Overview

Urban, agricultural, and environmental protection practices for sustainable water quality

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Sustainable water management often emphasizes water resource *quantity*, with focus on availability and use practices. However, only a subset of the available water may be usable when also considering water *quality*. Water quality management is examined within three broad sectors—urban, agriculture, and environmental systems—to investigate how water quality sustainability (WQS) is defined by each and across the three sectors. The definitions determined for both urban and agricultural WQS mention downstream human and ecosystem use; however, regulatory policy does not always support these definitions. This challenge of managing water quality locally and downstream, coupled with interactions across multiple sectors, has led to a fragmented approach to water quality management. Legislation typically divides water quality management into compartments without considering the entire system. Within the United States, there is an uneven distribution of responsibility regarding water quality protection, and notable policies which counteract efforts to improve water quality. The review suggests that despite a growing intention to use a single system approach where water is considered as a limited resource that must supply all competing interests, one does not yet exist and is even hindered by current policies and regulations. Recent policy is signaling a shift toward increasing interagency coordination; however, the basic definitions of WQS remain disconnected across sectors. It is the conclusion of this review that sustainable water quality is not currently practiced in the United States.

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INTRODUCTION

On the spatial and temporal scales of most natural environments, the quality of water is managed as it cycles and filters through the landscape; however, pollution from human activities and increased demands for clean water have stressed that natural system, requiring intentional water quality management. The transition from natural processes to human designed systems has supported human population growth and development. The 2015 United Nations World Water Development Report admonishes society for using resource management models where economic growth is prioritized at the expense of the world's water resources needed to sustain that activity over the long term.[1] The report cites overexploitation of resources and ecosystem disruption through urbanization and agricultural practices, and an undermining of ecosystem services. The question remains, though, how does each of these sectors define sustainable water quality, and what are the markers and metrics used to measure the greater goal of 'sustainability.' The objective of this article is to

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review and discuss current practices, challenges, and regulations in water quality management for three sectors: urban, agricultural, and ecosystem management. Urban water quality includes domestic and municipal water, wastewater, and industrial water quality issues. Agricultural water includes irrigation water and water quality issues caused by agricultural practices. The third assessment includes practices and policy influencing ecosystem water requirements to sustain healthy, natural environments. The intersection between water quality evaluation and policy and/or regulation is a major focus for all three sectoral investigations.

In the United States, major infrastructure and water policies have guided the water management trajectory that supported urban growth, agricultural development, and protection of environmental systems. In the cases of drainage systems, sewer construction in major cities, and major dam construction in the 18th, 19th, and 20th centuries, respectively, these development efforts shaped the very flow and use of water. As we approach an era where many of these systems must be replaced or repaired,[2,3] we have an opportunity to evaluate whether current practices and policies support sustainable water quality, and modify our development plan based on those findings. The judgment of these practices as sustainable or not starts with how sustainability is defined as it relates to water quality.

Definition of Sustainable Water Management

Proper management of water resources to protect quality is critical to most definitions of water sustainability. Early definitions regarding water quality in sustainable water development describe the hazardous capacity of water while emphasizing the sufficiency of our water resources given proper water management plans and practices.[4] Richards and Woodman[4] illustrate the entwined difficulties of sustainable human development and water quality in that water can be used to remove pollution from one location yet it also delivers such hazards to downstream users. Water, by its chemical and physical properties, is an efficient transporter of contamination, disease, and nutrients for better or for worse. Harnessing water to support various populations, and ensuring responsible development while maintaining the resource's quality remain central to the management of water systems in the 21st century for modern, connected communities.

Nearly a century later, Gleick[5] provided a framework for water sustainability based in part on the Brundtland Report[6] which defined sustainable development as supporting current needs without sacrificing the needs of the future. Broadly, Gleick defined sustainability as water use that supports the 'ability of human society to endure and flourish into the indefinite future without undermining the integrity of the hydrological cycle or the ecological systems that depend on it,'[5] and outlined seven criteria for sustainable water planning with three directly related to water quality. The water quality criteria include: (1) that minimum standards for water quality will be maintained dependent upon usage, (2) that humans will not impact the long-term renewability of sources, and (3) that data on availability, use, and quality should be collected and shared. This assessment structure provided a broader view of sustainability whereas Richards and Woodman, as chemists, focused on how the chemical properties of water impact water quality management. Carter et al., reflecting on the failure of many water and sanitation projects in developing regions, proposed that water sustainability evaluation should include three tests: (1) does water extraction continue at the same rate and quality as when the supply system was designed, (2) are disposal systems functioning and used as planned, and (3) does the environmental quality continue to improve.[7] Both the Gleick and Carter et al. definitions address the sustainability of the water infrastructure or management system, as well as the sustainability of the natural hydrological system as a resource, though with differing emphases. Carter et al. are more concerned with water and wastewater system sustainability and, therefore, emphasize protecting the environment within the context of the implemented infrastructure, differing from Gleick's emphasis on achieving basic provisions within the structure of an ecosystem. More recent iterations of sustainable water management definitions include balancing social, economic, and environmental needs within the greater sustainable development context.[8,9] The definition put forth by Gleick still remains widely cited and used, but increasingly sustainability is defined with more consideration for the human dimension.[10] While the broad objectives of sustainable water management have evolved and clarified, the details of water quality protection and management in the urban, agricultural, and ecosystem management sectors remain relatively arbitrary and in some cases vague, making it difficult to assess whether 'sustainability' has been achieved.

Publication History for Major Water Quality Categories

A method of framing how water quality is broadly defined in the context of sustainable development is to assess the number of publications addressing these issues. The number of publications with ‘water’ and ‘sustainability’ in the title have increased exponentially over the past two decades. Searches for ‘water’ and ‘sustainability’ and ‘agriculture’ or ‘urban’ or ‘ecosystem’ on the Web of Science database limited to journal articles published in English resulted in over 9000 articles; however, these terms are too broad and can include a number of articles that only mention sustainability. Refining this search further, to include ‘sustainable + water + management + development’ resulted in 7355 results, of which 4208 citations were retrievable. A random sample of 100 titles was reviewed for search accuracy and 2% were deemed unrelated to the topic. Assuming the random sample represented the complete set of retrievable articles, approximately 4125 articles are expected to match the search criteria. The articles date back to 1963, while articles within the subcategory of ‘agriculture’ date back to 1983, and those with ‘ecosystem’ or ‘urban’ were first published in 1987. Articles in these categories that explicitly focused on water quality did not appear until the 1990s (Figure 1). Outside of these subcategory searches, 1835 articles related to ‘sustainable + water + management + development’ and another topic, such as coastal management or fishing, creating an ‘other’ category in Figure 1. Typically less than 25% of the publication count in each of the three subcategories focused on ‘water quality’ (Figure 1).

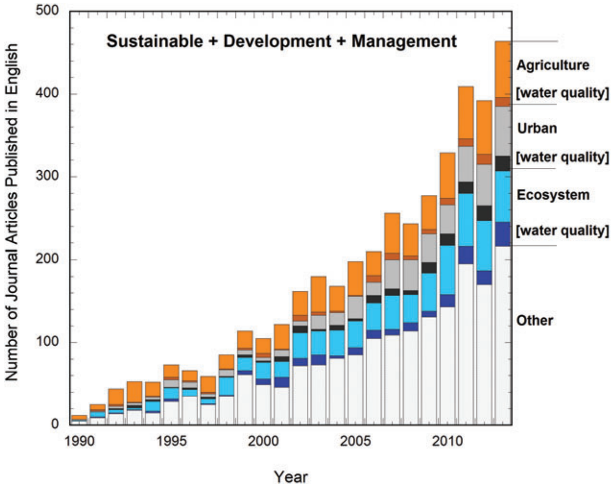

FIGURE 1 | Article search results from the Web of Science database highlighting the contribution of agriculture, urban, and ecosystem publications to the overall publication record on ‘sustainable + development + management’. The darker colors in each category are the returns including ‘water quality’ in the search.

