environment[4] and their role in supporting resilient social-ecological systems.[9] As adaptive capacity is one of the key elements contributing to whole system resilience,[10] capturing the temporal and spatial scales of the system components and governance actions is also key to resilience.[11]

Broader research on community resilience has shown that it has different connotations at different scales and degrees of autonomy.[9] For instance, Lazrus et al.[12] found that groups considered to be highly vulnerable could still achieve a high degree of resilience where community linkages were strong or where the individuals were empowered to direct their own responses to hazards. Similarly, the impacts of climate

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change are experienced at a multiplicity of scales, related to how people may be able to respond to or influence the trajectory of outcomes.[5,13]

While acknowledging all of the spatial and temporal scales involved in resilience is important, it can rapidly devolve into a theoretical exercise that serves little practical purpose. Thus, it is useful to reframe the question as "resilience of whom/what, and to what?".[14] To address this need, Wardekker[15] identified four typical framings for urban resilience that can lead to different sets of topic foci, resilient outcomes, and governance frameworks. The fourth of these framings, "resilient community development", has the greatest potential to accommodate multiple governance scales and challenges as they relate to specific urban communities. Identifying the target community is essential in breaking down silos to address socio-political inequalities[15] and to facilitate the practical implementation of resilience attributes.[16]

A natural extension of the resilient urban community framing is that of the food-water-energy nexus ("Nexus") where the intrinsic connections between each component affect the sustainable use of the others.[17] Balancing competing demands for finite resources is not new, but it is more challenging in an increasingly populous and interconnected society.[18] The urban environment creates a novel set of challenges concerning the Nexus and its governance, as in most respects the population comprises consumers rather than producers.[19] Thus, governance is often defined by actions, collaborative or competitive, to acquire resources from outside the urban periphery.[20] In this way, the Nexus has to accommodate multiple spatial scales that extend beyond the urban periphery, natural and physical boundaries, or governance jurisdictions.

Many have demonstrated that urban system challenges can be neatly articulated within the Nexus framework,[21,22] and that new perspectives can be elucidated from a comprehensive assessment of the cross-scale dynamics.[23] The challenge is to ensure that the resilience of one aspect of the Nexus is not achieved by ignoring the influence of its governance (or vice versa) on other systems.[24,25] Notably, implementing either the Nexus or urban resilience is hampered by the governance challenges presented by the disparate nature of the actors involved and the spatial and temporal scales on which they operate.[26,27] As Hogeboom et al.[5] summarize, effective Nexus thinking can be complementary to resilience thinking to avoid counterproductive cross-sector adaptation,[28] and to generate multiple cross-scale resilience benefits[29]; ineffective Nexus and resilience thinking ignores governance panarchy.[23] The impacts of climate change add one more layer to an already complex system and raise the importance of considering multiple scales, as we will demonstrate in this article.

Cash et al.[30] describe how one of the most common problems faced in achieving sustainability is the mismatch between the spatial and temporal scales of ecological responses and human actions. Such spatial and temporal mismatches are also frequently observed in the resilience literature,[4,5,14,16,31] governance of the Nexus,[5,21,26,32] or adaptation to climate change.[2,10,11,33] In particular, the mismatch of scales is a hindrance to articulating clearly which resilience attributes are most desirable for a particular urban area[16] and so to implementing resilience plans. If approached with caution, urban resilience planning offers flexibility to incorporate many different contributors, disciplines and their interactions.[34] Furthermore, urban resilience is highly dependent on the interconnectedness of the urban systems—most notably energy and transportation—with long-term effects felt most acutely in the water system[3,35] making the Nexus an obvious additional layer in the urban resilience planning fabric.

It is apparent that many urban locations consider resilience from a very "engineered" lens[33] that focuses simply on the ability of infrastructure and systems to recover and rebound from risks in the urban environment. However, resilience is a multifaceted concept that encompasses many different spatial scales, and that is dynamic as to the groups involved and temporal scales over which it is explored.[36] Similarly, the Nexus concept is often approached within a specific geographic area[37,38] and emphasizes the tangible contributions of different elements and their interconnections. But as Tye et al.[39] pointed out, Nexus systems are not constrained by municipal or other physical boundaries but fluctuate dynamically. Within this context, climate change acts as a stressor at all scales, aggravating already existing weak points within Nexus systems.

Whether resilience is approached from a Nexus perspective, or the Nexus from a resilience perspective, there are considerable overlaps between the two research areas.[5] Thus, how can the two concepts be integrated to develop a richer understanding of the impacts of climate change on an urban community? This paper focuses on water availability, demonstrating the connections with water supply for local resilience in an urban context, such as for community gardens or for thermoelectric power station cooling. By focusing on water, we highlight the different spatial and temporal scales of climate change impacts on the water-dependent energy and food systems. Climate change is most evident in the frequency of extreme weather, with changes in hydrometeorology being one of the most tangible drivers of effects on human and environmental systems.

In this article, we examine how climate change will affect water availability and the associated urban Nexus dependencies for a medium-sized coastal city on the east coast of the USA. We present an example of the projected changes in temperature and precipitation over the Delaware River Basin and how those changes may be interpreted with respect to the existing resilience stress points in the city's Nexus. Taking a Nexus lens to the impacts of climate change highlights the complexity and multiple spatial scales involved as well as the indirect nature of many climate impacts. We assess indices of extreme temperature and precipitation whose projected changes may have the largest cascading effects for the Nexus and vulnerable systems. We then describe the additional future resilience implications not included in the city's resilience plan, demonstrating how using a Nexus lens at multiple geographic scales facilitates a broader assessment of resilience.

