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Perspective

Net Zero Urban Water from Concept to Applications: Integrating Natural, Built, and Social Systems for Responsive and Adaptive Solutions

Courtney Crosson,* Andrea Achilli, Adriana A. Zuniga-Teran, Elizabeth A. Mack, Tamee Albrecht, Padmendra Shrestha, Dominic L. Boccelli, Tzahi Y. Cath, Glen T. Daigger, Jennifer Duan, Kevin E. Lansey, Thomas Meixner, Stephanie Pincetl, and Christopher A. Scott

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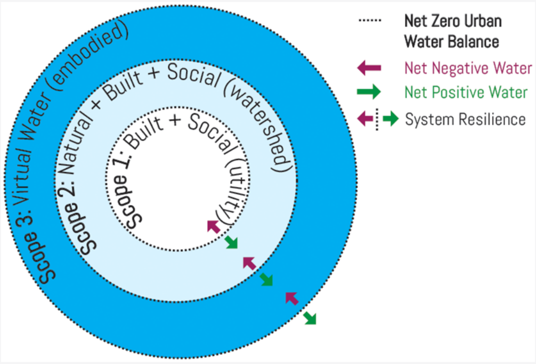
ABSTRACT: Innovation in urban water systems is required to address drivers of change across natural, built, and social systems, including climate change, economic development, and aged infrastructure. Water systems are complex socio-technical systems that interact with biophysical systems to supply and reclaim water. We present a vision for enhancing urban water system resilience through a net zero urban water (NZUW) approach, which meets the needs of a given community with a locally available and sustainable water supply, without detriment to interconnected systems or long-term water supply. NZUW is an integrative approach with progressive targets assessed using a quantitative framework to expand adaptive and responsive solutions for urban water self-sufficiency. Decision makers can use NZUW to understand trade-offs between future interventions to urban water systems across spatial and temporal scales. We present the overall NZUW approach, drivers of change, applications, and research gaps.



1. INTRODUCTION

Urban water systems, both managers and infrastructure, are challenged to respond to the acute shocks and chronic stressors of several drivers of change (e.g., climate change, economic development, and aged infrastructure). These complex socio-technical systems interact with biophysical systems to supply cities with water, but they are products of old 20th century understandings of precipitation regimes,[1] engineering science (including supply, sanitation, and stormwater systems), and city administrative organization.[2] For example, the sanitary city movement, which sought to eliminate disease from cities, successfully used a centralized, compartmentalized approach. However, this approach and the institutions used to build, manage, and regulate these systems are no longer adequate for addressing the uncertainties facing water systems and integrating new knowledge and technological advances. Thus, net zero urban water (NZUW) is an integrative approach that uses progressive targets and a quantitative assessment framework for adapting to the challenges created by multiple drivers of change without detriment to interconnected systems and long-term water supply.

1.1. An Integrative Urban Water System Approach. The NZUW approach is aligned with other concepts, such as One Water, integrated water resource management, integrated urban water management, and water sensitive urban design. One Water acknowledges that water supply and wastewater must be considered as a single water resource; there is no such thing as "waste" water. Urban water is then approached as a resource that must be treated as the water available to that city in perpetuity. NZUW goes beyond One Water and other previous integrative water management approaches by providing (1) a progressive target within a defined scope and (2) a quantitative framework that can be used to assess the trade-offs of adaptive and responsive solutions toward urban water self-sufficiency.

Table S1 contains further details about the differences between the conceptual approaches of One Water, integrated urban water management, and NZUW. Although all three approaches encompass similar water systems, NZUW addresses a broader set of scales and objectives.

1.2. A Progressive Target within a Defined Scope. Net zero water is a term that has gained more attention in the past

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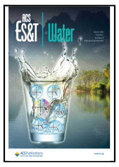

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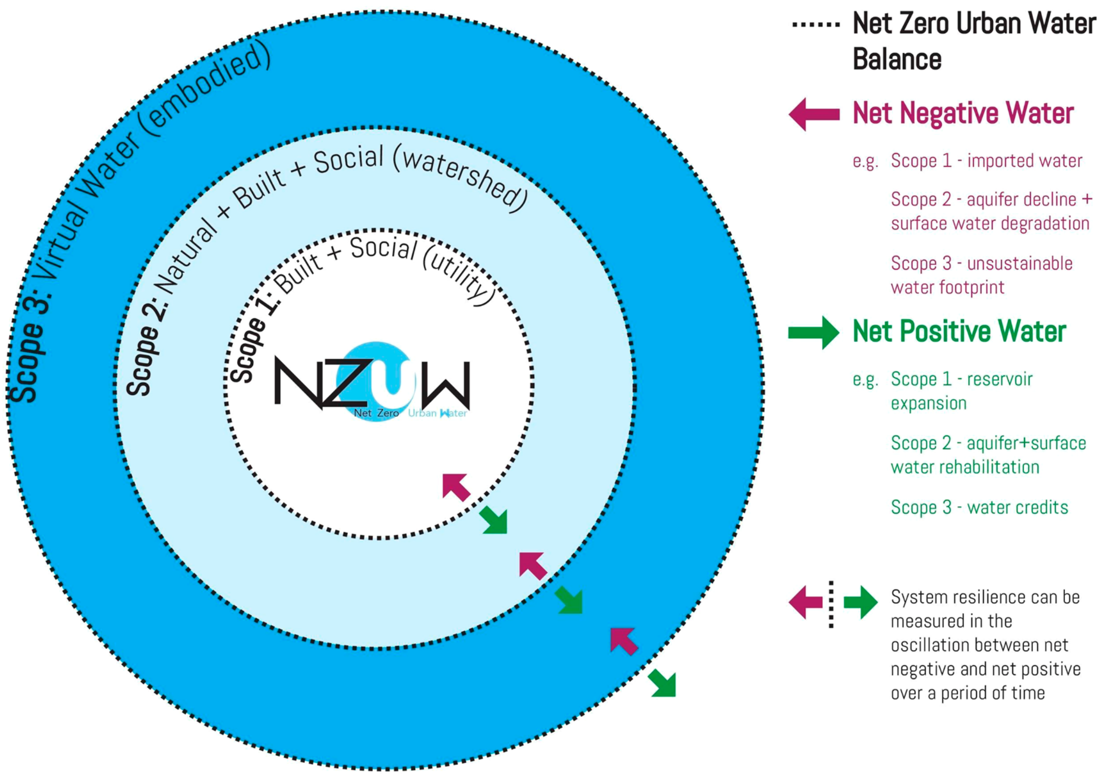

Figure 1. NZUW is a progressive target across three scopes, including the potential for long-term net positive urban water outcomes. NZUW logo by Courtney Crosson (2020).

several decades that, as a concept, operates across multiple spatial scales (e.g., building, district, and watershed). The overall approach refers to using technologies and management strategies for limiting water consumption and returning water back to its source so as not to deplete either the quantity or quality of water resources.[3,4] While net zero water performance standards at the building scale have been proposed by the International Living Futures Institute,[5] the NZUW concept we advance here is intended for broader spatial scales to tackle larger natural, built, and social systems.