This initial database assessment indicates that while water sustainability research has grown over the past two decades, the number of articles that investigate these specific fields and water quality sustainability (WQS) remain relatively small in number compared to publications on other sustainable water management and development topics. This relative lack of WQS publications and the complexity involved in defining what sustainability exactly means in terms of water quality is the premise upon which this review begins. The objective of this review is to determine how WQS is defined and managed for each sector and, in a holistic, one-water view, determine how these management practices and definitions relate, contradict, and compare to the popular definitions of sustainability discussed in the previous section. Due to variability in management practices and infrastructure, this review focuses on issues of WQS in the United States.

URBAN WATER QUALITY

Urban water and wastewater systems are designed to provide potable water to residents, remove toxins from waste, manage stormwater, and eliminate wastewater from the city to prevent unhygienic conditions.[11] Sustainable water quality management in an urban context should meet the population’s water demands while preventing effluent from ruining the water quality within and surrounding an urban center, closely aligning to the definition outlined by Carter et al.[7]

Urban Wastewater Treatment Systems

The history of civil and environmental engineering in the United States stems from the need of growing cities to manage waste streams, understanding that there was a large, yet manageable impact of human development on water quality. The first urban drainage system in the United States was built in Boston in the 1700s, with major cities including New York City and Chicago building sewer systems in the 1850s and 1860s. The majority of sewage construction in the United States occurred during 1890s–1900s in response to the cholera epidemics earlier in the 19th century.[12] Despite being the largest city affected by the 1866 cholera outbreak, New York’s sanitary campaign, designed and implemented before the outbreak, is credited with a decrease in cholera-related fatalities.[13] The centralized water management scheme replicated throughout the United States and many parts of the world was used to effectively remove wastes from the city.[13–15] Wastewater management and sanitation advances had notable positive impacts on sustainable urban living.[16,17]

Merely collecting and removing water waste from a city does not meet modern definitions of WQS. Treated wastewater and stormwater must be reintegrated with the environment to sustain the health of the city and not degrade the surrounding and downstream environments. In addition to treated wastewater effluent, major contaminant sources from urban areas include stormwater runoff and combined sewer overflow (CSO) events. In the *National Water Quality Inventory: 2000 Report to Congress*,[18] urban runoff was identified as a major source of water quality impairment, ranking second in influence for estuary impairment. Although urban runoffs ranking improved in the *2004 Report to Congress*[19] for all categories considered (rivers and streams, lakes, and estuaries), urban runoff remained a major contributor to surface water impairment. Methods of urban runoff management such as treatment with other wastewater or channeling flow to nearby detention areas began in the 1800s. Despite the intended benefits of a central management scheme, pathogens can enter surface water sources from urban areas in almost any sewer configuration, but the highest contaminant loads typically come from combined sewer systems.

In cities with combined sewer systems, where stormwater is managed using wastewater sewer pipelines, large rain events can overwhelm treatment systems and trigger raw sewage releases into the environment. In 2004, over 800 combined sewer systems released approximately 3.2 million m^3 of untreated sewage into local water bodies.[20] In the Gowanus Canal area of New York City, 10 discharge points line the canal with approximately 50 discharge events each year. As little as 2.7 mm of rainfall occurring over an hour period is enough to trigger a CSO event in the Gowanus Canal.[21] The 2008 United States Environmental Protection Agency (USEPA) Clean Watershed Needs Survey estimated that of the reported $298.1 billion required for water quality assurance, 21% was needed for CSO correction.[22] Given the magnitude of the issue, centralized management alone cannot address the CSO problem, therefore many locations are integrating distributed low impact development (LID) techniques, into their planning and management. For CSO abatement, LID technologies include porous pavement and green roofs, while centralized infrastructure may include large detention tanks for controlling the flow patterns of stormwater to treatment facilities.[21,23] Most CSO-related LID techniques mimic natural hydrologic processes with the intent of detaining, storing, infiltrating, or even treating urban stormwater runoff[23–25] creating the opportunity for localized, sustainable management of the problem.[26,27]

As research in the area of CSO flow control continues to progress, evaluation of changes regarding the quality of urban runoff using LID technologies for CSO-abatement lags.[23,28,29] More literature focuses on the repurposing of harvested rain water as a potable source through treatment[26,30–32] than on the impacts of water released back into the environment. A remaining challenge in defining WQS with respect to CSOs is that the measurement of success focuses almost exclusively on decreased number of CSO events rather than reduction of actual water quality contaminant concentrations beyond coliform measurements.

Cities of any size and infrastructural configuration are stressors on environmental health, increasing contaminant export as population density increases,[33,34] however, total population is not always a direct indicator of environmental impact. A study investigating the impact of urban design and layout on water quality found that differing housing density configurations led to varied contaminant loading.[35] Goonetilleke et al.[35] concluded that denser urban configurations had a smaller negative impact on nitrogen and phosphorous contamination than if that same population was spread over a larger area (e.g., a subdivision, suburban areas, peri-urbanization). Less densely urbanized areas will experience increases in these nutrients while dense urban centers have higher probabilities of pathogen and coliform contamination.[36–39] As urbanization continues in the United States and abroad, it is important to account for changes in pollutants originating from these centers and the impact on downstream residents' ability to use the water, including recreational and drinking water purposes, if applicable.

Water quality can also be affected post-treatment, as water travels through distribution and in-home plumbing systems. The organizations, agencies, and companies tasked with maintaining WQS are limited by the extent and age of their infrastructure. The recent crisis in Flint, Michigan, USA, caused by switching to a more corrosive water source which mobilized lead from old pipes, highlighted this reality. This crisis alerted the nation to what most drinking water professionals already knew: the US's infrastructure is old and in need of repair[3,40]; however, Flint is not an isolated case. In 2000, Washington, DC switched disinfectants to reduce the carcinogenic byproducts from chlorine disinfection, but this switch changed the water chemistry causing lead to leach from service line pipes.[41–43] Contamination can be introduced after treated water enters the distribution system to include *coliforms*, *Escherichia coli* (in certain circumstances), *Legionella*, disinfection byproducts, and heavy metals including lead, thus making WQS at the individual household level difficult to centrally manage. These water quality management issues are not all new, yet they present an increasing challenge as infrastructure ages and water resource options decline. Management of treated water chemistry, distribution pipes, and household plumping are crucial to ensuring water deliveries remain clean at their point of use.

As infrastructure is replaced and expanded, there is a distinct opportunity to redesign how we use high quality water in urban areas. Typically, US households receiving water from a treatment facility only have one type of water entering their home, thus potable water is used for all activities, including flushing toilets, irrigating lawns, and washing cars and sidewalks.[44] The average US family of four uses 1500 L (400 gallons) of water a day, where 70% is used indoors. Less than 20% of the indoor water use in the United States is from the faucet, potentially related to consumption-related activities.[45,46] In the United States, a projected $498 billion dollars in drinking water pipeline expansion is needed to simply keep pace with the growth of cities from 2011 to 2035,[3] offering an opportunity to redesign distribution and reconsider our current, single stream approach to water supply in these growing communities.[40] It is suspected that WQS in urban areas will soon require that systems are flexible enough to add treatment for new contaminants and/or dynamic enough to allow for the implementation of a multifaceted distribution system based on the water quality requirements of the end use. This focus on adaptability of treatment processes contrasts with sustainable water quantity supply, which just needs the ability to meet increasing water demand.[9] Urban sustainable water management must plan for population growth while effectively integrating waste streams with the environment, adhering to government legislation and water quality policy, and managing chemical contaminants in water sources.

