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Assessing the Sustainability of Urban Water Supply Systems

THE PERPETUAL NEED FOR SAFE WATER PRESENTS COMMUNITIES AND UTILITIES WITH 21ST-CENTURY CHALLENGES; A RECENTLY DEVELOPED SERIES OF INDICATORS CAN HELP IN ESTABLISHING AND MONITORING WATER SUSTAINABILITY EFFORTS.

Public water providers face many challenges in meeting the needs and expectations of the communities they serve. Providing an adequate supply of safe water remains a preeminent goal of all urban water providers, of course, but the nature of the challenges inherent in continuously meeting that goal have changed dramatically since the first public water supply systems were developed thousands of years ago. As public concerns over water continue to evolve in the 21st century, so too do perspectives on what "sustainability" might mean for urban water supply systems.

Some of the earliest water supply systems date back to the period when human societies began shifting from hunting and gathering food and water to living in sedentary, agrarian communities. With this transition came a fundamental shift in our vulnerability to the vagaries of weather and water availability: instead of traversing the landscape to find water, we became largely dependent on water coming to us. Not surprisingly, the earliest population centers and ancient water supply systems developed where abundant and reliable water supplies could be extracted from adjacent rivers, lakes, and springs. Long before the concept of sustainability was formulated, communities understood that they could only be sustained as long as their water uses remained within the limits of local water supplies.

THE DRIVE FOR SUSTAINABILITY

The ability to store large volumes of water in reservoirs—thereby buffering fluctuations in river flows across dry months or years—greatly increased the volume of water available for human use and expanded the realm of water sustainability for many communities. Similarly, when rivers in many parts of the world became fully allocated and aquifers became depleted, continued growth in urban and agricultural demands were increasingly met by importing water from distant sources; today, more than 40% of the water consumed in major cities comes from water importation schemes (McDonald et al. 2014). In recent decades, new technologies and infrastructure have further increased the water supply for cities, such as through recycling wastewater, ocean water desalination, or harvesting rainwater and stormwater.

Bolstering water supplies and staying ahead of growing urban water demands has been, and will continue to be, a key aspect of the sustainability of water supply systems. But now the needs and expectations of urban residents are forcing water providers to consider much more than simply providing sufficient volumes of safe water. For instance, customers are demanding that water be provided at a cost that is affordable to all; that water users be strongly encouraged to use water in the most conservative manner possible; that the waste of water due to leaking pipes be eliminated; that carbon emissions of the energy used to move and clean water be reduced; that the volume of water extracted from freshwater ecosystems that imperils aquatic species be reduced; and that water suppliers give due consideration to the likelihood of reduced water supply as the climate changes. These concerns shape customer opinions as to whether their water managers are performing in a sustainable manner as measured by 21st-century standards, and these best practices also influence the attractiveness of a city to new residents and businesses.

DESIGN OF SUSTAINABILITY INDICATORS

Our research group at the University of Virginia has developed a suite of sustainability indicators that address many of these considerations, with the hope that the proposed indicators can help guide urban water providers toward the highest standards of sustainability, and help citizen activists in their advocacy for well-managed, safe, and affordable water systems.

Focusing on the sustainability of water supply systems, this article provides an indicator framework that can be used as a self-evaluation tool for cities and citizens to use in developing public inquiries on water-supply issues. This suite of sustainability indicators is summarized as a simplified scorecard in Table 1.

TABLE 1 Indicator scorecard

Indicator	Fully Meets	Partially Meets	Does Not Meet
Water governance			
Well-functioning governance system			
Strategic planning			
Enforcement of governance			
Budgeting and pricing			
Drought and other emergency preparedness			
Planning and preparedness			
Water reserves			
Water monitoring			
Data collection			
Progress tracking			
Water affordability and social justice			
Affordability			
Access			
Social justice			
Water-use efficiency and conservation			
Water conservation plans			
Conservation incentives			
Per capita water use			
Leak detection and repair			
Water quality			
Safe quality			
Transparency and reporting			
Watershed protection			
Watershed protection plan			
Watershed protection and restoration actions			

Short explanations of the purpose and rationale for each indicator follow, along with illustrative examples from applying these indicators to selected cities across the United States.