Case study description

The case study city, Wilmington, Delaware, is one of three mid-sized coastal cities that were the focus of a JPI Urban Europe and Belmont Forum funded research project, Creating Interfaces.[40] Creating Interfaces compared data-governance and decision-making processes around the Nexus in three cities near water—Słupsk (Poland), Tulcea (Romania)[41] and Wilmington, DE (USA). Wilmington is a post-industrial coastal city with a population of around 71,000[42] located in New Castle County, Delaware; it lies within the tidal estuary of the Delaware River on the east coast of the United States. The city is highly urbanized with extensive transportation infrastructure but limited public transport and alternative travel modalities. Wilmington was historically dominated by mining and heavy industry but is now dominated by government, financial services, and healthcare, employing an ex-urban workforce.[43] Many areas of the city are subject to frequent tidal and stormwater flooding and, as a result of its industrial heritage, are at risk of pollution.

Figure 1 shows Wilmington's location within the tidal zone of the Delaware River Basin on the confluence of two smaller watercourses. The city-controlled source of public water supply, Brandywine Creek, originates out of state in Pennsylvania and is managed by the Delaware River Basin Commission and operated by several upstream water utility companies.[43] Brandywine Creek is also used as a supplemental source to facilitate groundwater recharge in times of excess demand. Highly porous soils and rocks in the area have substantial capacity for groundwater storage and are also vulnerable to rising sea levels. Recent reports from agricultural land to the south of Wilmington point to higher salinity affecting crop production.[44]

Agriculture in New Castle County has been declining since 1980 and represents <8% of the land use in the Delaware portions of the Brandywine Creek and Christina River watersheds, none of which falls within the Wilmington city limits.[45,46] The majority of agricultural land lies to the south of Wilmington, with only a few urban "farms" within the city limits. As a result, and similar to most industrialized locations, food in Wilmington is primarily imported rather than produced locally (i.e., within a radius of around 60 miles of the city[47]). Furthermore, the center of Wilmington is a food desert[48] with no supermarkets and few corner stores[49] reducing the food security, and hence resilience, of most local residents.

Wilmington has a combination of conventional and renewable energy sources, including a renewable energy biosolids facility associated with the wastewater treatment plant and solar generation at the city's water treatment plant. However, the majority of city energy generation and distribution are owned by external private companies.[43] These facilities are also reliant on imported fuel sources, and are all located in the floodplain with cascading impacts on energy supply in the event of a flood.

Given this background, interviews with local residents and decision makers identified equitable access to food and reliable sources of energy as two of the greatest challenges facing Wilmington.[50]

RESULTS

The nexus, resilience, and governance scales

The paragraphs aforementioned help to illustrate the complex geography of different administrative boundaries as they relate to governance of the Nexus.[39,50] Figure 2 (adapted from Tye et al.[39] Figure 3A) depicts how the different Nexus sectors interact with respect to Wilmington's ability to control decisions, highlighting in darker colors where the city has a higher degree of engagement or decision-making power. Solid arrows show primarily paths of interaction between the Nexus sectors under the active control of the city. The outer boundary lists the principal actors and governance instruments that have a higher level of authority.

For instance, Wilmington city may own and operate the city's water treatment plant, but local water quality and quantity is dependent on river management and agricultural practices that are controlled by other county, state, and federal agencies. Similarly, energy production is controlled by state and federal guidelines (e.g., EPA air pollution controls) and Wilmington is reliant on imported energy sources, so it is sensitive to governance and operability at several spatial scales. The absence of supermarkets and dependence on small corner stores in the urban center[49] increases sensitivity to global disruptions in food production and distribution. Finally, a coastal city at the mouth of a watershed is dependent on many governance interactions to manage the impacts of climate change—from localized flood control measures to interstate agreements for watershed management to Federal mandates on emissions reductions.

Focusing on resilience as an outcome of the Nexus brings the spatial scales of governance into sharper focus, as resilience actions should ideally occur at the scale where decisions are made.[37] This is even more important with competing demands for resources additionally challenged by climate change. Just as different levels of autonomy affect individuals' views of the Nexus and its relevance, and can occur at different spatial scales, the impacts of climate change are experienced in different ways at different spatial scales.

A recent report on the impacts of climate change and associated actions for resilience[51] reflects the considerable change in interest in climate-related resilience, and efforts to collaborate across disciplines and government entities in recent years.[16] However, in common with other coastal cities the interactions between Nexus systems are not well evidenced.[52] Furthermore, we observe that the definition of resilience used to frame the report does not directly support nexus thinking across physical systems and governance levels.[35] Rather it is centered where the city has the greatest autonomy to effect change[39]—e.g., addressing increased flood risk, and other local adaptation solutions. Wilmington's Resilience Plan[51] identifies a need to improve food provisioning and touches on the probable disruptions to food and energy from increased flooding, but does not consider the local impacts that may cascade from events beyond the city boundary.

There is a perception by some decision-makers that the Nexus approach has little relevance in an urban environment.[32] To make the Nexus, resilience, and climate change tangible and actionable we need to "unpack, traverse, (and) share" all three concepts[5 p.13]. Figure 3 identifies some of the different spatial scales that are pertinent to decision-making and the number of sectoral related interest groups in Wilmington.[53] Understanding who makes the decisions and how those decisions connect to other parts of the Nexus requires an entry point.[39] Figure 3 flags the water sector as natural entry point for decisions and conversations due to the number of interest groups at every governance scale.