Urban Water Quality Regulations

Urban areas, through runoff and waste streams, can impart a significant strain on local water sources. Water quality regulations passed related to urban water aim to promote urban WQS and offer clear distinctions on how urban WQS is defined. The Safe Drinking Water Act (SDWA) and the Clean Water Act (CWA) both address water quality through a set of standards; yet, with few exceptions, there is little overlap in these two programs. SDWA regulates on maximum contaminant levels in potable water delivered to residents while CWA focuses water quality standards for ambient water and wastewater effluent. The SDWA includes 87 drinking water contaminant rules currently regulating the concentrations of over 90 chemical contaminants in the water supplied by any given drinking water utility. Of those 87 regulations, only nine apply to naturally occurring constituents. Industrial and urban practices are associated with 51 contaminants with an additional five that are produced by both agricultural and industrial practices. New ‘emerging’ contaminants are under periodic review by the USEPA for regulatory determinations. Ninety-two chemical contaminants related to industrial processes, personal care products, or pharmaceuticals were listed on the 2016 Fourth Contaminant Candidate List (CCL4), a list comprised of chemicals known or anticipated to occur in public water systems but are not currently regulated by the SDWA.[47] While the SDWA and CWA regulate various types of water, the CWA ambient and effluent regulations directly impact what the SDWA must regulate for downstream urban centers.

Individually, many USEPA programs incorporate risk-based and geographic targeting to a degree, but they are scattered across different state commissions, departments, and agencies. In 1991, the USEPA drafted the Watershed Protection Framework Approach (WPA), later updated in 1996, to integrate all the individual efforts into a single management plan to encourage states and stakeholders to view a watershed more holistically.[48,49] A statewide watershed approach consisted of five criteria to include (1) delineating a state into watersheds/basins, (2) defining of a management steps to guide regulatory and nonregulatory actions, (3) coordinating water resource programs, (4) codifying a process to involve stakeholders, and (5) focusing on environmental results. Approximately 20 states adopted this statewide watershed approach[50] and it is estimated that use continues in 18 states.[51] How each state codified management was not prescribed by the approach framework, yet many had the National Pollutant Discharge Elimination System (NPDES), a program that regulates the pollution concentration thresholds emitted through a permitting process,[52,53] as a part of statewide watershed management. Despite states agreeing that basin-wide NPDES permitting can lead to more effective permit limits, issuing these permits on a basin-wide schedule was difficult. In a review of eight states' experience implementing the management plan, there were several main barriers related to NPDES, including: (1) uneven permitting across basins, (2) federal initiatives and new programs that diverted resources from the basin permitting cycle, (3) USEPA and court imposed total maximum daily load (TMDL) schedules and processes that impacted permit cycles, and (4) pressure from the regulated community to issue permits outside of the cycle periods.[50]

Inclusion of the NPDES program into a statewide watershed management program and the issues encountered are not exclusive to this program. The WPA was an attempt to merge several fragmented, output-oriented programs into a single process. Programs that relate to watershed protection and would, essentially, require integration to achieve a watershed approach include Wetlands, Nonpoint Source, NPDES, NPDES/CSO, NPDES/Stormwater, Groundwater Protection, SDWA/SDWTR, among others, many of which directly related to management of urban water quality.

In Europe, a similar regulation was issued that moved away from the 'emission limit' approach, and toward one focused on ecological health. The 2000 European Water Framework Directive (WFD) placed the focus on the ecological state of a river, defining catchments based on river basin boundaries and not political boundaries,[54–56] going beyond the approach of the USEPA WPA in eliminating state boundaries as well. The WFD also aims to promote water quality management within sustainable development by a 'polluter pays' statute.[57] Levying taxes on polluters in proportion to the amount of contamination discharged is a different approach than allowing polluters the ability to transfer discharge licenses by buying and selling them, a practice common in the US system. Adopting this approach could remove pressure from US drinking water treatment plants and improve the ecological health of surface waters by reducing contamination at the source, rather than relying on downstream treatment to protect human and ecosystem health. Using this framework, a full cycle view of water quality impacts of an urban area and a more realistic assessment of sustainability is possible.

Unbalanced Expectations from Water Utilities

A major component of urban water is the supply of potable drinking water to residents. As previously mentioned, drinking water sources, especially surface water sources, are directly influenced by upstream urban and industrial waste streams. Safe drinking water programs are not significantly involved in state assessment, planning, and management programs, thus creating an important disconnect with potential statewide management. A primary barrier to including drinking water in a watershed management approach is the fact that it was administratively placed in a different division from the USEPA and the state agencies concerned with watershed management. Additionally, SDWA and CWA focus on two different types of water (potable vs raw water) leading to the SDWA and CWA stressing different standard setting approaches and different contaminant concerns.[50]

An unintended consequence of a fractured approach to emission-based regulation is the burdening of the water treatment utilities, and not the entire community of water users and waste producers, to maintain WQS. For example, in response to the industrial chemical spill of 4-Methylcyclohexanemethanol (MCHM) by Freedom Industries' into the Elk River, West Virginia, USA, the Governor placed the burden of restoring acceptable water quality on the local utility, American Water.[58] Before questions regarding the safety issues behind the spill itself surfaced, the drinking water utility was criticized for its vulnerability to the contamination.[59] This unbalanced assessment of the spill continued as, in the aftermath, the Governor signed a new bill that regulated above-ground chemical storage, but also required American Water and all utilities in West Virginia to install early monitoring systems and develop written plans for *any* future chemical spills in the water supply (SB 373). The new bill in West Virginia has placed a larger infrastructural burden on water utilities to ensure water quality resiliency given all potential types of upstream contamination events. This unbalanced burden conflicts with the infrastructure and management aspects of WQS.

Defining Urban WQS

The definition of urban WQS includes maintaining the provision of reliable, potable water for consumption and industrial processes, and ensuring wastewater does not inhibit downstream use by ecosystems and humans. In the United States, the pair of water quality requirements regulating urban water quality—before use and after use—are fractured and have unequal geographic impacts. While the management structure is in line with Gleick's water quality criteria in that minimum standards for water quality are maintained dependent upon usage, this overlooks a key flaw in the system. The very nature of regulating standards dependent upon usage in a system that is hydrologically linked does not take a holistic view of the scenario. At the scale of a residence, use-based treatment standards may be appropriate when the use can be controlled. However, because the waste streams and consumption-based intake locations for a given city are often not colocated, there is little incentive for upstream cities to bear the infrastructural and financial burdens required to improve their own waste stream quality when the impacts are only felt downstream.

AGRICULTURAL WATER QUALITY

Just as water is a vehicle for waste and pathogen transport in urban areas, it transports nutrients and pesticides away from agricultural fields to underlying, adjacent, and downstream water bodies. Farmland area in the United States has increased from ~300 million acres in 1850 to 914 million in 2012, accounting for over 40% of all US land.[60,61] Intensive agricultural practices deplete nutrients from the soil, requiring the addition of fertilizer or other chemical amendments. WQS in the agricultural sector requires management of agrochemical pollution, soil and water salinization, and sediment loading. Similar to urban water quality management which has two primary types of water, agriculture WQS addresses local consumed water (e.g., irrigation, soil water, and groundwater), and the runoff which impacts downstream water bodies.

Local and Downstream WQS

The impact of agriculture on groundwater quality has been demonstrated for several decades.[62,63] On-farm water quality issues are typically caused by excess nutrient applications as well as salinity and sodicity accumulation in soil water. WQS must account for the direct impacts on the sustainability of potable water supply for rural households relying on private wells (about 15% of the US. population[64]). Nitrate is most likely to impact groundwater, compared to pesticides which degrade over time in the subsurface and phosphorus which sorbs to particles and materials in the aquifer.[65] Regions with high agricultural nitrogen application, high water inputs, well drained soils, and permeable aquifers are more likely to have groundwater nitrate concentrations exceed USEPA drinking water standards than areas with low nitrogen and water application, poorly drained soils, and low permeability aquifers.[66–68] Elevated nitrate levels can cause human health issues such as *methemoglobinemia* (blue baby syndrome).