The concept of NZUW operating across three scopes of influence, similar to carbon or energy, is illustrated in Figure 1. The first scope incorporates the infrastructure of water systems, such as a utility service area, that allows for straightforward accounting between the input and output of an engineered water system. The second scope includes the boundary of the natural, built, and social systems, such as the watershed or ecological and hydrological area of influence. The third scope is virtual, meaning the total water footprint including embodied water in all consumed products. As illustrated by the arrows, urban systems may move between net negative (deficit) and net positive (surplus) water statuses in each of the three scopes. Urban water system resilience may be assessed over a period of time by measuring the degree of change between these statuses. Our NZUW approach centers on the first and second scopes (infrastructure and the social, built, and natural system). The third scope, virtual water, is beyond the aim of this analysis. The details of the integrated NZUW system across the three scopes are depicted in Figure 2.

1.3. A Quantitative Framework for Assessing Trade-offs across Temporal and Spatial Scales. The NZUW approach is a place-based, comprehensive, quantitative framework for guiding the development of resilient water systems. By utilizing a quantitative framework, a suite of alternative future interventions at building, district, and city scales and over short- to long-term horizons can be evaluated to assess the trade-offs involved in mitigating the human impact on natural water systems. As a result, a diverse urban water supply portfolio, including recycled and reused water and demand management, with decentralized and centralized solutions and robust storage options[6] is a precursor to the NZUW transition. For these transitions to occur, evidence of the successful performance of these adaptations to urban water systems is necessary for broader acceptance.[7] The NZUW framework will provide for continual performance evaluation and incorporation of new information to assess resilience across the integrated systems over time. Thus, the historically elusive goals of transforming urban water systems to reach self-sufficiency can be assessed and achieved with decision support from the NZUW quantitative framework.

NZUW approaches can alter collection and use patterns within its defined system and potentially reduce flows to downstream users (e.g., environmental demands) beyond its boundaries. While achieving their own sustainability, NZUW systems must respect current allocations and needs and coordinate among all affected parties.

2. DRIVERS OF CHANGE: NATURAL, BUILT, AND SOCIAL SYSTEMS IN AN NZUW BALANCE

Key drivers of change within each of the natural, built, and social systems and the interaction over short- and long-term horizons are visualized in Figure 3.

2.1. Natural Systems: The Ceiling and Supply. The natural system includes surface and subsurface water sources that are diverted from nature to an urban setting as well as the

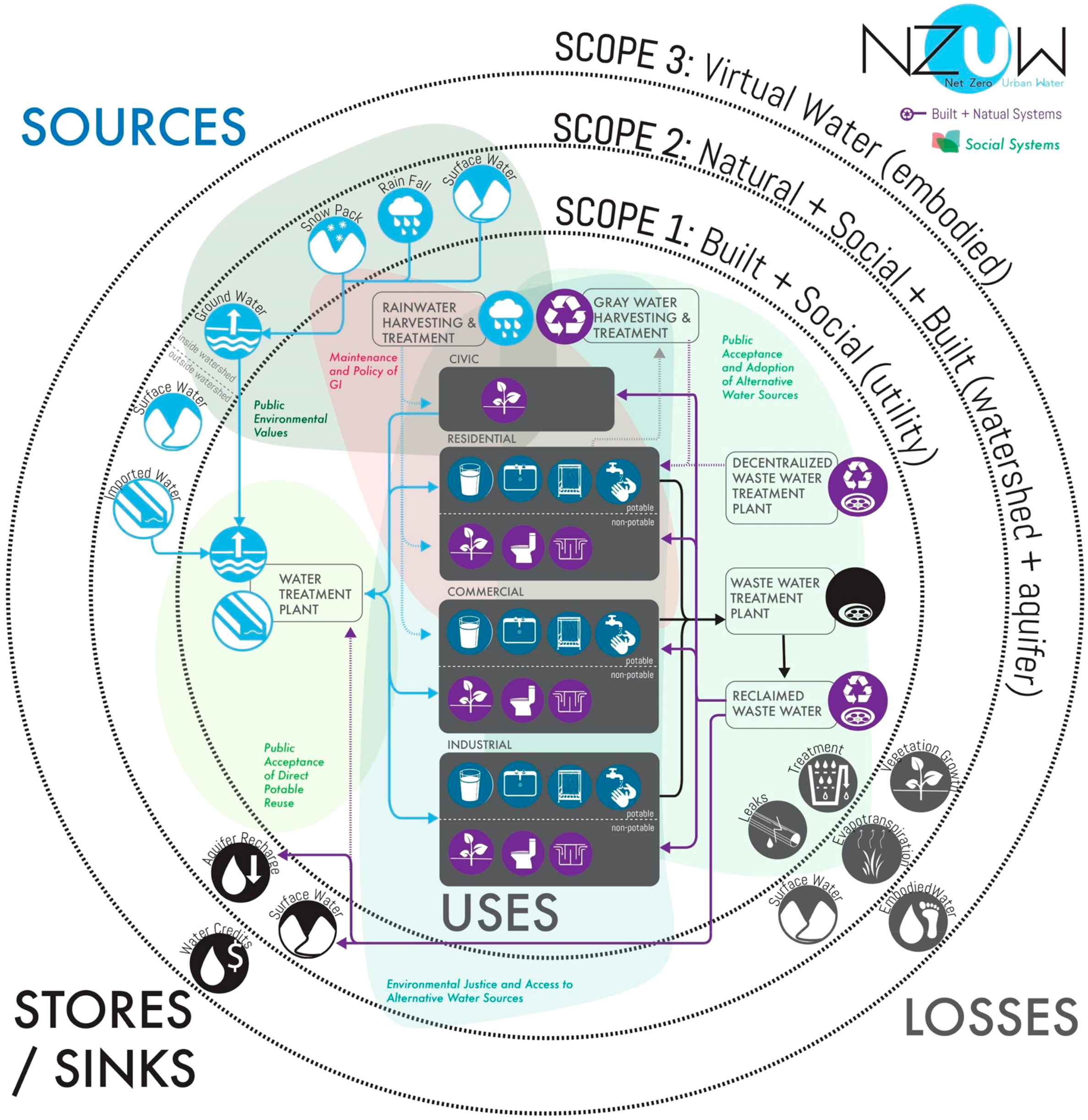

Figure 2. NZUW approach that integrates complex interactions across three scopes and natural, built, and social systems. NZUW logo by Courtney Crosson (2020).