Projected climate change

In this section, we turn the focus to the impacts of climate change on the water system, and in doing so highlight the importance of spatial and temporal scales and polycentric governance. Indices of precipitation and temperature extremes are described in Table 1.

Figure 1. Location of Wilmington, DE in relation to administrative and physical boundaries

While actions can only be enforced within the city boundary, water supply is dependent on the watershed scale and associated governance; food and energy supplies are affected by cross-county and cross-state dynamics. The impacts of climate change are experienced at all spatial scales but may be exacerbated by decisions made at the national and international scale.

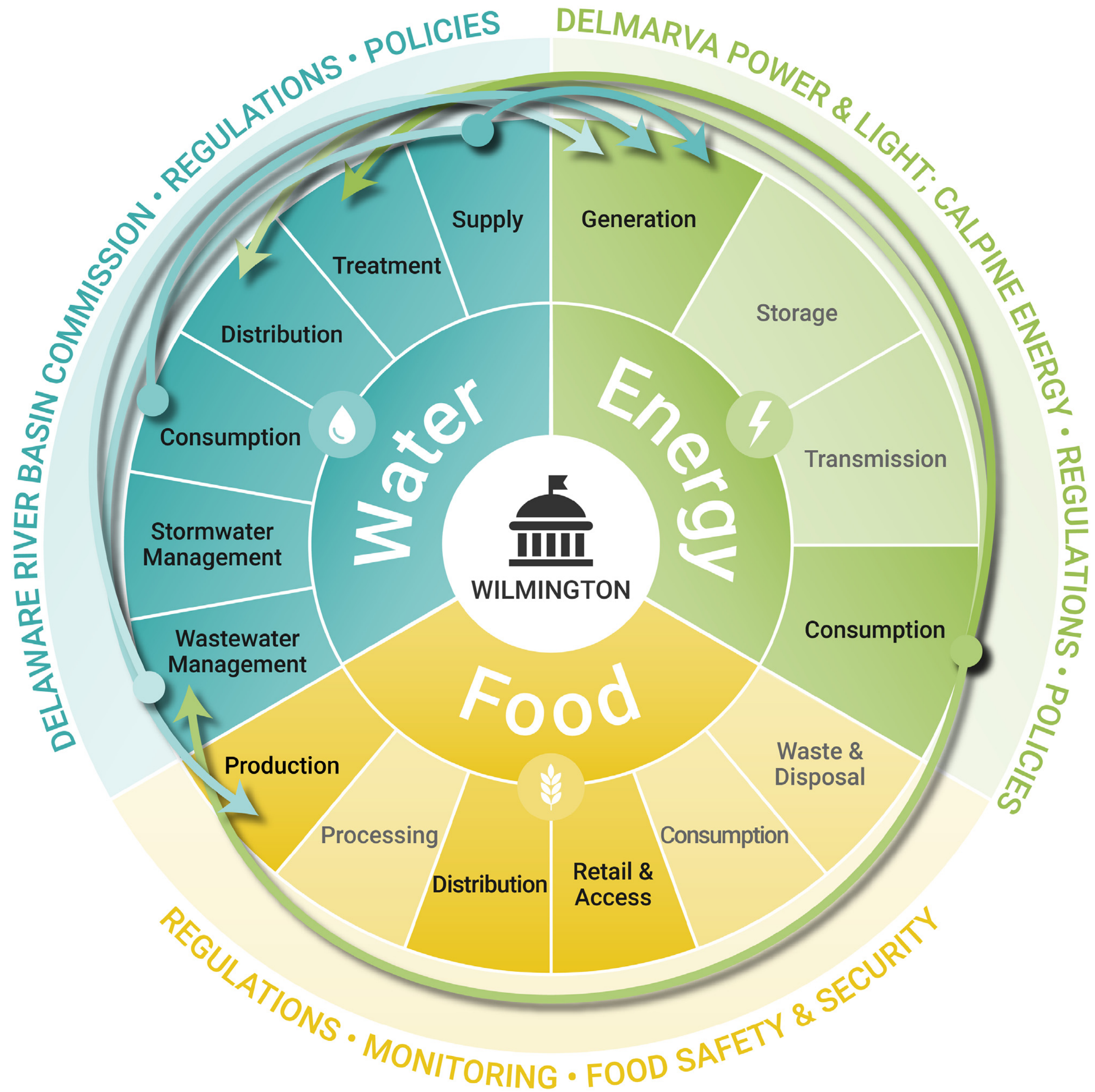

Figure 2. Interactions between Wilmington, DE controlled entities with different elements of the food, water, and energy systems

Elements in darker colors indicate those where the city has a higher degree of engagement or decision-making power, lighter colors indicate passive decisions. Solid arrows show primarily paths of interaction. Black text indicates primary activities controlled by the city, gray text indicates activities where the city is not usually active. Adapted from Tye et al.[39] Figure 3A.

The overall picture for Wilmington and the Delaware River Basin is one of a warmer and wetter future, although with some nuances (Figure 4). The coldest days of the year are projected to be warmer but will remain below freezing under both climate scenarios. While absolute projections of snow cover are not reliable, projected increases in the number of winter wet days coupled with below-freezing temperatures are indicative of increases in snow frequency (not shown).