In addition to direct contamination from agrochemicals, agricultural activities can impact groundwater and soil water quality through soil salinization. Salt accumulation can result from irrigation and excess nutrient application, which may impact shallow aquifers via percolation.[69] The FAO reports that ~20% of irrigated soils are salt affected,[70] with an approximate area increase of 1% per year.[71] Soil salinization is typically combatted by flushing solutes from soil with large quantities of water which can further lead to degraded surface and groundwater quality. Therefore, soil salinization is especially problematic when coupled with waterlogging.[72] The installation of drains can reduce soil salinization, water logging, and leaching of agrochemicals to shallow groundwater.[73] Although farmers are motivated to maintain the quality of their groundwater and soil water, the costs of some best management practices may be prohibitive relative to the perceived risk of unsustainable water resources.

Similar to urban WQS concerns regarding effluent impact on downstream users, agricultural WQS must account for water and ecosystem sustainability beyond the extents of each agricultural land holding. The 2000 and 2004 USEPA Reports to Congress on the state of the environment listed agricultural influences as the top source of impairment to rivers and streams and the third greatest influence on affected lakes in 2004.[18,19] Since 2008, more than 50% of surveyed rivers and streams in the United States have been classified as threatened or impaired.[74] In a study of 946 rivers worldwide, catchments dominated by agricultural crops had nitrogen exports twice that of pastures and four times as high as forested areas.[33] The American prairie, a historically productive grassland, receives some of the highest concentrations of nitrogen-based fertilizer, more than any other area in the United States.[75] Downstream water bodies, including the Gulf of Mexico, experience seasonal or persistent eutrophication caused by elevated nitrogen and phosphorous levels, resulting in algal growth and hypoxic zones. In the Midwest, agricultural runoff is a leading contributor to algal blooms in Lake Erie.[76] These blooms, formerly in recession during the 1980s,[77] are largely reoccurring due to the increased temperatures and spring time phosphorous and nitrogen loading originating mainly from western Ohio and eastern Indiana.

Nutrient and pollution loading are heavily influenced by rainfall events, antecedent moisture conditions, and a wide array of land management practices.[33,78] Most nutrient contamination is quantified by a discharge concentration or total loading, but does not account for the range of impacts on the receiving water bodies, which can vary with stream discharge, system sensitivity, and buffering capacity. For example, rain events can increase streamflow and dilute the nutrient concentrations, or conversely can increase nutrient concentrations due to runoff from within the watershed. Rain and wind may also cause soil erosion from agricultural fields contributing sediment to surface water bodies.[79] Sediment can be detrimental both by increasing turbidity and by transporting adsorbed nutrients, like phosphorus, to the water body.[80]

The impacts of agricultural activities and management plans enacted in the United States can provide valuable lessons for developing nations. Global application of nutrients (nitrogen, potash, and phosphate based fertilizers) has increased 34% from 2002 to 2014[81] and will likely continue to rise as Green Revolutions progress in Africa and Latin America.[82] The United States has relatively stable nutrient application rates over the time period without decreases in yields, similar to many other developed countries, due to increasing efficiencies in other management practices.[83] Pesticide use (fungicides, bactericides, herbicides, and insecticides) in the United States, has also remained relatively constant since the 1990s[81], however, legacy pesticides persist in the environment and continue to pose a challenge to surface water quality.[84]

Agriculture Water Quality Regulations and Responses

Agriculture WQS includes regulations to protect water quality for use on farms, and to protect downstream users from the impacts of agricultural activities. The former is primarily focused on the reuse of municipal or industrial wastewater for irrigation. The USEPA regulates recycled water quality for irrigation,[85] while some states have their own regulations (e.g., the California Water Recycling Criteria, Title 22 of the state Code of Regulations). Contaminants of concern vary based on the origin of the water and the intended application, and may include nutrients, heavy metals, pharmaceuticals, and pathogens.[86] The sustainability of irrigation and soil water quality is not regulated; however, best management practices are typically in the economic interest of the farmer. Management responses may include adoption of salt tolerant crops, maintenance of adequate soil drainage,[73] and modification of irrigation methods.[87]

Policy measures that promote WQS by mitigating downstream agricultural water pollution include mandatory regulations and potential voluntary actions. The NPDES permit program under the CWA is used to limit wastewater discharge and industrial effluent; however, agricultural runoff remains largely unregulated. The nature of agricultural runoff as a nonpoint source pollution, and the strength of the agricultural industry lobby have helped keep nutrient TMDLs largely exempt for agricultural polluters, while adherence to load-reduction practices is voluntary. One portion of the agricultural sector required to obtain NPDES permits are the discharging concentrated animal feeding operations (CAFOs).[88] Discharging CAFOs must meet the water quality standards set by the state based on the use and quality criteria set for the receiving water body.

In lieu of water quality regulations, many national and state-level farm groups promote nutrient management best practices as a means to reduce pollution and improve agricultural production. Agricultural water contamination can often be prevented through good crop husbandry and proper management of chemical additives.[89–91] Despite education and training efforts, voluntary changes are difficult to solicit, in part, because the impacts of pollution are typically felt downstream from the individual farmer, thus removing the personal incentive to invest in WQS promoting activities. Motivation to adopt best management practices may come through financial assistance designed to promote technology adoption or more labor intensive, environmentally beneficial practices.

Due to continued nutrient runoff challenges, several programs help to promote alliances between water utilities and agricultural communities such as the USEPA CWA Section 319 and Healthy Watershed Consortium grants, the US Geological Society's Cooperative Water Program, and various activities of the Department of Agriculture at the state level.[92] However, when sectors are unwilling to partner, water utilities are starting to challenge responsible parties. In January 2015, Des Moines Water Works filed a federal lawsuit under the CWA and Iowa code Chapter 455B against the drainage district officials in Sac, Buena Vista, and Calhoun Counties for the discharge of nitrate pollutants into the Raccoon River without NPDES permits.[93–96] Similar to the Governor of West Virginia passing legislation which increased the burden on the local water utilities to treat industrial spills, government officials in Iowa have been unsympathetic to the water utility. State Senator Feenstra attempted to block the lawsuit calling for an economic boycott of the Des Moines metro area, and Governor Branstad continues to oppose this type of intervention in agriculture,[97] including regulating water quality emissions from farms. The Iowa Supreme Court ruled against the utility stating that the least-cost method for removing nitrates is the water utility, which already has an obligation to do so.[98]

Defining Agricultural WQS

The definition of agricultural WQS includes maintaining adequate soil, irrigation, and groundwater quality, in addition to preventing agrochemical runoff or leaching from harming downstream ecosystems or hindering human use. Contrary to the cases of urban and industrial water quality in the United States, much of the decision-making regarding agricultural WQS is made by farmers without government regulation. Significant effort has gone into development of nutrient, salinity, and soil erosion best management practices, though most remain optional and unsubsidized. Farmers may have more individual incentive to maintain on-farm irrigation and soil water quality, because of the direct impact it has on crop production. However, protection of downstream water quality is not a priority as it can conflict with crop production and cost of cultivation. Widespread groundwater contamination, soil salinization, eutrophication, and ecosystem damage suggests the United States does not practice agricultural WQS, however, one may argue that it should be evaluated in the larger framework of food, energy, and economic sustainability.