natural system processes within the site (or place) boundary (e.g., city). Although surface and subsurface flows are connected, their drainage boundaries are not always the same. Systems draining to the city can be large watersheds or extensive aquifer systems. The geopolitical area of a city can occupy one part of or an entire watershed that may be naturally gaining or losing water to its neighbors. In addition, the natural system is evolving as climate changes; for example, in the southwestern United States, the precipitation intensity is expected to increase while drought periods will be longer.[8]

While flows in the natural systems supporting cities may be large, so is the variability of these flows. The costs of diverting water from these systems (monetary, social, and environmental) as well as the drought and flood risks inherent in natural systems need to be taken into account in attempting to exploit these resources. Critically, the alteration of the hydrology by the urban form has important implications for NZUW. Due to the substantial proportions of impervious cover that is significantly interconnected, cities tend to have high peak runoff and low baseflow.[9] In addition, impervious surfaces usually introduce non-point source pollutants into the water systems, which are difficult to regulate and remediate. The natural context of a city (e.g., a community's physiography in terms of geology, soils, drainage network, and climate) influences how urbanization affects its hydrology.[9] Importantly, water in the environment provides societal benefits in terms of use and non-use ecosystem services, and these benefits need to be recognized and protected.

Climate change poses multiple environmental challenges in cities that currently have arid to humid environments in the 21st century and has changed how we adapt.[10] The key impacts of projected climate changes include increased rainfall intensities and flood hazards, more extended drought periods, and higher temperatures that threaten to exacerbate urban heat island effects and outdoor water consumption. NZUW should

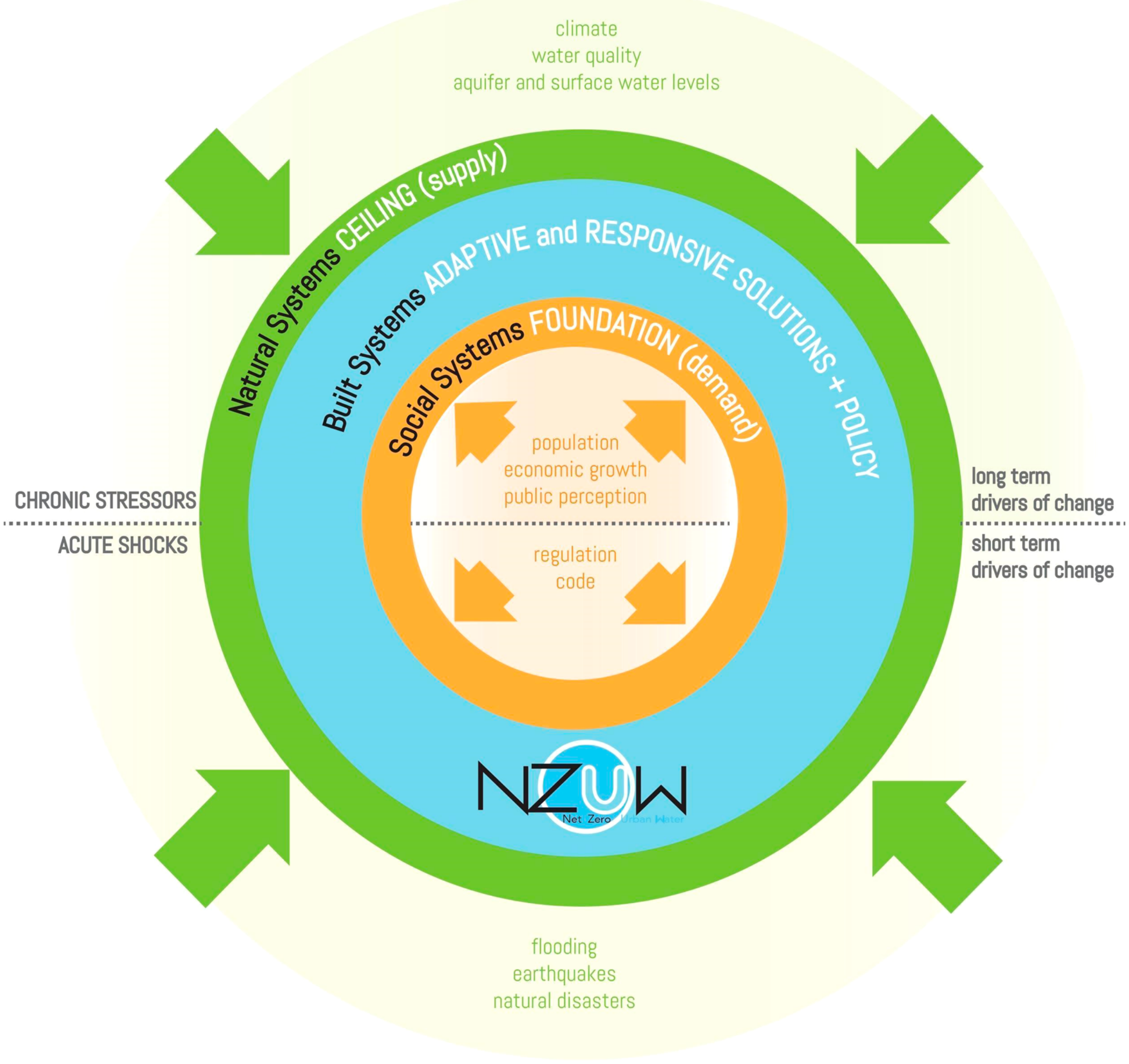

Figure 3. NZUW is at the intersection of multiple disciplines and bracketed by a natural system ceiling and social system foundation. NZUW logo by Courtney Crosson (2020). The conceptual doughnut in this graphic was inspired by the doughnut visual framework developed by Kate Raewoth (2017).

aid utilities in their adaptation, conservation, and efficiency efforts.

2.2. Social Systems: The Foundation and Demand.

Pursuing NZUW will require better integration of the social systems, from water governance to public acceptance, with natural and built systems so as not to exacerbate supply—demand imbalances.[11] Key to the pursuit and governance of NZUW will be making the transition from current, conventional, supply-oriented approaches to integrated systems that are more resilient to climate, growth, aging infrastructure, and other challenges.[12] To illustrate this point, we note that several cities are adopting "One Water" approaches. For example, the Los Angeles Department of Sanitation and Tucson Water have developed collaborative approaches to manage watersheds, water resources, including reclaimed water, and water facilities under the umbrella of "One Water", a step in a more integrated management of the water system. This transition includes a blending of funding streams and changes in service rates to reflect the need for new infrastructure. Los Angeles's One Water 2040 Plan recognizes the importance of developing more fiscally responsible water planning solutions.

NZUW would include recreating local agencies and departments that manage water into single agencies that see water holistically, not supply and waste separately. Supportive regulatory frameworks can ease the transition to net zero strategies and technologies.[13,14] In particular, the coordination among local, state, and national agencies can assist in technology rollouts and implementation through efficient approvals and regulations.[15]

Economic development and population growth are examples of complex drivers of change within social systems. Growing cities face pressures to conserve water but have more people to pay for NZUW implementation,[16] whereas the converse is true in places with declining populations.