Water governance. The role of water governance is to establish, maintain, and enforce a system for reliable water provision with public accountability, equity, and participation, and to do so in a manner that is sustainable and affordable for all water users. A properly functioning governance system will help ensure that the utility delivers water in the most affordable and environmentally sound manner, including giving preference to water supply options that minimize energy requirements; fully capitalizes on demand management options and thereby minimizes the need to extract additional water from freshwater ecosystems; and prices water in a way that fully covers all maintenance and operational functions and discourages water waste.

Good water governance also helps centralize and coordinate a community's water management decisions, thereby minimizing confusion or conflicting interests surrounding water use. By establishing clear goals and decision-making authority—informed by meaningful stakeholder input—governing unit(s) can make decisions that improve water use efficiency and sustainability over the long term. The preparation, regular updating, and tracking of progress of a strategic water supply plan is essential to sustainable water management.

As public concerns over water continue to evolve in the 21st century, so do perspectives on what "sustainability" might mean for urban water supply systems.

Drought preparedness and other emergency response capabilities. Abrupt changes in water availability threaten a utility's ability to provide adequate water supplies, and a lack of drought or disaster preparation could potentially lead to a severe water shortage with attendant human health and ecosystem impairment. Planning and preparedness are important in case of water contamination from pollutants, natural disasters, or other changes in water availability.

The public needs to be informed about associated risks and understand what may be required should a disruption in supply occur. A primary line of defense for preventing water shortages during droughts is the ability of a community to swiftly implement a drought management plan, which depends on the existence of a plan that includes actions that can be readily and effectively implemented. Effective responses to supply disruptions caused by contamination events usually depend on an ability to switch to alternative sources; if other water supplies are not adequate, the ability to lower demands quickly will be very important.

This indicator focuses on a community's readiness and capabilities for implementing such responses. There exists a strong interconnection between drought and disaster responses and the overall strategic plan for a water utility, as discussed in the water governance indicator; a strategic plan should explicitly account for immediate disasters and longer-term shortfalls and, to the extent feasible, ensure that sufficient water resources are available to minimize hardship during disruptions in supply.

Water monitoring. Monitoring water availability, use, and quality is essential in efforts to manage water supplies and demands and to protect human health. Data on water quality and quantity can inform plans for infrastructure renewal or replacement, alert utility managers to the need for drought or emergency responses, enable assessments of the ecological health of freshwater ecosystems, and support enforcement of rules and regulations. Monitoring water quality and use can also reveal which customer groups are using the most water or contributing the most pollution, which can aid water conservation or remediation initiatives.

Water affordability and social justice. A water utility must be committed to upholding and supporting the basic human right to water, and social justice must be honored in all aspects of water management. Access to water should be nondiscriminatory and affordable for all. Carefully tailored rate structures—in some instances supported by governmental subsidies—can enable a utility to generate sufficient revenue to properly operate and maintain its water treatment and delivery system, yet at the same time provide water for essential human needs at an affordable cost. During times of overall water shortage, access to water should be fairly distributed without prejudice or preference for certain members or subsectors of a community. Another key social justice concern is the siting of water infrastructure, particularly facilities such as water treatment plants that may generate foul odors or attract undesirable pests such as mosquitoes. The placement and operation of such facilities must be conducted in a manner that does not disadvantage poorer neighborhoods.

Water use efficiency and conservation. Communities can minimize their water needs by fostering water use efficiency in homes, businesses, industries, and outdoor irrigation, and by encouraging adoption of water conservation practices in all sectors through education and incentives. Demand management can reduce the volume of water that must be extracted from freshwater ecosystems and potentially avert or delay the need for expensive new infrastructure such as water treatment plants or storage reservoirs.

A community's vulnerability to disruptions in water supply during droughts is also commensurate with the volume of its water demands, so aggressive demand management can lower a city's risk of water shortages. Many communities depend on water sources such as river basins that are also used for non-urban purposes, such as for irrigated agriculture outside city limits. Opportunities may exist for utilities to work in partnership with non-urban water users to implement water efficiency and conservation strategies and thereby reduce the risk of water shortages or to free up water that can be traded or shared with the city. This approach can better enable communities to balance their water demands with available supplies cost-effectively.