ENVIRONMENTAL WATER QUALITY

Human development has altered nutrient cycles which balance the concentrations of several key elements in nature. The changes to chemical concentrations can be simultaneously beneficial and injurious to different components of the ecosystem, thereby making sustainable water quality management for ecosystems particularly difficult to define. WQS for ecosystems requires an understanding of the integrated impact of all sectors; therefore, environmental WQS should adhere to Gleick's[5] definition to not undermine ecological systems. The realization of ecological WQS is primarily dependent upon the effect of water quality regulations on the surrounding environment, including those discussed previously from the urban and agricultural sectors.

Environmental Water Quality Regulations

As discussed previously, human development leads to increased nutrient loading from urban and agricultural practices. Pesticides are present in almost all rivers and streams within the United States and in some cases at levels harmful to fish and wildlife.[99] Despite the direct negative impacts on the environment, few policies account for the minimum water quality needs for the environment in the same way that environmental flow (quantity) requirements have become a popular area of study and policy.[100–104] The CWA does aim to 'restore and maintain' the chemical integrity of US waters, yet agricultural and urban pressures still remain a major problem for sustaining healthy waterways.

In the late 1940s, declines in coastal ecosystem health were correlated with a noted increase in the use of agricultural nitrogen over the previous 10 years.[105] Hypoxic zones created by localized eutrophication are mentioned as early as 1930 in the Baltic Sea, with the number of zones, globally, doubling each decade since the 1960s.[105–107] The Federal Water Pollution Control Act of 1948 was the first major US law to address water pollution. However, it was not until the 1972 amendments forming the CWA that public concern was sparked and legislative efforts to control water pollution began. The CWA established the basic structure for regulating pollutant discharges in the United States and granted the USEPA the authority to establish wastewater standards for industry, set water quality standards for all contaminants in surface water, and made it unlawful to discharge pollutants into navigable waters from identifiable point sources unless a permit was obtained. These laws largely pertain to point source polluters; therefore, agricultural pollution still threatens many surface water sources. Nonpoint source pollution, or diffuse pollution, is especially difficult to legislate and control in both emission and watershed management approaches.

Currently, there are over 400 coastal systems that have recorded and monitored accounts of eutrophication hypoxic zones associated with more than 245,000 km^2 of stressed ecosystems.[105] The second largest hypoxic zone in the world is in the Northern Gulf of Mexico. It is caused by excessive nutrient loading, physical changes to the basin to include channelization and loss of wetlands, and stratification in the water of the Northern Gulf due to fresh river water meeting the saltwater of the Gulf.[108] Approximately 90% of the nitrate loads are from nonpoint sources and 56% enter the Mississippi River above the Ohio River. In years with low Mississippi flows at the confluence to the Gulf, the hypoxic zone shrinks, though never disappears.[105] To combat the growing hypoxic zone, in 2008, the Gulf Action Plan established a goal of reducing the 5-year average of hypoxic zone areal extent from

14,000 km^2 (the average from 1996 to 2000) to less than 5000 km^2.[108]

At the same time, the *Energy and Security Act of 2007* (EISA of 2007) was passed, which unintentionally conflicted with the goals to reduce the size of the hypoxic zone through the Gulf Action Plan. The act requires a ninefold increase in renewable fuel production between 2006 and 2022, half of which will be advanced biofuel, e.g., corn, sugar starch, and waste material (U.S. CRS 2007). As a result, this policy caused an increase in corn production[109] which has relatively high fertilizer and pesticide application requirements, compared to previously grown crops.[109,110] In 2013, more than five years after the Gulf Action Plan set the goal of a 5000 km^2 hypoxic area, the actual hypoxic area extent of the northern Gulf of Mexico was still 14,000 km^2 and in 2015 it exceeded 17,000 km^2. In total, the nutrient loading reduction benefits from the policies enacted to protect environmental water quality were counteracted by policies aiming to improve national energy security.

The complexity of combined impacts from environmental and development-oriented policies makes it difficult to project the success of individual regulations. These conflicting policies are one example of the deterioration of environmental water quality, while seemingly meeting economic and energy production objectives. Upon a broader inspection, the problems of water pollution and environmental degradation likewise can stress human and economic development.[8] For example, the long-term economic impacts from the Gulf of Mexico hypoxic zone on commercial and recreational users are still under investigation.[111] In a study quantifying the economic impact of eutrophication in the United States, economic losses were categorized by recreational water usage, real estate impacts, increased spending related to endangered species, and drinking water-related costs. In total, hypoxic zones in the United States result in over $2 billion annual losses and associated costs.[112] This is most likely an underestimation as the peak summertime algal blooms, when recreational uses are highest, were not captured in the analysis. Proactive watershed protection programs can provide cost-effective alternatives to technological interventions. In Boston and New York City, extensive watershed protection programs surrounding the cities' drinking water sources have precluded a need for expensive water treatment. New York City invested in their protection program as a direct response to the 1989 SDWA Surface Water Treatment Rule which required filtration of all drinking water unless the watershed is sufficiently protected. It is estimated that the $1.5 billion New York City spent on watershed protection has avoided $6 billion in capital costs and $300 million in annual operating costs for a subsequent filtration program.[113]

A common theme in policy efforts to address the shortcoming of past regulations is to promote interagency collaboration and coordination. Section 404 of the CWA focuses on nonpoint source pollution and a 1990 provision calls for needed interagency cooperation to sustain and protect the health of wetlands.[114] As discussed earlier, the WPA attempts to coordinate permitting and other factors on a watershed basis to shift the focus to the health of a basin. Recently, the USEPA established the Urban Waters Federal Partnership (UWFP) program to address urban impacts on environmental water quality. The UWFP consists of 19 designated community locations that are attempting to coordinate federal agencies and community-led efforts to improve water systems within the urban area.[115] Setting this apart from the WPA are the core principles which promote reconnection to local waterways and encourage conservation over simply coordinating permitting and regulation. While there is an apparent shift toward a more cohesive, cooperative, interagency, and local community partnership in address environmental WQS, it is still not how most locations operate. These partnerships are still in pilot phases, with less than 20 states implementing the WPA and less than 20 cities using a UWFP approach to urban water, but they have the potential to set the tone for regulatory approaches to come.

Defining Environmental WQS

The definition of environmental WQS includes balancing the policy and regulation of other sectors with ecological requirements throughout the watershed. Much of the decisions regarding environmental WQS are components of regulations in other sectors. Urban WQS considered ecological health only as it pertained to waste loading and agricultural WQS was not codified to consider the environment. A methodical accounting of impacts from all regulations related to a watershed, repeated across the United States, is required to truly know the status of environmental WQS.

CONCLUSIONS

The definitions of WQS across sectors must share a common consideration for downstream ecosystems and users. This spatial challenge, coupled with interactions across multiple sectors, has led to a fragmented approach to water quality management. Legislation typically divides water quality management into compartments without considering the entire system: the energy legislation of EISA negates attempts to decrease the Gulf of Mexico hypoxic zone; the aftermath of the Elk River chemical spill bypasses ecological WQS and instead requires utilities to manage water quality; and the yearly algal blooms in Lake Erie have had little to no impact on upstream agricultural practices and only recently, with the Des Moines Water Works lawsuit, might the ecological health of rivers, streams, and lakes improve with respect to agricultural runoff. In many US policies, water quality and sustainability is measured second to economic development, and is most strictly defined for municipal water supply; yet, a shift in policy to promote sector coordination is noticed.

Sustainable water quality also includes the sustainability of the infrastructure and water used within the system, making WQS a pressing issue for cities in the United States. The burden for ensuring high-level water quality for human consumption is placed heavily on the drinking water utilities, a sector with aging infrastructure. The policy and regulations in the United States uphold this uneven management practice, with the latest law enacted in West Virginia exacerbating this imbalance. While drinking water utilities are responsible for supplying potable water to residents, they should not be responsible for treating excess contaminants caused by the lack of regulation in agriculture. Management practices and policy enactment should consider urban, industrial, agricultural, and ecosystem water as a single connected hydrologic system. Without a balanced water quality management policy, parties ultimately responsible for degrading the quality of water will have no incentive to reverse harmful practices.