While new technologies and policies are developed, the economic capacity of communities and residents will impact the rate of adoption and implementation. Higher-income communities may have a tax base that allows for more rapid adoption of NZUW, such as the redesign of buildings and parks based on NZUW principles. Higher-income households also have the financial means to make investments in new fixtures and xeriscaping. Lower-income communities may be less economically nimble and may need creative approaches for overcoming financial barriers to NZUW implementation (infrastructure costs, rate design, consumer adoption, etc.). Beyond economic capacity, the challenge of NZUW adoption is related to public acceptance of its different components. Pilot projects and technology demonstrations, in combination with public consultation and education, can improve the efficacy of risk-based regulations and public acceptance.[15,17]

2.3. Built Systems: Adaptive and Responsive Solutions. Situated between the natural system ceiling (supply) and social system foundation (demand) in Figure 3, built systems incorporate the treatment and conveyance of potable, storm, and sanitary water systems; residential, commercial, and industrial water uses; and the outdoor built environment that includes both engineered and natural systems. Thus, these built systems offer key opportunities for adaptive solutions to balance supply and demand toward NZUW accounting. However, their successful design, implementation, and maintenance rely on associated natural system dynamics and broad social acceptance.

As communities search for the next bucket of water, alternative water supplies from stormwater, gray water, wastewater, and rainwater for potable and nonpotable water needs paired with increased storage are key components for achieving NZUW. For example, building roofs collect rainwater and streets serve as catchments and conduits for stormwater. In addition, the traditional "waste" stream, along with sanitary flows, can be captured in place, treated, and reused as nonpotable and potentially potable water supplies. The ability to decentralize our water infrastructure can provide long-term benefits associated with adaptive treatment technologies for delivering water quality appropriate for the end use. Additionally, energy can be saved by removing the need to pump water from a centralized treatment plant and back across the urban landscape.

Aged infrastructure is a key driver of change for NZUW. In the United States alone, it is estimated that to make upgrades, wastewater and stormwater systems need $271 billion and drinking water systems $384 billion in the next 20 years.[18] An outstanding question, bolstered by mounting evidence of cost savings through system design, is whether the present infrastructure should be upgraded and/or replaced or if a more efficient distribution and collection system would reduce capital costs and recurring costs.

3. APPLICATIONS ACROSS SPATIAL SCALES

To reach an NZUW target, an urban water system will need to implement adaptive and responsive solutions across building, district, and city and regional scales. Examples of net zero buildings and some district- and city-scale alternative water implementations demonstrate the potential of a comprehensive NZUW approach. Net zero design generally first maximizes opportunities for conservation, then utilizes passive systems, and finally relies on active systems to meet the remaining water needs within the defined scope. Examples of conservation, passive, and active system strategies across the three scales are summarized in Table 1 and discussed in this section.

3.1. Building-Scale Applications. At the building scale, net zero can be achieved in different ways based on building size and occupancy. Reducing primary water use for irrigation is a first step toward net zero but is not sufficient in itself. Irrigation reduction can be achieved through conservation by promoting landscapes that rely on natural precipitation and

Table 1. Net Zero Strategy Examples across Scales

conservation	passive systems	active systems
	Building-Scale Examples	
Bullitt Center, Seattle, WA, 2013, https://bullittcenter.org. Socio-technical innovations: water saving devices of composting toilets used throughout the urban six-story building	Phipps Center for Sustainable Landscapes, Pittsburgh, PA, 2015, https://living-future.org/lbc/case-studies/phipps-center-for-sustainable-landscapes/. Socio-technical innovations: sanitary water treated through biological systems via a constructed wetland	Brock Environmental Center, Virginia Beach, VA, 2015, https://living-future.org/lbc/case-studies/the-chesapeake-bay-brock-environmental-center/. Socio-technical innovations: rainwater is collected from roofs, treated on site, and used to meet all potable water needs
	District-Scale Examples	
The SW Ecodistrict, Washington, DC, 2013, https://www.ncpc.gov/plans/swecodistrict/. Socio-technical innovations: low-flow and low-flush fixtures used throughout the district to contribute to a total 70% water reduction	Fort Riley, Kansas, 2019, www.epa.gov/water-research/net-zero-projects. Socio-technical innovations: green infrastructure for reduced sewer impact and increased ecosystem services from vegetation irrigation	Emory University Water Hub, Atlanta, GA, 2015, www.campserv.emory.edu/fm/energy_utilities/water-hub/. Socio-technical innovations: district sewer mining, hybrid mechanical−natural treatment, and reuse in central plant and toilet flushing
	City-Scale Examples	
new building project offsets based on water equivalency units, Morro Bay, CA 2014, www.allianceforwaterefficiency.org;. Socio-technical innovation: building projects that increase water usage must offset a water equivalency at a 2:1 ratio. City staff assists developers in locating retrofit opportunities that prioritize low-income households	Green Stormwater Infrastructure Fee, Tucson Water, Tucson, AZ, 2020, www.tucsonaz.gov/gsi. Socio-technical innovations: customers pay a monthly fee with their water bill to support the implementation of green stormwater infrastructure projects throughout the city	direct potable reuse, Big Springs, TX, 2013, www.twdb.texas.gov/publications/shells/WaterReuse.pdf. Socio-technical innovations: 2 million gallons per day of direct potable reuse water safely provided to customers
Home Plumbing Assistance Program, Portland Water District, Portland, ME, 2016, www.pwd.org/sites/default/files/conservation_program_bill_stuffe.pdf. Socio-technical innovations: repairs, replaces, and installs low-flow fixtures and water-saving devices	Stormwater Retention Credit Trading Program, Washington, DC, 2014, https://doee.dc.gov/src. Socio-technical innovations: projects can generate credits from reducing stormwater runoff and sell and/or trade through a municipal price-lock program	Rainwater Harvesting Low Income Grant/Loan Program, Tucson Water, Tucson, AZ, 2019, www.tucsonaz.gov/water/rainwater-harvesting-grant-loan-program. Socio-technical innovations: grants of up to $400 and loans of up to $2000 for low-income households for rainwater harvesting implementation

sensors to avoid overconsumption of water. Large conservation gains inside the building can also be made through low-flow and low-flush fixtures, such as new composting toilet designs.[19]

On-site water harvesting such as rainwater or gray water treatment and reuse through passive and active systems is a next step toward net zero. A large fraction of water can be recycled for different uses with minimal treatment, which include toilet flushing, irrigation, and even evaporative cooling, further offsetting building energy use. A step further is the recycling of wastewater produced on site.[20] This approach can include urine recovery through separation and treatment at the source[21,22] and processes for converting carbon and nitrogen into energy.[23,24] Wastewater can be treated to different levels to tailor water quality to the proposed end use ranging from nonpotable to potable water reuse quality. While membrane technologies offer a robust treatment platform,[25] additional technological challenges, including the need for sensors that monitor water quality and smart control systems for autonomous water treatment at the building scale,[26] need to be resolved and/or addressed to minimize public health risks. Specifically, as real-time sensing and quantification of contaminants of emerging concern and pathogens in distributed systems are limited, in the interim we must rely on robust real-time sensors for surrogate water quality parameters and data-driven platforms for early detection of system failure and water impairment. This will lead to autonomous systems that can self-correct and forecast process performance in distributed, fit-for-purpose water systems supported by consumer confidence.