Water quality. Water provided for human consumption must be free of contaminants, and return flow to the environment after use must be clean enough to avoid environmental degradation or problems for other water users located downstream. Not only does water pollution affect the vitality of ecosystems, it can also reduce the effectiveness of ecosystem services.

Watershed protection. Efforts to protect source watersheds or aquifers and implement green infrastructure can be significantly cost-effective and promote the quality and health of the surrounding ecosystem. Watershed protection is important in providing a clean and reliable water source. For instance, stormwater runoff is filtered by healthy watersheds, reducing the introduction of pollutants such as sediment, nutrients, and heavy metals into surface waters, especially in urban areas. Watershed protection also provides sufficient clean water to sustain healthy natural ecosystems upstream and downstream. Healthy ecosystems provide ecosystem services to humans and habitat for other species that degraded ecosystems cannot.

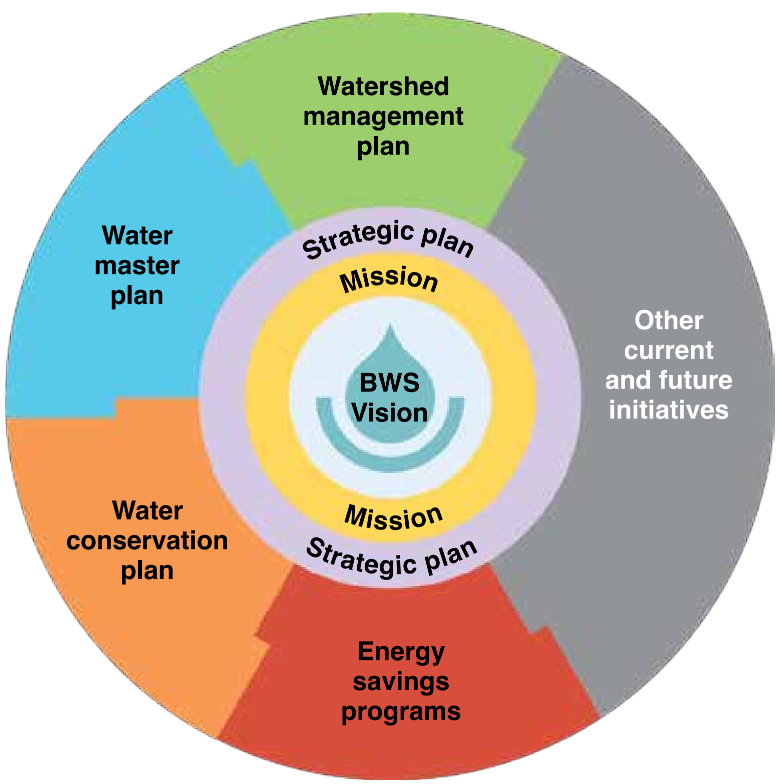
SUSTAINABILITY INDICATORS IN USE

Several medium- to large-sized US cities were randomly selected for pilot applications of the sustainability indicators. These pilot evaluations revealed challenges in acquiring the data or other information necessary in evaluating communities based on these indicators. The following sections provide overviews of these evaluations that illustrate how each indicator is intended to be used.

Water governance in Honolulu, Hawaii. Evaluation of this complex indicator focuses on four components: a well-functioning governance system, strategic planning, enforcement of rules or codes, and budgeting and pricing. The Honolulu Board of Water Supply (BWS) supplies water to both the city and county of Honolulu and the almost one million residents on the island of O'ahu. Water sustainability is especially critical for island cities such as Honolulu, as their water supply options are limited and highly vulnerable to the vagaries of climate.