While some recent policy is signaling a shift toward increasing interagency coordination, the basic definitions of WQS remain disconnected across sectors. An integrated approach is needed to define sustainable ecosystem water quality management, as it is linked to urban, industrial, and agricultural water management. Approaches to pollution abatement and regulation need to go beyond simply keeping pollution below hazardous upper limits and instead must strive to achieve lower thresholds. The very nature of the emission-based approach to regulating pollution places ecosystem and human health at a disadvantage and suggests that sustainable ecosystem water quality management will conflict with development plans.

It is the conclusion of this review that sustainable water quality is not currently practiced, not as Gleick or Carter et al. proposed nor as a hypothetical unified approach. In urban environments, contaminants are diverted downstream to preserve the health of the immediate vicinity, and regulations have to balance water quality with industrial productivity so as not to hinder economic progress. Both urban and agricultural systems rely on downstream treatment of pollutants released into the environment. Just as the founders of sustainable development tried to integrate environmental, economic, and social aspects without skewing focus to one of these three categories, water quality management will not be truly sustainable until it considers and addresses impacts across sectors and within the entire watershed or region.

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REFERENCES

1. WWAP. *The United Nations World Water Development Report 2015: Water for a Sustainable World*. Paris; United Nations Educational, Scientific and Cultural Organization. 2015.
2. ASCE. *Report Card for America's Infrastructure*. Reston, VA:ASCE; 2013. https://doi.org/10.1061/9780784478837.
3. AWWA. *Buried No Longer: Confronting America's Water Infrastructure Challenge*. Denver, CO: AWWA; 2012.
4. Richards EH, Woodman AG. *Air, Water, and Food from a Sanitary Standpoint*. New York: John Wiley & Sons; 1900.
5. Gleick PH. Water in crisis: paths to sustainable water use. *Ecol Appl* 1998, 8:571–579.
6. United Nations World Commission on Environment and Development. *Our Common Future: Report of the World Commission on Environment and Development. Document A*. New York: United Nations; 1987. https://doi.org/10.1080/07488008808408783.

7. Carter RC, Tyrrel SF, Howsam P. The Impact and Sustainability of Community Water Supply and Sanitation Programmes in Developing Countries. *J Chart Inst Water Environ Manag* 1999, 13:292–296.
8. Huang GH, Xia J. Barriers to sustainable water-quality management. *J Environ Manage* 2001, 61:1–23. https://doi.org/10.1006/jema.2000.0394.
9. Russo T, Alfredo K, Fisher J. Sustainable Water management in urban, agricultural, and natural systems. *Water* 2014, 6:3934–3956. https://doi.org/10.3390/w6123934.
10. Beck M. Vulnerability of water quality in intensively developing urban watersheds. *Environ Model Softw* 2005, 20:381–400. https://doi.org/10.1016/j.envsoft.2004.02.002.
11. Hellström D, Jeppsson U, Kärrman E. A framework for systems analysis of sustainable urban water management. *Environ Impact Assess* 2000, 20:311–321.
12. Daly WJ. The black cholera comes to the central valley of America in the 19th century-1832, 1849, and later. *Trans Am Clin Climatol Assoc* 2008, 119:143–153.
13. Pyle GF. The diffusion of cholera in the United States in the nineteenth century. *Geogr Anal* 1969, 1:59–75.
14. Harremoes P. Integrated water and waste management. *Water Sci Technol* 1997, 35:11–20.
15. College of Physicians of Philadelphia. *Report of the College of Physicians of Philadelphia, to the Board of Health, on Epidemic Cholera*. Philadelphia, PA: Thomas Desilver; 1832.
16. Miller BC. Cholera as it prevailed in Chicago, in 1873. *Public Heal Pap Rep* 1873, 1:261–264.
17. Census reveals lower death rate. *The New York Times*, August 21, 1901.
18. USEPA. *National Water Quality Inventory: 2000 Report* (EPA-841-R-02-001). Washington, DC: USEPA Office of Water; 2000.
19. USEPA. *National Water Quality Inventory: Report to Congress 2004 Reporting Cycle (EPA 841-R-08-001)*. Washington, DC:USEPA; 2009.
20. USEPA. *Report to Congress on Impacts and Control of CSOs and SSOs*. Washington, DC:USEPA; 2004. https://doi.org/10.1227/01.NEU.0000028680.51299.00.
21. Montalto F, Behr C, Alfredo K, Wolf M, Arye M, Walsh M. Rapid assessment of the cost-effectiveness of low impact development for CSO control. *Landsc Urban Plan* 2007, 82:117–131. https://doi.org/10.1016/j.landurbplan.2007.02.004.
22. USEPA. *Clean Watersheds Needs Survey 2008 Report to Congress (EPA-832-R-10-002)* Washington, DC: USEPA; 2008.
23. Dietz ME, Clausen JC. Stormwater runoff and export changes with development in a traditional and low impact subdivision. *J Environ Manage* 2008, 87:560–566. https://doi.org/10.1016/j.jenvman.2007.03.026.
24. Alfredo K, Montalto F, Goldstein A. Observed and modeled performances of prototype green roof test plots subjected to simulated low- and high-intensity precipitations in a laboratory experiment. *J Hydrol Eng* 2010, 15:444–457. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000135.
25. Elliott AH, Trowsdale SA. A review of models for low impact urban stormwater drainage. *Environ Model Softw* 2007, 22:394–405. https://doi.org/10.1016/j.envsoft.2005.12.005.
26. van Roon M. Water localisation and reclamation: steps towards low impact urban design and development. *J Environ Manage* 2007, 83:437–447. https://doi.org/10.1016/j.jenvman.2006.04.008.
27. Freni G, Mannina G, Viviani G. Urban storm-water quality management: centralized versus source control. *J Water Resour Plan Manag* 2010, 136:268–279.
28. Kessler R. Stormwater strategies: cities prepare aging infrastructure for climate change. *Environ Health Perspect* 2011, 119:A514–A519.
29. Barrett ME, Walsh PM, Malina JF, Charbeneau RJ. Performance of vegetative controls for treating highway runoff. *J Environ Eng* 1998, 124:1121–1128.
30. Mendez CB, Klenzendorf JB, Afshar BR, Simmons MT, Barrett ME, Kinney KA. The effect of roofing material on the quality of harvested rainwater. *Water Res* 2011, 45:2049–2059. https://doi.org/10.1016/j.watres.2010.12.015.
31. Vialle C, Sablayrolles C, Lovera M, Jacob S, Huau M-C, Montrejaud-Vignoles M. Monitoring of water quality from roof runoff: Interpretation using multivariate analysis. *Water Res* 2011, 45:3765–3775. https://doi.org/10.1016/j.watres.2011.04.029.
32. Lee JY, Bak G, Han M. Quality of roof-harvested rainwater—comparison of different roofing materials. *Environ Pollut* 2012, 162:422–429. https://doi.org/10.1016/j.envpol.2011.12.005.
33. Alvarez-Cobelas M, Angeler DG, Sánchez-Carrillo S. Export of nitrogen from catchments: a worldwide analysis. *Environ Pollut* 2008, 156:261–269.
34. Smith SV, Swaney DP, Buddemeier RW, Scarsbrook MR, Weatherhead MA, Humborg C, Eriksson H, Hannerz F. River nutrient loads and catchment size. *Biogeochemistry* 2005, 75:83–107.
35. Goonetilleke A, Thomas E, Ginn S, Gilbert D. Understanding the role of land use in urban stormwater quality management. *J Environ Manage* 2005, 74:31–42. https://doi.org/10.1016/j.jenvman.2004.08.006.
36. Farnham DJ, Lall U. Predictive statistical models linking antecedent meteorological conditions and

waterway bacterial contamination in urban waterways. *Water Res* 2015, 76:143–159. https://doi.org/10.1016/j.watres.2015.02.040.