Overall, NZUW building application systems must balance a diverse set of variables that incorporate quality of life and open space utilization (e.g., natural vs mechanical treatment) to achieve acceptance. Additionally, the impact of NZUW solutions within the built environment must consider the impact on adjacent and intersecting systems, which can also play a role in energy management or flood mitigation. Building water regulation is also historically conservative due to associated public health risks (e.g., avoidance of toilet flushing with reclaimed water due to fear of cross connections). In addition, codes regulating built water systems are often uncoordinated and inhibitory.[27] Thus, coordination is required across federal, state, and local jurisdictions of building, plumbing, public health, and environmental health codes. To this end, many technological advancements are challenged to responsibly manage system byproducts within a net zero bounded approach (e.g., brine from desalination or leachate from compost toilets).

Dozens of net zero water buildings have been certified through the Living Building Challenge (Table 1). These solutions share the common systems of rainwater collection for potable purposes, water reuse, and onsite wastewater treatment or composting toilets.

3.2. District-Scale Applications. Net zero targets can be achieved with additional efficiency at a district or neighborhood scale, a neighborhood being a demarcated area with multiple buildings and associated landscape. The advantages of a net zero district model arise from the diversity of buildings and land use types and the reciprocal supply−demand efficiencies created by this diversity. With multiple buildings, more varied physical characteristics can provide expanded opportunities for water supply. For example, rainwater from a warehouse with a large roof for catchment, but minimal water demand, can be used to meet other district building demands. Efficiencies in large-scale storage could include a parking structure designed with a cistern sized for district-scale stormwater or rainwater storage (and treatment) at a lower construction and operation cost than many individual storage units. Streets and impervious surfaces represent a key source of runoff to be leveraged and connected for irrigation of landscape to realize ecosystem services for the district (e.g., street trees for shade, heat island reduction, and water quality improvement). These benefits can be scalable and targeted for expanded equity within a specified area. Diverse occupancy profiles can also provide unique reciprocities for supply and demand, temporally, spatially, and by water quality. For example, a large apartment building may generate a significant quantity of gray water from showers and distribute that water, following appropriate treatment, for irrigation within a larger area (e.g., urban agriculture). Hybrid mechanical and natural treatment approaches may also be easier to design at a district scale due to a diverse water input and increased land area (e.g., reciprocating wetlands, "living machines", and sewer mining for direct potable reuse). A district-scale net zero system can also efficiently and cost effectively address centralized water system oversubscription by reducing loads. District-scale water reuse can reduce both potable water and wastewater conveyance and treatment requirements, while green infrastructure can reduce impacts on stormwater systems, including combined sewer systems. The size of such a system can be phased to provide needed water system capacity in a just-in-time fashion for new builds, greatly facilitating community growth.

District-scale regulation and permitting can be more difficult to negotiate compared to a single owner, building, or land use type as liability for water use and reuse must be negotiated. A potable reuse system may need to comply as a public water supply due to its size. Strict regulation from local, state, and federal codes creates multilayer and multisector regulatory compliance pathways for public water suppliers.[27] District boundaries may or may not be a self-contained watershed and require careful accounting for upstream and downstream impacts within and outside the demarcated boundary. Table 1 describes some representative district-scale systems.

3.3. City- and Regional-Scale Applications. City-scale net zero technologies can include conservation through efficient and optimal water delivery systems;[28] passive systems like green infrastructure;[29−31] active systems like centralized and distributed wastewater treatment;[32−34] and indirect and direct potable reuse.[35] Nonstructural alternatives may also become more viable at this scale, including demand reduction incentives, in particular for consumptive uses (e.g., high-efficiency appliances and grass removal).[36] Table 1 provides examples of city- and regional-scale strategies.

Achieving net zero at the city scale is complicated by several factors: variable consumption, increases in impervious land cover with associated flooding, locations of infrastructure retrofit, land constraint of large water storage infrastructure, and identifying high-quality alternative potable water sources. As the urban environment expands with more impervious surfaces, the relationships between urban growth and natural water systems can be complex. Impervious areas result in more runoff, increasing the likelihood of floods in urban streams, resulting in higher risks of flooding and channel incision and reduced riparian habitat.[37] Urban centers are difficult to retrofit for storm detention. Alternative low-impact design or green infrastructure can utilize the limited open spaces to reduce