Honolulu has risen to these challenges by preparing a comprehensive Water Master Plan (Honolulu BWS 2016) and a strategic plan (Honolulu BWS 2017), as well as eight regional watershed management plans

FIGURE 1 Honolulu Board of Water Supply's water governance model



BWS—Board of Water Supply

The plans and programs that make up the Honolulu Board of Water Supply's water governance model are tightly integrated around its strategic plan, mission, and vision (Honolulu BWS 2016).

providing greater detail for each land use district on the island (Figure 1). The Water Master Plan provides a comprehensive understanding of O'ahu's water supplies and needs as well as the water storage and distribution system, giving BWS a road map to meet future needs, establish priorities, and adopt sustainable financing strategies. In addition to a seven-member board appointed by the Honolulu mayor, development of the Water Master Plan included formation and active engagement of a Stakeholder Advisory Group composed of 28 residents and community leaders with expertise in many disciplines.

The Water Master Plan and interrelated watershed management plans give central importance to protecting source watersheds, sustaining proper environmental flows throughout the island's stream network, accounting for future climate change, and prioritized use of the most reliable, affordable water supply options. By maintaining healthy watersheds, the utility ensures adequate groundwater recharge and protection for the island's aquifers, which are the sole source of supply for urban uses. Agricultural irrigation and industrial water uses are served with recycled and brackish nonpotable water supplies, thereby avoiding competition with urban needs. Demand management is also central to the utility's mission to "provide a safe, dependable, and affordable water supply now and into the future" (Honolulu BWS 2016).

Drought preparedness in Charlottesville, Va. This indicator focuses on two components: planning and preparedness as well as the availability of emergency water reserves. An initial assessment of this indicator focused on drought-induced challenges rather than on water contamination emergencies because, as a result of security concerns, many communities are unwilling to share information on their emergency response plans.

Although it annually receives 48 in. of rain on average, Charlottesville experienced a drought of record in 2002 that fundamentally changed the city's perspective on potential water shortages. As water levels in the city's reservoirs plummeted during the drought, the water utility imposed mandatory conservation requirements that angered the local business community, including requiring an immediate 25% reduction in water use. As a result, even the best restaurants in the city were forced to serve meals on paper plates to avoid running dishwashers, and some restaurants installed portable toilets outside as they closed their bathrooms. Many citizens also became alarmed when all release of water from storage reservoirs was curtailed, causing some reaches of the rivers downstream to nearly dry up, with adverse impacts on aquatic life.

In response, in 2004 the community created the Rivanna Regional Drought Response Committee, tasked with formulating a drought response and contingency plan (RWSA 2015) that defined an approach for predicting and identifying drought conditions, specifying drought stages, identifying appropriate use restrictions for each drought stage, and notifying citizens of necessary water use restrictions. The committee is composed of representatives from both the city and outlying rural areas, reflecting the full community served by this regional water provider. The drought plan was completed in 2008 and subsequently revised in 2015.

Typical of many urban drought response plans, Charlottesville's plan is based on drought stages that progress from watch to warning to emergency stages, each with different water conservation requirements. Of particular note, however, is the means by which these drought stages are determined, adopted, and communicated. Rivanna Water & Sewer Authority (RWSA) uses a probability-based hydrologic model to project the rate at which water storage levels are expected to drop on the basis of a historical record of river inflows and expectations of water demand reductions as new drought stages are declared. These model-based forecasts enable water managers to determine when it will become necessary to call on the public for increasingly restrictive water conservation measures.

For example, a drought warning is issued when there is a "10% or greater probability that total useable reservoir storage will be less than 60% of full within 10 weeks" (RWSA 2015). These drought stages and their associated water use restrictions are then communicated through a widespread media campaign. The model-informed drought response has been designed such that reservoir storage should not drop below 50% of useable capacity, even during another drought of record. In addition, the drought plan notes that two additional recreational reservoirs could be tapped in the case of extreme emergency.

Importantly, the use of probability-based modeling for drought forecasting has enabled regional water managers to reduce the number of false alarms calling for restrictive conservation measures. In turn, these models provide confidence for releasing water downstream for environmental purposes even when it is not raining.

Water monitoring in Denver, Colo. Evaluation of this indicator focuses on two components: data collection (for a variety of water quantity and quality parameters) and reporting on progress toward goals.