Figure 4 illustrates statistically significant increases in the hottest day of the year (TXX) of 3°C–5°C, the number of warm days (TX90) and days above 90°F ("90 degree days") could become almost constant over the summer season—increasing from 10 days per year to 45 days per year—under the RCP 8.5 scenario. Tied to the increase in temperature is a change in rainfall distribution, with more extreme events and fewer moderate events. The proportion of the annual total falling as very heavy or extreme rain (P95Tot) is projected to increase for both emission

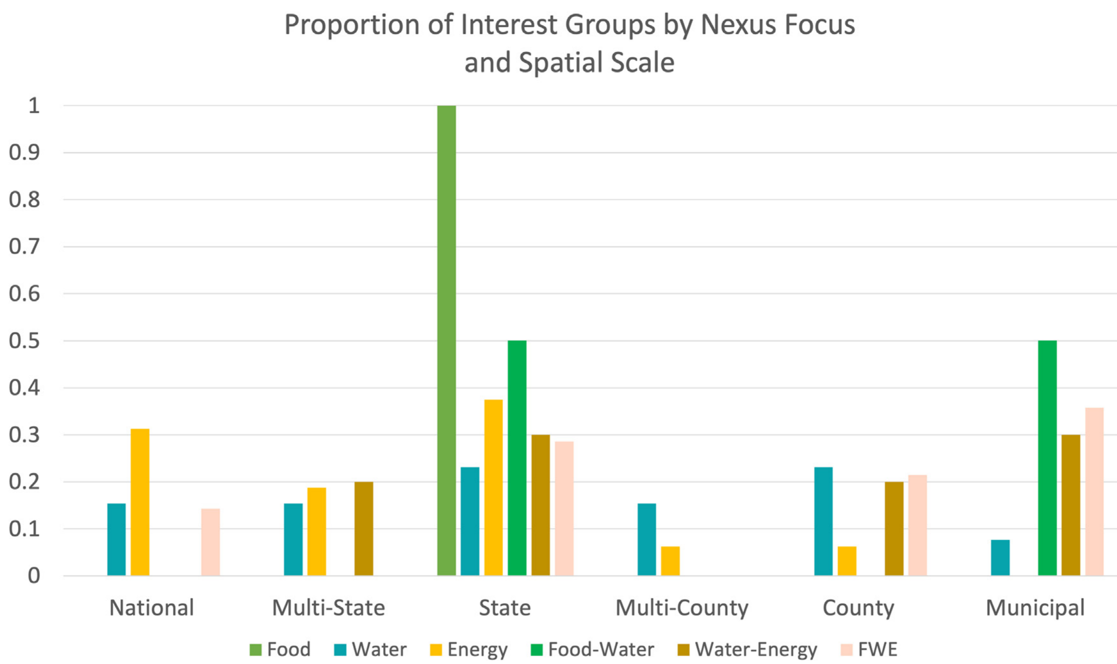

Figure 3. Proportions of Governance Actors involved with Food, Water, and Energy in Wilmington, DE, by Nexus focus and approximate spatial scale of operations

scenarios (Figure 5A). Summer precipitation is also projected to increase in frequency and intensity. Figure 5B shows a small but statistically significant increase in the number of wet days (R1mm) and the duration of the longest consecutive number of days with rain (CWD, wet spell) under RCP 8.5. The duration of the longest consecutive number of days without rain (CDD, dry spell) is projected to remain approximately constant, but the interannual variability (indicated by whisker length) is projected to decrease. Statistically significant increases in the frequency of very heavy rain days (N95) are projected to different degrees across all seasons and both emission scenarios. The projected increases in winter N95 may be related to increased snow depth, but this was not explicitly examined. Of greater potential concern is the projected increase in variability from year to year indicated by the increased spread in whisker length. This will result in rapid swings from very dry to very wet years and less predictability to plan for dependent Nexus responses.

Table 1. Indices of extreme temperature and precipitation used to assess the impacts of climate change on water availability in Wilmington

Index	Long Name	Definition
R1mm	Wet days	Annual frequency of days with ≥1mm precipitation
R10mm	Heavy rain days	Annual frequency of days with ≥10mm (~3/8") precipitation
N95	Very heavy rain days	Number of days per year exceeding the 95th percentile of all wet days (1981–2010)
P95Tot	Annual proportion of very heavy rain	Ratio of the total rainfall from N95 days to the annual total
CDD	Longest dry spell	Annual duration of longest spell of consecutive days with ≤1mm rain
CWD	Longest wet spell	Annual duration of longest spell of consecutive wet days
TX90	Warm days	Annual frequency of days with daily maximum temperature >90th percentile of daily maxima (1981–2010)
TXX	Hottest day	Annual maximum daily maximum temperature
	Ninety degree days	Annual number of days exceeding 90°F (~32°C)