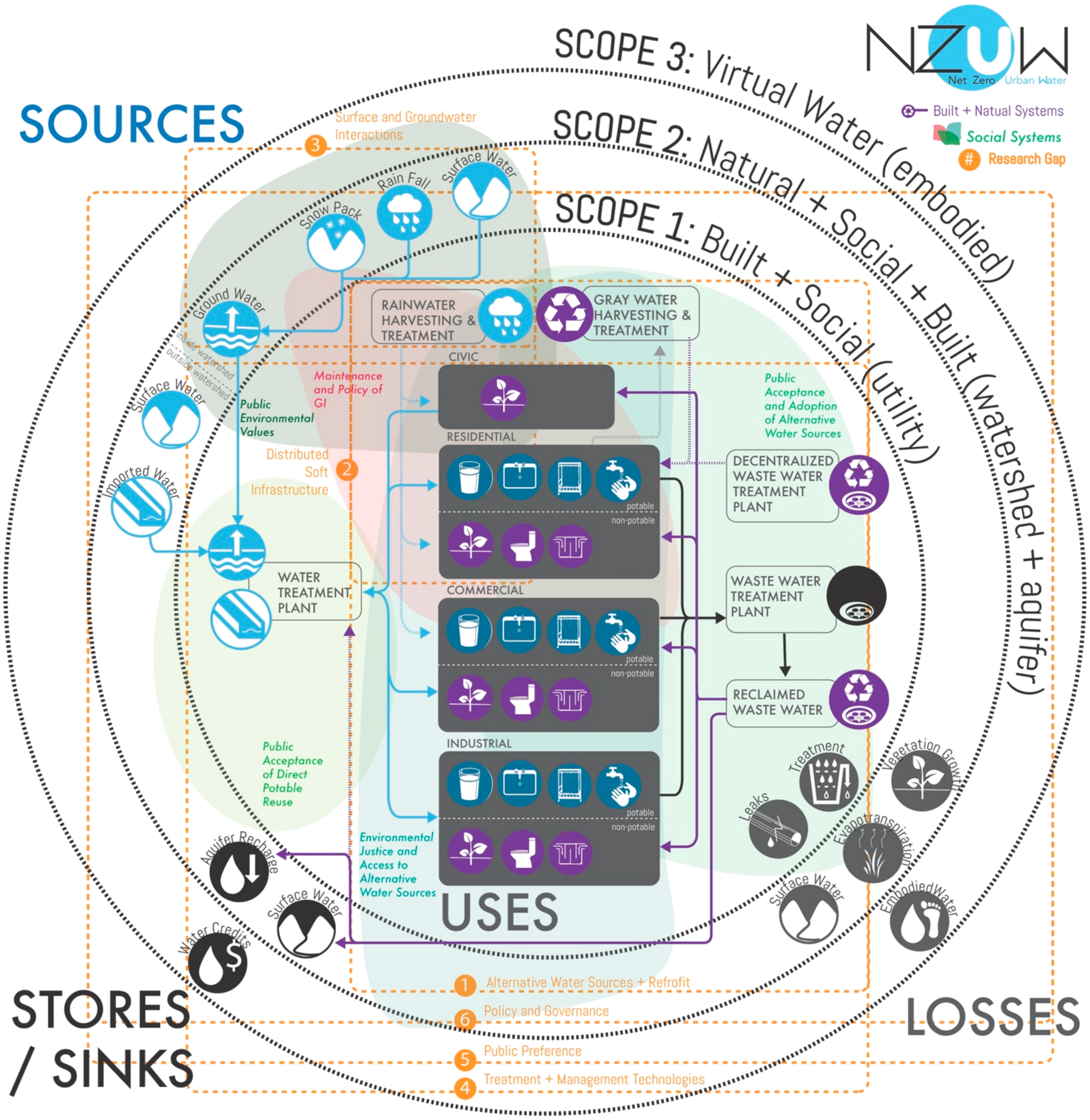

Figure 4. Examples of research gaps within the NZUW approach. They include (1) alternative water sources and retrofit, (2) distributed soft infrastructure, (3) surface and groundwater interactions, (4) treatment and management technologies, (5) public preference, and (6) policy and governance. NZUW logo by Courtney Crosson (2020).

urban flood hazards, water quality issues, and water resource challenges.[38]

Regional wastewater treatment either centralized or decentralized is intimately linked with the distribution of reclaimed water. Treatment facility locations must account for the cost of distributing its effluent. Providing reclaimed water for individual residences can be costly, and many utilities limit reuse to large turf areas such as golf courses and schools. Groundwater storage of treated water through basin infiltration or injection can overcome the temporal supply−demand imbalance under the proper aquifer conditions.

The challenge of developing a high-quality potable source within a net zero urban area remains. Indirect potable reuse is implicitly implemented by many communities that remove water from rivers or aquifers after it has been used by upstream utilities for potable purposes and returned to the environment after treatment. Direct potable reuse with an engineered barrier under strict monitoring may improve on the removal of a natural system of a range of chemical and biological contaminants. Utilities are urging regulations to allow direct potable reuse.[39] A major challenge is integrating planning to identify combinations of the alternatives described above that include demand management that achieve water sustainability and are robust and resilient against the acute and chronic disruptions that the systems will face.

4. RESEARCH GAPS: TOWARD A COMPREHENSIVE QUANTITATIVE FRAMEWORK

Decision support through an NZUW quantitative framework is needed to address drivers of change across natural, built, and social systems. Research gaps exist across this comprehensive NZUW approach. Building upon our multidisciplinary collaboration, several current, prominent research gaps have been identified to illustrate the potential for the NZUW approach to expand in breadth and depth. As research gaps are filled and more refined data sets become available, NZUW numerical tools will improve in accuracy for communities. The six research gaps identified in this section are grouped as follows: (1) alternative water sources and retrofit, (2) distributed soft infrastructure, (3) surface water and groundwater interactions, (4) treatment and management technologies, (5) public preference, and (6) policy and governance (Figure 4).

4.1. Alternative Water Sources and Retrofit. Alternative water sources are an essential piece to an NZUW strategy; however, questions about integrating these supplies across existing centralized systems and the impact of a diverse portfolio of urban water sources on water quality and delivery persist. The traditional, centralized urban water delivery and management approach is likely unsuitable for the effective incorporation of the alternative water sources needed to address the current, heterogeneous challenges of climate change, population and economic growth (or decline), and failing infrastructure.[40−45] Existing centralized systems will require an additional distribution pipe network to deliver reclaimed water and likely incur high energy costs to convey centrally treated waters back to the end user. Decentralized treatment, on the contrary, provides more flexibility and is expected to be part of an integrated solution. Collecting spatially varying and temporally intermittent stormwater may also be more efficiently collected, treated, and utilized locally rather than centrally.

The appropriate spatial decentralization scale (e.g., building, district, regional, and system-wide) to collect, treat, and utilize these alternative sources to replace and/or supplement potable water, however, remains an unanswered question. The development of alternative water sources, storage, and distribution systems presents the obvious trade-offs associated with infrastructure costs. Less obvious trade-offs include positive benefits associated with reduced transportation costs and more targeted treatment for the expected water quality need and negative impacts on potable water quality resulting from increased residence times and reduced solid transport in existing sanitary systems. To adequately understand the trade-offs and design new integrated systems, the overall impacts on water quantity, water quality, and energy require holistic modeling strategies.

4.2. Distributed Soft Infrastructure Systems. Green infrastructure, or using vegetated spaces to capture and manage stormwater, has been adopted by municipalities and communities in the past several decades as a way to reduce the impacts of flooding, comply with water quality regulations, and increase ecosystem services to an area.[46] Several research gaps that would inform the inputs into an NZUW quantitative framework currently exist. First, there are challenges associated with the design, planning, implementation, and maintenance of green infrastructure systems over the long term, which include the development of place-based design standards, regulatory frameworks and policies, continuous funding, socioeconomic disparities, and the adoption of innovation.[47] Many green infrastructure installations are not properly maintained,[48] and their actual performance, particularly in the long term, is unknown.[30,49] In addition, green infrastructure interventions have variable upstream and downstream impacts on water quantity and quality in an urban area, depending on the rain event and design of the intervention. Quantifying the distributed impact of green infrastructure on aquifer recharge is an area that would benefit from more extensive modeling and tailoring to specific locations and soil conditions. Similarly, quantifying the social benefits of green infrastructure systems (aesthetics, stress relief, heat reduction, and resilience) is challenging. Assessment of green infrastructure for urban resilience, in general, needs a multidimensional approach that includes aspects related to policy, performance, connectivity, and social, all of which involve stakeholder participation and community engagement.[50]