Metropolitan Denver's water comes from snowmelt-fed rivers flowing both east and west from the Rocky Mountains' Continental Divide. Denver Water—which serves 1.4 million customers (25% of Colorado's population)—collects daily readings at stream gauges and reservoirs throughout its system to track streamflow, diversions, snowpack, and other water supply data that it makes available on the utility's website (Denver Water 2017a). Denver Water also maintains a leak detection crew that surveys more than 11 mi of distribution pipe each year and a dam inspection team that evaluates the conditions of all of Denver Water's dams annually.

Denver Water also prepares regular Water Watch Reports that provide its Board of Water Commissioners updates on current conditions (Denver Water 2017b). These reports, prepared monthly during the winter and weekly during the summer, provide useful tabular and graphical summaries of water storage levels in each reservoir, day-by-day water usage, precipitation, snowpack water content, and inflows into reservoirs. The utility also participates in several local and regional environmental initiatives, many of which are designed to maintain or restore healthy environmental flow conditions and endangered species popula tions throughout its source watersheds (Denver Water 2017c).

In addition to keeping a close eye on the quantity of its supplies, in 2016 Denver Water collected more than 35,000 water quality samples from its raw (source) water, its water distribution system, and from lead and copper testing in more than 500 homes (Denver Water 2017b). Notably, Denver Water offers free lead testing for any homeowner requesting it.

This extensive and comprehensive data collection system has enabled Denver Water to gain deeper understanding of the variability within its water sources, and how the water it distributes is used among its customer classes. This knowledge informs the utility's regularly updated strategic plan, its nationally recognized water conservation program, and its infrastructure development plans.

Water affordability and social justice across the 16 cities sampled. Evaluation of this indicator focuses on three components: affordability, access, and social justice. The sample of US cities used in this study revealed that while it is common for some water and wastewater treatment facilities to be located in impoverished communities, no cases were found in which these facilities appeared to be exclusively or predominately located in disadvantaged neighborhoods. Detection of systematic bias in the locations of water infrastructure—particularly wastewater plants—would require a deeper investigation than this cursory review allowed. Therefore, assessment of this indicator focused mostly on affordability.

Long before the concept of sustainability was formulated, communities understood that they could only be sustained as long as their water uses remained within the limits of local water supplies.

In its review of the US Environmental Protection Agency's (USEPA's) mandates for affordability in water and wastewater provision, a consulting firm pointed out that USEPA's guideline of maintaining the cost of these services at less than 4.5% of the median household income (MHI) may not be appropriate, given that MHI "is a poor indicator of economic distress and bears little relationship to poverty or other measures of economic need within a community" (Stratus Consulting 2013). Instead, this report recommended examining the effect of rising water bills across the entire income distribution—and especially at the lower end—rather than simply at the median. In applying this approach, all 16 cities in our sample had at least 20% of their populations paying more than 4.5% of their household income for water and wastewater services, and for some cities, this level exceeded 40% of the population.

This is a serious issue, one that deserves heightened attention because many urban households may find their utility bills to be a financial burden. This finding suggests that the decision processes that communities use to prioritize their water supply options, the assistance provided to citizens to help them become more water-efficient, and the rate structures used to recover the costs of service must all be scrutinized and in many cases improved.

There are numerous examples of utilities attempting to address this problem. For example, San Francisco Public Utilities Commission (2017) offers a 15% discount on water and a 35% discount on sewer charges through its Community Assistance Program, and Seattle Public Utilities (2017a) offers a 50% discount through its Utility Discount Program for qualifying residential single-family customers. New York City's Department of Environmental Protection (2017) has offered an annual credit of $116 to qualifying homeowners through its Home Water Assistance Program, as well as deferment of debt payment through its Water Debt Assistance Program.

Water use efficiency and water conservation in Charlotte, N.C. Evaluation of this indicator focuses on four components: water conservation planning, conservation incentives, per capita water use rate, and leak detection and repair.

An example of an excellent water conservation plan is the one developed for Charlotte through its collaboration with a regional planning group called the Catawba-Wateree Water Management Group (CWWMG), which represents 18 water supply utilities. In 2014 this group prepared a comprehensive Water Supply Plan that includes a water use efficiency section

(CWWMG 2014). Measurable water conservation goals have been set for each water basin supplying water to the member utilities on the basis of an assessment of each water utility's conservation potential; these conservation goals are explicitly accounted for in the water budget (supply and demand) projections for each water basin through 2055.