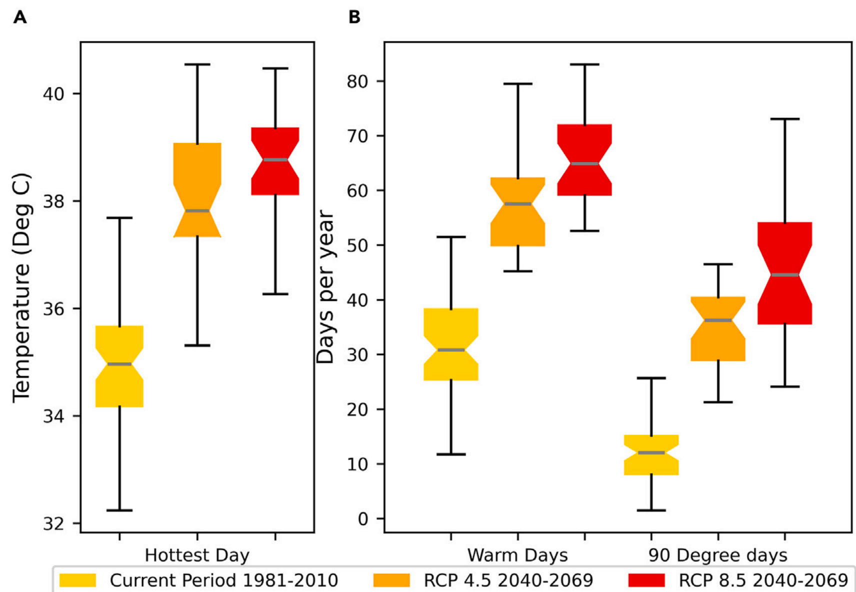

Figure 4. Projected changes in high temperatures over the Delaware River Basin

Areal mean of interannual variability in (A) hottest day per year (TXX) and (B) number of days exceeding the 90th percentile (TX90), and number of days exceeding 90F (32.2C) for 1981–2010 in gold, 2040–2069 under RCP4.5 in orange, and 2040–2069 under RCP8.5 in red. Whiskers extend to the ensemble quartiles, notch and horizontal lines indicate ensemble medians.

Figure 6 presents the mean annual frequency of heavy rain days (R10mm) for the present and future scenarios. Wilmington city boundary is highlighted along with state and county boundaries, and principal watercourses. This highlights spatial variability across the Delaware River Basin, emphasizing the need to understand projected changes in climate and the resultant impacts on resilience beyond the immediate local scale.

The nexus and future resilience

Wilmington's Resilience Plan[51] ("The Plan") identifies the community-level vulnerability points and, while not explicitly linked to the Nexus, the interplay between potential actions to improve resilience and offset climate change. As noted before, the Plan focuses on actions that are within the governance of the City of Wilmington. The Plan explicitly considers four focus areas related to current issues and climate change: waterfront development, sewerage and storm water, transportation, and public health. While the Plan assessed the impacts of flooding and sea level change quantitatively with hydrodynamic models, other impacts such as changes in temperature were evaluated qualitatively. We provide a similar qualitative assessment of the additional impacts on resilience that become apparent when considering the broader spatial scale of the Nexus.

Starting with the last focus area, public health, the Plan identifies a need for healthy access to food, which is proposed to be filled through increased support of local supply. The absence of large-scale food production in Wilmington city means that increasingly uncertain agriculture conditions nationally and globally will be experienced primarily through food shortages or increased prices. Flooded transportation routes may disrupt food supply, as identified in the Plan. However, projected changes in the frequency and intensity of extreme rainfall during the summer could also damage local food production. Projected increases in summer temperatures may increase agricultural water use to control heat stress and increased evaporation, and in dry years could lead to increased competition for a restricted water supply.

Increased summer extremes could have direct health impacts both on chronic illnesses and arising from extreme heat exposure.[54] While the Plan outlines some of the effects from rising temperatures in more detail and acknowledges the likely increases in air conditioning use, it does not consider the broader implications. Higher energy demands could lead to power brownouts due to competing demands from across the region and neighboring states. Increased energy use would likely be accompanied by increased demand for water—both as a direct cooling source and to cool thermoelectric plants—competing with the increased agricultural demands. Finally, increases in flooding would impact energy generation and distribution through disruptions to coal in addition to the direct consequences identified in the Plan.

However, to address these additional impacts from climate change and achieve resilience will require actions at several different governance levels and coordination with other entities, both private and public. For instance, The City of Wilmington can reduce future energy consumption through updating design standards to mandate improved building efficiency, in addition to the proposed flood protection improvements.[51] The Plan also suggests improving the building efficiency and setting reduced energy goals for their own building stock. By