4.3. Surface and Groundwater Interactions. Quantifying recharge to groundwater systems is difficult because it cannot be directly measured. However, it is clear that alterations to the land surface and water courses should affect groundwater recharge. Past studies have shown that impervious surfaces increase stream base flows in humid settings,[51] implying a decrease in recharge with traditional urbanization. Studies have also shown increases in groundwater recharge through leaks in urban distribution and wastewater systems.[52,53] Green infrastructure (e.g., permeable pavement and rainwater-harvesting gardens) has promise for increasing infiltration in urban development. However, quantitatively measuring the impact of both urbanization and green infrastructure practices on groundwater recharge is still challenging because of the large variety and spatial distribution of green infrastructures and permeable pavement systems.[54,55]

Research is needed to quantify the effect on recharge from both existing urban infrastructure (e.g., roads, parking lots, and buildings) and the effect of changes to the urban form through green infrastructure and low-impact development. Infiltration and recharge estimates of green infrastructure implementations require abundant observations to understand both surface conditions, such as periods of inundation, soil properties permitting infiltration, and deeper subsurface soil structures to understand deep percolation. These studies will have to be implemented alongside advanced computer simulation of integrated surface and subsurface flow systems that enable the understanding of how urban infrastructure has altered urban runoff and how to use green infrastructure to increase groundwater recharge in cities.

4.4. Treatment and Management Technologies. In the past few decades, advanced treatment and membrane systems have been adopted by small communities and decentralized systems when physical space is limited and advanced water reuse is being considered.[56,57] These advanced treatment systems, designed to reclaim and reuse water, are increasingly available and have been deployed for district irrigation (e.g., Tucson, AZ), aquifer recharge (e.g., Aurora, CO), saltwater intrusion barrier (e.g., Orange County, CA), and direct potable water reuse (e.g., Wichita Falls, TX and Windhoek, Namibia). In all of these projects, wastewater is centrally collected and treated, first by a conventional wastewater treatment facility and then by an advanced treatment system. Often, the effluent from these systems is blended with other water sources before being distributed or utilized for aquifer recharge. Additional

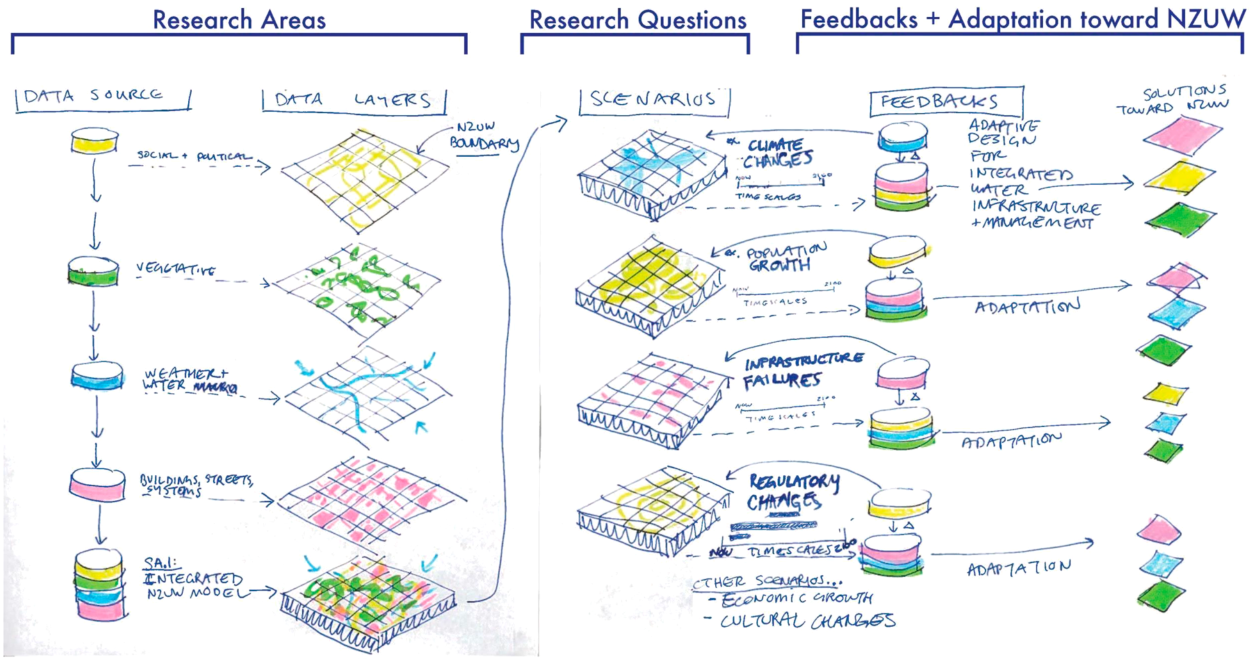

Figure 5. NZUW provides a quantitative framework for assessing trade-offs and implementing adaptations to the urban water system.

innovations to promote solid, nutrient, and brine management and recycling and for monitoring and attenuation of contaminants of emerging concern will be necessary to sustain the long-term success of these water reclamation and reuse processes.[58−61]

Water treatment and management technologies capable of monitoring and controlling decentralized water/wastewater treatment systems in real time are also emerging, and further research is needed to understand implications for NZUW. Examples of real-time modeling and control at the systemwide scale include stormwater[62] and potable water system modeling and control.[26,63,64] These systems will continue to require robust real-time sensors for water quality monitoring to provide feedback to the treatment process and enable process fault detection, system self-correction, and performance forecasting, but most importantly to enhance consumer confidence in reclaimed and reuse water.

4.5. Public Preference. The public is essential for NZUW transitions, including elements that are at the core of reducing consumption, even though in the short term such goals may run counter to public habits. Changing habits can be a long-term endeavor:[65,66] once public trust is lost, it can be extremely difficult to regain. However, years of drought in places like California have made residents more water conscious and potentially much more receptive to NZUW. Multiple approaches have been shown to induce customers to reduce water consumption, including public participation in visioning and planning initiatives;[36] engagement with nongovernmental organizations and citizen movements; consumers' understanding of water shortages and the experience of drought;[41] rebates and incentives for low water use; sourcing and showcasing innovations at consumer, building, and service area levels; and flexible or innovative pricing structures (e.g., charging for indoor and outdoor water use differently or mechanisms other than volumetric pricing).

Principles that enhance public support for NZUW and associated urban water management practices include transparency, inclusion, willingness to modify plans and strategies, and accountability for both utilities and consumers.[67] Utilities can further enlist low-income customers by providing customer assistance programs that offer assistance to upgrade plumbing and fixtures to conserve water. Municipalities can also work with architects and city planners to promote buildings and development practices that meet NZUW standards.