37. Kelsey H, Porter DE, Scott G, Neet M, White D. Using geographic information systems and regression analysis to evaluate relationships between land use and fecal coliform bacterial pollution. *J Exp Mar Bio Ecol* 2004, 298:197–209. https://doi.org/10.1016/S0022-0981(03)00359-9.
38. Mallin MA, Williams KE, Esham EC, Lowe RP. Effect of human development on bacteriological water quality in coastal watersheds. *Ecol Appl* 2017, 10:1047–1056.
39. Young K, Thackston EL. Housing density and bacterial loading in urban streams. *J Environ Eng* 1999, 125:1177–1180.
40. Grigg N. Assessment and renewal of water distribution systems. *J Am Water Work Assoc* 2005, 97:58–68.
41. Edwards M, Dudi A. Role of chlorine and chloramine in corrosion of lead-bearing plumbing materials. *J Am Water Work Assoc* 2016, 96:69–81.
42. Edwards M, Triantafyllidou S, Best D. Elevated blood lead in young children due to lead-contaminated drinking water: Washington, DC, 2001–2004. *Environ Sci Technol* 2009, 43:1618–1623. https://doi.org/10.1021/es802789w.
43. Triantafyllidou S, Parks J, Edwards M. Lead particles in potable water. *J Am Water Work Assoc* 2016, 99:107–117.
44. Davis JA. Adsorption of natural dissolved organic matter at the oxide/water interface. *Geochim Cosmochim Acta* 1982, 46:2381–2393.
45. Mayer PW, DeOreo WB, Opitz EM, Kiefer JC, Davis WY, Dziegielewski B, Nelson JO. *Residential End Uses of Water*. 1999.
46. USEPA. *WaterSense: An EPA Partnership*. Washington, DC:USEPA 2017.
47. USEPA. Drinking water contaminant candidate list (CCL) and regulatory determination. 2016. Available at: www.epa.gov/ccl. (Accessed January 29, 2017).
48. USEPA. *Watershed Approach Framework (EPA 840-S-96-001)*. Washington, DC:USEPA; 1996.
49. USEPA. *The Watershed Protection Approach Framework Document*. Washington, DC:USEPA; 1991.
50. USEPA. *A Review of Statewide Watershed Management Approaches—Final Report*. Washington, DC: USEPA; 2002.
51. Ormsbee L, Ph D, Wre D, Asce F, Mcalister M. Evolution of a Watershed-Management Framework in the Kentucky River Basin. *J Water Resour Plan Manag* 2014, 140:1–11. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000398.
52. Freni G, Mannina G, Viviani G. Emission standards versus immission standards for assessing the impact of urban drainage on ephemeral receiving water bodies. *Water Sci Technol* 2010, 61:1617–1629. https://doi.org/10.2166/wst.2010.887.
53. Gaba JM. Generally illegal: NPDES general permits under the Clean Water Act. *Harvard Environ Law Rev* 2007, 31:409–473.
54. Kaika M. The Water Framework Directive: a new directive for a changing social , political and economic european framework. *Eur Plan Stud* 2003, 11:299–316. https://doi.org/10.1080/0965431032000070802.
55. Benedetti L, Langeveld J, Comeau A, et al. Modelling and monitoring of integrated urban wastewater systems: review on status and perspectives. *Water Sci Technol* 2013, 68:1203–1215. https://doi.org/10.2166/wst.2013.397.
56. Hering D, Borja A, Carstensen J, et al. The European Water Framework Directive at the age of 10: a critical review of the achievements with recommendations for the future. *Sci Total Environ* 2010, 408:4007–4019. https://doi.org/10.1016/j.scitotenv.2010.05.031.
57. European Commission. *Report from the Commission to the European Parliament and the Council on the Implementation of the Water Framework Directive (2000/60/EC) River Basin Management Plan*. Brussels; 2012.
58. Zucchino D. More questions on tainted water; In West Virginia, a top health official sees a “world of confusion” over chemical spill. *Los Angeles Times*, February 1, 2014, A-10.
59. Nuckols B. W.Va. spill shows vulnerability of water supply. *AP*, January 16, 2014, 1–6.
60. U.S. Department of Agriculture. *Census of Agriculture 2012: Volume 1, Part 51*. Washington, DC: USEPA; 2014.
61. U.S. Bureau of the Census. *Census of Agriculture 1950: Volume V, Special Reports, Part 6*. Washington, DC:USEPA; 1952.
62. Spalding RF, Exner ME. Occurrence of nitrate in groundwater—a review. *J Environ Qual* 1993, 22:392. https://doi.org/10.2134/jeq1993.00472425002200030002x.
63. Follett. *Nitrogen Management and Ground Water Protection. Developments in Agricultural and Managed-Forest Ecology*. New York: Elsevier; 1989.
64. USEPA. About private water wells. 2016. Available at: https://www.epa.gov/privatewells/about-private-water-wells. (Accessed January 29, 2017).
65. Bohlke JK. Groundwater recharge and agricultural contamination. *Hydrogeol J* 2002, 10:153–179. https://doi.org/10.1007/s10040-001-0183-3.
66. USEPA. *2012 Edition of the Drinking Water Standards and Health Advisories*. Washington, DC; 2012. doi:EPA 822-S-12-001.

67. Nolan BT, Hitt KJ. Vulnerability of shallow groundwater and drinking-water wells to nitrate in the United States. *Environ Sci Technol* 2006, 40:7834–7840. https://doi.org/10.1021/es060911u.

68. Nolan BT, Hitt KJ, Ruddy BC. Probability of nitrate contamination of recently recharged groundwaters in the conterminous United States. *Environ Sci Technol* 2002, 36:2138–2145. https://doi.org/10.1021/es0113854.

69. Schoups G, Hopmans JW, Young CA, Vrugt JA, Wesley W, Tanji KK, Panday S. Sustainability of irrigated agriculture in the San Joaquin California. *Proc Natl Acad Sci USA* 2015, 102:15352–15356.

70. FAO. *Management of Salt Affected Soils: Soil Management under FAO SOILS PORTAL*. Washington, DC:USEPA; http://www.fao.org/soils-portal/en/. Accessed September 2016 2016.

71. Abbas A, Khan S, Hussain N, Hanjra MA, Akbar S. Characterizing soil salinity in irrigated agriculture using a remote sensing approach. *Phys Chem Earth* 2013, 55–57:43–52. https://doi.org/10.1016/j.pce.2010.12.004.

72. Singh A. Soil salinization and water logging: a threat to environment and agricultural sustainability. *Ecol Indic* 2015, 57:128–130.

73. Ritzema HP. Drain for gain: managing salinity in irrigated lands-a review. *Agric Water Manag* 2016, 176:18–28. https://doi.org/10.1016/j.agwat.2016.05.014.

74. USEPA. *National Summary of Impaired Waters and TMDL Information*. ias.pub.epa.gov/waters/ir/index.html. Accessed on September 2016.

75. Potter P, Ramankutty N, Bennett EM, Donner SD. Characterizing the spatial patterns of global fertilizer application and manure production. *Earth Interact* 2010, 14:1–22. https://doi.org/10.1175/2009EI288.1.

76. Stumpf RP, Wynne TT, Baker DB, Fahnenstiel GL. Interannual variability of cyanobacterial blooms in Lake Erie. *PLoS One* 2012, 7:e42444. https://doi.org/10.1371/journal.pone.0042444.

77. Makarewicz JC, Bertram P. Evidence for the restoration of the Lake Erie ecosystem. *Bioscience* 1991, 41:216–223.

78. Nyamangara J, Jeke N, Rurinda J. Long-term nitrate and phosphate loading of river water in the Upper Manyame Catchment, Zimbabwe. *Water SA* 2013, 39:637–642.