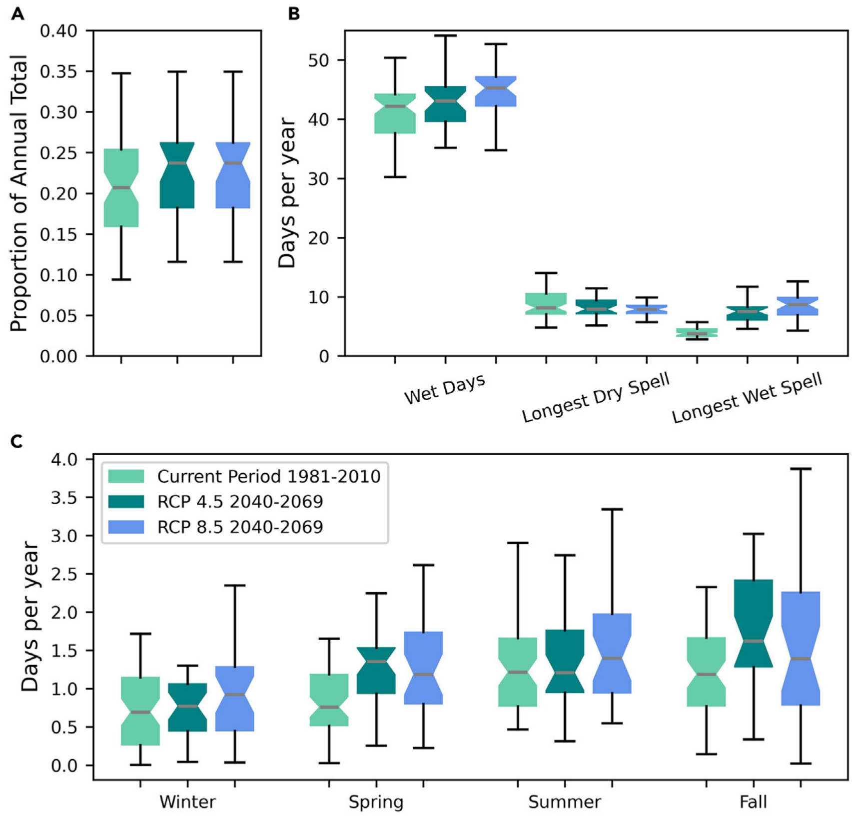

Figure 5. Projected changes in heavy rainfall over the Delaware River Basin

Areal mean of interannual variability in (A) proportion of the annual total falling on the wettest days (P95Tot); (B) summer number of wet days (R1mm), duration of the longest dry spell (CDD) and longest wet spell (CWD); and (C) Number of very heavy rain/snow days in each season (N95) for 1981–2010 in aquamarine, 2040–2069 under RCP4.5 in teal, and 2040–2069 under RCP8.5 in blue. Whiskers extend to teh ensemble quartiles, notches and horizontal lines indicate ensemble medians.

working with state and federal institutions, they could also leverage recent funding opportunities[55,56] to increase the efficiency of privately owned buildings. However, reducing the dependence on imported energy sources to improve energy resilience will necessitate an increase in the use of renewables or other ways to diversify energy supply. This, in turn, depends on collaboration with outside parties. Combatting the climate risks posed to the food sector would also require broader interactions with outside parties such as: protecting local agricultural land from flooding or water restrictions; incentivizing increased local production and distribution; or enhancing trade agreements to import food. In this regard, the state of Nexus governance in the City of Wilmington (Figure 2) differs from that of the generic governmental entity described in Tye et al.,[39] by only controlling activities related to one Nexus sector.

We emphasize that just as the Nexus transcends spatial boundaries and individual systems,[27] climate change responses occur at many different scales that also impact the local community. Similarly, adaptive capacity and resilience are inherently linked to embedded decisions (e.g., existing infrastructure) and the autonomy of those making decisions. Thus, the City of Wilmington may be able to facilitate new opportunities for food supply or distribution, for instance, but without significant cooperation from many other entities, it would be extremely challenging to ensure food security through local food production alone as suggested in the Plan.[51]

Many climate adaptation plans use an operational approach to resilience that addresses the symptoms of "fragility"[3] as demonstrated by an increased ability to recover from disasters. But resilience needs to go beyond solely addressing the impacts of climate disasters to understand how other less tangible changes may gradually erode the resilience of a system. An objective approach to resilience thinking[57] is more inclined to account for different scale dynamics to build as complete a picture of the system as possible. While this approach is more flexible, it is still generally applied to one system at a time (e.g., urban area, watershed, eco-system) and does not necessarily account for the interplay between governance and the system(s) under consideration.[31]

Framing the question of resilience around the urban area of Wilmington, we identified previously where the Nexus intersects with the decision-making power to achieve resilience. Enacting those decisions requires that the focus of urban resilience is identified[15] and clearly articulated for the people who will be involved.[34] We find that Wardekker's[15] "Resilient Community Development" framing is appealing both in its clearly articulated approach to resilience, and its parallels with multiple time scales of the Nexus. While Wahl et al.[17] caution that the community focus can inadvertently lead to a localized focus that ignores consequences and maladaptive consequences, when properly integrated