Key research gaps in the area of public preference include moving beyond individual choice based on rational-actor assumptions that lead to price elasticity explanations of water demand; assessment of collective action and environmental stewardship approaches to water conservation and, potentially, to water reclamation and reuse; the role and influence of local, state, and federal financing for urban water transitions leading toward NZUW; and application of innovation−adoption−diffusion understandings to water conservation and reuse at individual household, community, and utility scales.

4.6. Policy and Governance. The policy and governance aspect of the NZUW quantitative framework may be the most difficult to address. This is because society's inability to move toward more sustainable urban water practices is based on socio-institutional rather than technical barriers.[68] Overcoming these barriers will require ongoing assessment and coordination and long-range planning that critically assess the current conditions of water management at multiple administrative levels.

This level of coordination may require the elimination of silos where the provision of water services is highly fragmented to reduce coordination costs. It will require transparency about changes, cultural reform initiatives, and capacity building being critical for achieving successful water management transitions.[7] Planning efforts should also avoid changes that foster inequities and enhance vulnerabilities unintentionally.[69] Here community engagement is key because it has been identified as a key element for an equitable policy design and implementation.[70]

To move toward NZUW quantitative frameworks, information about best practices and successful policies is needed[44,71] so that people across administrative units can see how successful practices and policies were implemented and the problems encountered along the way. For example, economic instruments, such as the use of water pricing (tariffs) according to the type of water consumed (drinking water, reclaimed water for irrigation, etc.), may encourage water conservation and water reuse and can be easily evaluated for their effectiveness in reducing demand for potable water. Pairing long-term planning with information from ongoing assessments over time and case studies can provide all parties involved with a sense of where water provision is now and can be in the future.

4.7. Addressing Research Gaps: Toward an Integrated Model. The previous sections outline a set of research activities that generally address knowledge gaps in specific areas of the overall NZUW approach. The overarching complexity of the problem is illustrated in Figure 5, which includes the systems, drivers of change, and feedbacks that must be simultaneously considered to achieve the NZUW objective. The figure highlights a critical need for a framework capable of representing both individual system and intersystem dynamics to provide the foundation for systemwide decision making. The resulting framework must not only account for water quantity and quality but also address other important attributes such as energy utilization, economic impacts, societal acceptance, and stakeholder equity. The systemwide framework represents the potential responses to acute shocks and chronic stressors, as well as the associated uncertainties, over a forecast time horizon. Using this information, the trade-offs across the built, natural, and social systems can be evaluated for decision support. Example outcomes may include physical infrastructure retrofit, policy or governance changes, or interagency agreements for overall water management oversight. The resulting framework is an adaptive and responsive system that incorporates new information, updates data associated with drivers of change, and reassesses decisions over time. Overall, the resulting framework is an essential tool for making comprehensive decisions across multiple systems with various stakeholders to move our water systems toward NZUW.

5. CONCLUSION: TOWARD AN NZUW FUTURE

The objective of the NZUW approach is to allow the transition of a defined community toward meeting its water needs without detriment to interconnected systems and future water availability. Multiscale and multidimensional decision support is needed to adapt the built environment toward an NZUW future, in view of natural and social system dynamics and constraints. NZUW is a place-based, comprehensive, quantitative framework to guide the development of resilient water systems that can respond to acute shocks and chronic stressors over time. Following the conceptual models of net zero energy and carbon systems, the purpose here was to define and examine the viability and value of pursuing an NZUW approach.

NZUW has similarities with integrated urban water management,[72] water sensitive urban design, and One Water concepts.[73] Similar to these existing concepts, NZUW is driven by the need for holistic integration of social, natural, and built systems on multiple temporal and spatial scales. NZUW must provide adaptability to acute shocks and chronic stressors and should lead the way to net positive water resources. The key differentiation between NZUW and these previous integrated urban water concepts is its overarching goals. While integrated urban water management emphasizes cost-effective infrastructure planning,[74] NZUW expands the goal of achieving self-sufficiency. NZUW goes beyond One Water by providing a quantitative framework to assess the trade-offs between multiple adaptation options.

Net zero water technologies have been demonstrated at the building scale, and incentives have been adopted by several districts and cities. Implementation barriers exist at all scales and require a shift in policies, governance and management structures, and technological improvements for comprehensive adaption to the urban water system. A set of research gaps have been identified that, if addressed, will accelerate and improve NZUW quantitative frameworks. The shift to an NZUW future ultimately depends on community consensus to change its relationship with water and the natural ceiling of place-based water supply.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsestwater.0c00180.

Differences among the conceptual approaches of One Water, integrated urban water management, and NZUW (Table S1) (PDF)

AUTHOR INFORMATION

Corresponding Author

Courtney Crosson − *College of Architecture, Planning, and Landscape Architecture, University of Arizona, Tucson, Arizona 85721, United States;* orcid.org/0000-0003-1757-8741; Email: ccrosson@arizona.edu

Authors

Andrea Achilli − *Department of Chemical and Environmental Engineering and Water & Energy Sustainable Technology Center, University of Arizona, Tucson, Arizona 85721, United States;* orcid.org/0000-0002-4345-8420

Adriana A. Zuniga-Teran − *College of Architecture, Planning, and Landscape Architecture and Udall Center for Studies in Public Policy, University of Arizona, Tucson, Arizona 85721, United States*

Elizabeth A. Mack − *Department of Geography, Environment, and Spatial Sciences, Michigan State University, East Lansing, Michigan 48824, United States*

Tamee Albrecht − *School of Geography, Development, and Environment, University of Arizona, Tucson, Arizona 85721, United States*

Padmendra Shrestha − *School of Geography, Development, and Environment, University of Arizona, Tucson, Arizona 85721, United States*

Dominic L. Boccelli − *Department of Civil and Architectural Engineering and Mechanics, University of Arizona, Tucson, Arizona 85721, United States*

Tzahi Y. Cath − *Department of Civil and Environmental Engineering, Colorado School of Mines, Golden, Colorado 80401, United States*

Glen T. Daigger − *Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, Michigan 48109, United States*

Jennifer Duan − *Department of Civil and Architectural Engineering and Mechanics, University of Arizona, Tucson, Arizona 85721, United States*

Kevin E. Lansey − *Department of Civil and Architectural Engineering and Mechanics, University of Arizona, Tucson, Arizona 85721, United States*
Thomas Meixner − *Department of Hydrology and Atmospheric Sciences, University of Arizona, Tucson, Arizona 85721, United States*
Stephanie Pincetl − *Institute of the Environment and Sustainability, University of California, Los Angeles, Los Angeles, California 90024, United States*
Christopher A. Scott − *Udall Center for Studies in Public Policy and School of Geography, Development, and Environment, University of Arizona, Tucson, Arizona 85721, United States*

Complete contact information is available at:
https://pubs.acs.org/10.1021/acsestwater.0c00180

Notes

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