79. Glendell M, Brazier RE. Accelerated export of sediment and carbon from a landscape under intensive agriculture. *Sci Total Environ* 2014, 476–477:643–656. https://doi.org/10.1016/j.scitotenv.2014.01.057.

80. Rickson RJ. Can control of soil erosion mitigate water pollution by sediments? *Sci Total Environ* 2014, 468–469:1187–1197. https://doi.org/10.1016/j.scitotenv.2013.05.057.

81. UNFAO. Agri-environmental indicators. 2014. Available at: faostat3.fao.org.

82. Sanchez P, Palm C, Sachs J, Denning G, Flor R, Harawa R, Jama B, Kiflemariam T, Konecky B, Kozar R, et al. *The African Millennium Villages*, vol. 104. 2007.

83. Doberman A. Nutrient use efficiency—measurement and management. In: *Conference on Proceedings of IFA International Work Fertilizer Best Management and Practice*, Brussels, Belgium, 7–9 March, 2007, 1–28.

84. Rasmussen JJ, Wiberg-Larsen P, Baattrup-Pedersen A, Cedergreen N, McKnight US, Kreuger J, Jacobsen D, Kristensen EA, Friberg N. The legacy of pesticide pollution: an overlooked factor in current risk assessments of freshwater systems. *Water Res* 2015, 84:25–32. https://doi.org/10.1016/j.watres.2015.07.021.

85. USEPA. *Guidelines for Water Reuse*. 2012.

86. Toze S. Reuse of effluent water—benefits and risks. *Agric Water Manag* 2006, 80 1–3 SPEC. ISS.:147–159. https://doi.org/10.1016/j.agwat.2005.07.010.

87. Oster JD. Irrigation with poor quality water. *Agric Water Manag* 1994, 25:271–297. https://doi.org/10.1016/0378-3774(94)90064-7.

88. EPA. *5 40 C.F.R. §122.23(e); EPA, Implementation Guidance on CAFO Regulations—CAFOs That Discharge or Are Proposing to Discharge*, 2010:EPA-833-R-10-006.

89. Hess T, Aldaya M, Fawell J, Franceschini H, Ober E, Schaub R, Schulze-Aurich J. Understanding the impact of crop and food production on the water environment–using sugar as a model. *J Sci Food Agric* 2014, 94:2–8. https://doi.org/10.1002/jsfa.6369.

90. Passeport E, Tournebize J, Chaumont C, Guenne A, Coquet Y. Pesticide contamination interception strategy and removal efficiency in forest buffer and artificial wetland in a tile-drained agricultural watershed. *Chemosphere* 2013, 91:1289–1296. https://doi.org/10.1016/j.chemosphere.2013.02.053.

91. Li H, Zeng EY, You J. Mitigating pesticide pollution in China requires law enforcement, farmer training, and technological innovation. *Environ Toxicol Chem* 2014, 33:963–971. https://doi.org/10.1002/etc.2549.

92. Fletcher A. *Water Utility/Agricultural Alliances: Working Together for Cleaner Water*. AWWA Research Foundation: Denver, CO; 2005.

93. Associated Press. Des Moines utility: lawsuit likely over nitrates in water leave a comment. *AgWeb*, November 20, 2015.

94. Associated Press. Lawmaker plans bill to stop Des Moines utility's lawsuit. *Washington Times*. http://

www.washingtontimes.com/. Published September 21, 2015.

95. Des Moines Water Works. *Board of Water Works Trustees votes to pursue lawsuit*. 2015. Available at: http://www.dmww.com/. January 18, 2017.
96. Meinch T. Water Works plans to sue three counties. *The Des Moines Register*. http://www.desmoinesregister.com. Published February 4, 2015.
97. Petroski W. Boycott flops, bill eyed to stop Water Works lawsuit. *The Des Moines Register*. http://www.desmoinesregister.com/. Published October 21, 2015.
98. The Supreme Court of Iowa. *Board of Water Works Trustees of the City of Des Moines Iowa vs. Sac County Board Of Supervisors, As Trustee Of Drainage Districts 32, 42, 65, 79, 81, 83, 86, and Calhoun County Board of Supervisors and Sac County Board of Supervisors as Joint Trustees of Drainage Districts 19 and 26 and Drainage Districts 64 and 105*, 2017, 16–76.
99. Postel SL. Aquatic ecosystem protection and drinking water utilities. *J Am Water Work Assoc* 2007, 99:52–+.
100. Poff NL, Richter BD, Arthington AH, Bunn SE, Naiman RJ, Kendy E. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshw Biol* 2010, 55:147–170. https://doi.org/10.1111/j.1365-2427.2009.02204.x.
101. Arthington AH, Bunn SE, Poff NL, Naiman RJ. The challenge of providing environmental flow rules to sustain river ecosystems. *Ecol Appl* 2006, 16:1311–1318.
102. Acreman MC, Dunbar MJ. Defining environmental river flow requirements—a review. *Hydrol Earth Syst Sci* 2004, 8:861–876. https://doi.org/10.5194/hess-8-861-2004.
103. Richter BD, Mathews R, Harrison DL, Wigington R. Ecologically sustainable water management: managing river flows for ecological integrity. *Ecol Appl* 2003, 13:206–224.
104. Smakhtin V, Lanka S, Revenga C, Döll P. A pilot global assessment of environmental water requirements and scarcity. *Water Int* 2004, 29:307–317. https://doi.org/10.1080/02508060408691785.
105. Diaz RJ, Rosenberg R. Spreading dead zones and consequences for marine ecosystems spreading consequences dead for marine. *Science* 2008, 321:926–929.
106. BK Sen G, Platon E. Tracking past sedimentary records of oxygen depletion in coastal waters. *J Coast Res* 2006. Vol III Special Issue 39:1351–1355.
107. Rabalais NN, Turner RE, Sen Gupta BK, Boesch DF, Chapman P, Murrell MC. Characterization and long-term trends of hypoxia in the Northern Gulf of Mexico: does the science support the action plan? In: *Hypoxia in the Northern Gulf of Mexico: Assessing the State of the Science*. New Orleans, LA, 2006.
108. Mississippi River/Gulf of Mexico Watershed Nutrient Task Force. *Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico*. Washington, DC; 2001.
109. National Research Council. *Water Implications of Biofuels Production in the United States*. Washington, DC: National Academy of Sciences; 2008.
110. Mubako S, Lant C. Water resource requirements of corn-based ethanol. *Water Resour Res* 2008, 44, 1–5. https://doi.org/10.1029/2007WR006683:n/a-n/a.
111. Rabotyagov SS, Kling CL, Gassman PW, Rabalais NN, Turner RE. The economics of dead zones: causes, impacts, policy challenges, and a model of the gulf of Mexico Hypoxic Zone. *Rev Environ Econ Policy* 2014, 8:58–79. https://doi.org/10.1093/reep/ret024.
112. Dodds WK, Bouska WW, Eitzmann JL, et al. Eutrophication of U. S. freshwaters: Analysis of potential economic damages. *Environ Sci Technol* 2009, 43:12–19. https://doi.org/10.1021/es801217q.
113. Postel SL, Thompson BH. Watershed protection: Capturing the benefits of nature's water supply services. *Nat Resour Forum* 2005, 29:98–108. https://doi.org/10.1111/j.1477-8947.2005.00119.x.
114. USEPA. Section 404 of the Clean Water Act. *Sect 404 Clean Water Act*. 1990. Available at: www.epa.gov/cwa-404. (Accessed February 2, 2017).
115. USEPA. *Urban Waters Partnership Handbook*. Washington, DC; 2016. Available at: urbanwaters.gov.