Utilities can evaluate and track these indicators over time in an effort to improve service reliability, financial viability, customer satisfaction, and environmental health.

The Water Supply Plan outlines four initial strategies for reaching water-use efficiency goals, including a public information campaign, education and outreach, landscape water management and demonstration gardens, and commercial and institutional water and energy user surveys. Once these initial strategies have been deployed, the water utilities are encouraged to implement incentive programs for installing water- and energy-efficient fixtures as well as water audit and loss control programs.

The CWWMG estimates that the Charlotte-Mecklenburg Utility Department has reduced its total utility per capita water use (total water use/number of residential customers) by more than 27% during 2002–2011 (from 113 to 85 gpd). The department was given a high performance rating for its existing conservation programs, which includes a tiered block-rate pricing structure and a drought management plan with five trigger levels (CWWMG 2014). The department also offers a Smart Irrigation Program that encourages water irrigation efficiency and conservation through a water rate incentive that kicks in when a smart irrigation controller, backflow assembly, and separate irrigation meter are installed and maintained on an irrigation system (Charlotte Water n.d.). The Utility Department has adopted a goal to further reduce its total water use by 13% by 2055. With adoption of a water audit and loss control program, the Utility Department would receive a high evaluation for its water use efficiency and conservation metrics.

Water quality in Seattle, Wash. Evaluation of this indicator focuses on two components: (1) appropriate quality and (2) transparency and reporting. The United States is fortunate to have strong water quality standards for public water supply utilities as well as requirements for regular reporting of water quality testing as specified in the Safe Drinking Water Act. From our sample of 16 cities, two were able to avoid any water quality violations for the past 10 years or longer and at least four additional cities implemented total-maximum-daily-load remedial plans within five years of reported violations. For instance, the City of Seattle has not had any water quality violations since 2004 (Environmental Working Group n.d.). It publishes its water quality report online each quarter (Seattle Public Utilities 2017b), and has also been implementing an aggressive aquatic-invasive-species control plan.

Watershed protection in New York City, N.Y. For this study, this indicator focused on two components: the existence of a watershed protection plan and the degree to which watershed protection and restoration activities are being implemented. The New York City water supply system—serving more than eight million people and delivering more than 1 bil gal of potable water per day, on average—spans 2,000 mi^2 to the north and west of the city, including a system of 19 reservoirs and three controlled lakes. The city's watershed protection program has long been recognized for its ambitious scope, the amount of funding allocated to it, and the geographic scale of the actions being taken.

The city's primary motivation for watershed protection relates to the city's desire to continue earning its Filtration Avoidance Determination from USEPA under the Safe Drinking Water Act, based on the simple premise that "it is better to keep the water clean at its source than it is to treat it after it has been polluted" (New York City DEP 2016). The central pillars of the city's watershed protection plan include a watershed agricultural program, land acquisition, and wastewater programs.

Before strengthening its watershed protection program in the 1990s, the city was potentially facing $8 billion to $10 billion for new filtration facilities with operational costs of $1 million/day (New York State DEC 2017). Since 1992, more than 350 farms have developed plans for controlling agricultural pollution in the city's source watersheds; to date, more than 7,000 best management practices have been implemented on these farms at a cost to the city of more than $58 million. Additionally, more than 140,000 acres have been protected through conservation easements or fee acquisition, amounting to 38% of the entire watershed area. Through its wastewater programs, the city has also helped remediate more than 5,000 failing septic systems, another 2,400 have been decommissioned, and all wastewater treatment plants in the watershed have been upgraded to tertiary treatment standards.

SUMMARY

The seven sustainability indicators described in this article can aid cities in their efforts to improve the overall sustainability of their water supply systems. Our research team found that many of the subcomponents of the indicators can be quantified and evaluated rather easily, but some will require considerable subjective judgment in their assessment and ultimate weighting. However, utilities can evaluate and track these indicators over time in an effort to improve service reliability, financial viability, customer satisfaction, and environmental health.

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https://doi.org/10.1002/awwa.1002

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