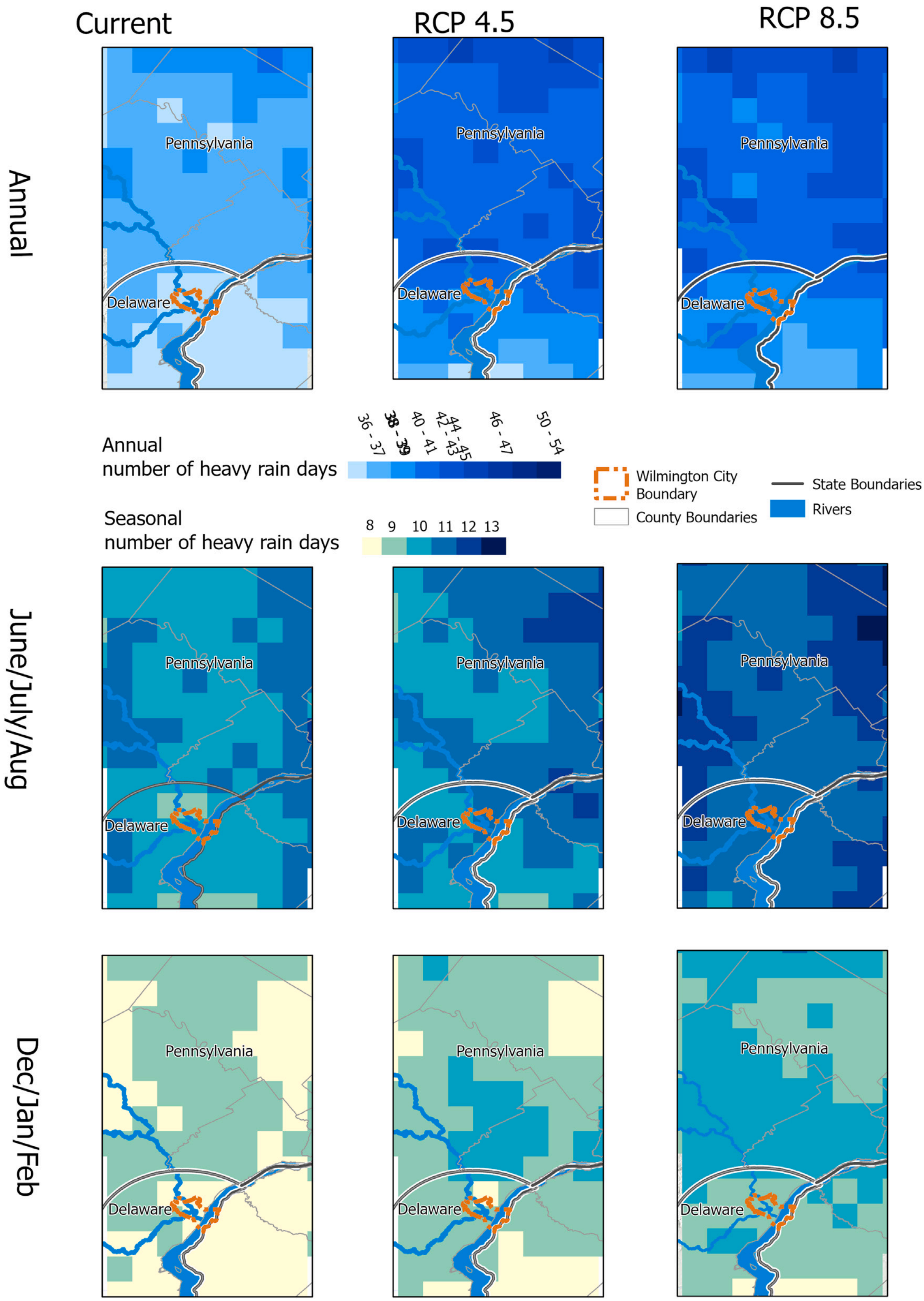

Figure 6. Projected changes in days with heavy rain over the Delaware River Basin

Mean number of days with >10mm rain (R10mm) (Top) annually, (Middle) summer and (Bottom) winter indicating city, county, and State geographical boundaries, and main rivers.

into higher-level strategies they can have far-reaching consequences for both the Nexus and resilience. This certainly mirrors our experience with local engagement in Wilmington, where community concerns were either very narrowly focused or beyond the capacity of the city to address.[41,58]

DISCUSSION

In our suggested mapping for a resilient and climate-ready Wilmington, we first developed individual narratives about the Nexus, climate change, and governance at different spatial and temporal scales. A key part of this narrative was the recognition that resilience to extreme weather, adaptation to climate change, and integration of the Nexus all vary with the perspective of the decision-maker. Enhancing and implementing the city's Resilience Plan involves engaging local and external communities to address the city's two greatest challenges: equitable access to clean energy and healthy food. While this does not directly address the impacts of climate change at locations further from Wilmington city's boundaries, there is a need to contain the ever-expanding circles of indirect consequences within a spatial boundary that can be reasonably addressed.[34] Wilmington could expand access to renewable energy through public private partnerships to facilitate the building of community solar gardens in collaboration with utility providers and citizens. In its governance capacity, it could also develop strategies to support multiple community focused food and energy projects, and ensure that there is cross-pollination of ideas across the communities and sectors of the Nexus.

We considered the multi-layered, and often nebulously defined, components of urban resilience planning, Nexus in the urban environment, and the impacts of climate change. While their vagueness can be a limitation to implementing any plan, it also offers flexibility to approach the *who*, *what*, *where*, *when*, *and why*, from multiple perspectives. Addressing urban resilience planning with a Nexus lens then becomes a pathway toward a more holistic implementation plan.

The case study of Wilmington, Delaware, USA demonstrated how the effects of climate change may be experienced locally even though they occur at different spatial scales. While the capacity for adaptation is connected to autonomy and governance, the Nexus lens demonstrated resilience planning goes far beyond the city boundaries, and is inherently dependent on the governance of different elements of the Nexus. Using future water availability as a focus for the Nexus is in some ways akin to the Integrated River Basin Management plans that preceded Nexus research.[59] However, we emphasize that all Nexus studies must have a starting point at one of the nexus elements as is often illustrated in literature,[60] and that access to potable water is a fundamental requirement to support human activity.[61]

The impacts of climate change will be experienced by everyone in many different ways, some more direct than others. For instance, increased temperature is readily translated into an increase in a metric that people are familiar with (for instance number of "90° days" in the USA). However, increased volatility in extreme weather events could have less tangible consequences such as floods and droughts affecting the global supply chain logistics.[62] While it is important to reflect on the many different scales of projected climate change, from the municipality up to county, state or watershed level, the focus needs to match the scale of governance for any adaptation to be effective. This is where a Nexus lens is helpful as it seeks to understand the scale-related challenges while identifying the prominent actors and their ability to engender change.

This article used the case study of a mid-sized coastal city in the United States to demonstrate that the effects of climate change are multifaceted and that any resilience assessment needs to account for the different spatial and temporal scales. In the same way, the Nexus has many scales on which it operates. Thus, taking a Nexus lens to evaluate the impacts of climate change can help to identify additional challenges where the system, city, or community is most fragile and that require action to improve resilience.

Limitations of the study

The example uses only one set of local climate projection model data, and so cannot be considered a full analysis. Furthermore, without access to detailed information on, e.g., energy production, it was not possible to carry out a full resilience analysis. Instead the article focuses on additional areas that could have been explored in the existing City of Wilmington Resilience Plan as an example for future reference.

It is also important to note that the illustrative climate projections used here focus only on the Delaware River Basin, but the City of Wilmington's reliance on imported food makes it sensitive to climate impacts across the United States and the globe. The example did not consider impacts on global food imports.

However, onerous some of the projected impacts from climate change are, they may be less onerous than in other urban locations within the United States,[63] where higher temperature, rising sea levels, increased storm activity, or increasing drought may pose greater risks to community resilience. This article did not consider the potential increased burden on stressed systems as populations migrate away from other more vulnerable regions to "climate havens"[64] such as Wilmington.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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- RESOURCE AVAILABILITY
  - Lead contact
  - Materials availability
  - Data and code availability

- METHOD DETAILS
- QUANTIFICATION AND STATISTICAL ANALYSIS

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The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Urban Living Lab Case Report	http://10.0.121.243/osf.io/y78dh	
Wilmington Story Map	https://ncar.maps.arcgis.com/apps/Cascade/index.html?appid=6c1e353b774d4f24bdf28a8b62472385.	
Climate Mapping for Resilience and Action	https://livingatlas.arcgis.com/assessment-tool/home/	
Software and algorithms		
Jupyter Notebooks	https://github.com/maritye/Wilmington_FWE	

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Mari R. Tye (maritye@ucar.edu)

Materials availability

This study did not generate new unique materials or data.

Data and code availability

This paper analyzes existing, publicly available data as referenced within the text and in the key resources table. Climate data are obtained from the Climate Mapping for Resilience and Adaptation (CMRA) database[65] of hazard projections. CMRA integrates downscaled climate projections from LOCA[66] at different time frames (near-term, mid-century, end-of-century) with demographic, environmental, infrastructure and economic data. Two emissions scenarios are available using Representative Concentration Pathways[67] 4.5 (medium-low emissions, RCP4.5) and 8.5 (high emissions, RCP8.5); we present both scenarios in the analyses. Jupyter notebooks to reproduce the indices and figures are available from GitHub, also referenced in the key resources table.

METHOD DETAILS

The current state of the Nexus in Wilmington, DE, is established from the research produced by the Creating Interfaces project and reported by Pierce et al.[43] in addition to resilience and climate change impact studies commissioned by the City of Wilmington.[51] The Creating Interfaces project centered around the use of citizen science and urban living laboratories (ULL) to facilitate greater community engagement and uptake of methods to improve nexus governance and literacy.[17,68] ULLs can mobilize FWE governance and local community involvement as they maintain a central role for citizens, officials, and scholars in the co-creation of knowledge around problems and solutions.

While broadening participation is key to promoting resilience and climate change adaptation related activities, thought needs to be given to explore who should be involved and how that occurs.[9] In particular there is a risk that the ULL will have a very localized focus that inadvertently omits or ignores the broader spatial challenges, responses and impacts elsewhere.[17] To navigate this challenge, we draw on various sources of information about local challenges and governance issues, including literature review and secondary GIS data,[69] semi-structured interviews and case report,[43,50] Wilmington's Climate Change Impact Study[51] and the Delaware Climate Action Plan (DNREC).[70]

A common theme across community/stakeholder engagement literature is that the problem to be addressed must be local and tangible and have bearing on current community needs.[36,68] This applies irrespective of the origin of the research question(s), whether Nexus,[17] resilience,[71] or climate change adaptation.[72] In the context of Wilmington, the primary concerns expressed by the citizens relate to unreliable energy supplies, access to affordable and healthy food, and racial and economic inequality.[50,51,73] Thus, drawing on the listed resources to identify current sources of vulnerability and fragility, we focus on the water sector as it is the only sector where the city has a high degree of autonomy, and that has interest groups at multiple spatial scales. Water has also been described as the "common currency" that helps scope the problems faced by climate change and to engender greater resilience.[31] In particular, we focus on the resilience gaps that may not be immediately apparent in planning exercises, but that will likely be exacerbated by climate change.

We use representative indices of extreme precipitation to analyze the most readily felt weather impacts of climate change on water resources. Indices are those defined by the World Climate Research Program's Expert Team on Climate Change Detection and Indices.[74–76] The specific indices are presented in Table 1. The precipitation indices selected are those found to resonate with water resource managers for decision-making under climate change.[77,78] Temperature indices are a combination of those proposed by the ETCCDI,[74] and an index often used by health officials and emergency managers - days above 90°F (~32°C, also referred to as "ninety degree days"). We also focus primarily on the projected changes in summer, as climate projections are notoriously weak with respect to projected changes in snow cover and frequency.[79]

The consequences from a resilience perspective are inferred from cross-sectoral collaborations and other cross-disciplinary research,[78,80,81] rather than fully quantified using specific measurements [e.g.,] [82]

QUANTIFICATION AND STATISTICAL ANALYSIS

The statistical significance of projected changes in precipitation and temperature indices was assessed using a leave-one-out bootstrap approach, removing one year in each iteration from the CMRA near-term and mid-century projections.