

Review

Sustainable Water Management in Urban, Agricultural, and Natural Systems

Tess Russo ^{1,2,*}, Katherine Alfredo ¹ and Joshua Fisher ³

¹ Columbia Water Center, Columbia University, 500 W 120th Street, New York, NY 10027, USA; E-Mail: ka2491@columbia.edu

² Department of Geosciences, The Pennsylvania State University, 310 Deike, University Park, PA 16802, USA

³ The Advanced Consortium on Cooperation, Conflict, and Complexity (AC4), Columbia University, 475 Riverside Dr. #253, New York, NY 10115, USA; E-Mail: jf2788@columbia.edu

* Author to whom correspondence should be addressed; E-Mail: russo@psu.edu or tr2378@columbia.edu; Tel.: +1-814-865-7389.

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Abstract: Sustainable water management (SWM) requires allocating between competing water sector demands, and balancing the financial and social resources required to support necessary water systems. The objective of this review is to assess SWM in three sectors: urban, agricultural, and natural systems. This review explores the following questions: (1) How is SWM defined and evaluated? (2) What are the challenges associated with sustainable development in each sector? (3) What are the areas of greatest potential improvement in urban and agricultural water management systems? And (4) What role does country development status have in SWM practices? The methods for evaluating water management practices range from relatively simple indicator methods to integration of multiple models, depending on the complexity of the problem and resources of the investigators. The two key findings and recommendations for meeting SWM objectives are: (1) all forms of water must be considered usable, and reusable, water resources; and (2) increasing agricultural crop water production represents the largest opportunity for reducing total water consumption, and will be required to meet global food security needs. The level of regional development should not dictate sustainability objectives, however local

infrastructure conditions and financial capabilities should inform the details of water system design and evaluation.

Keywords: sustainable water management; sustainability evaluation; urban water systems; irrigation; ecosystem water requirements; water reuse

1. Introduction

Water is at the foundation of sustainable development as it is the common denominator of all global challenges: energy, food, health, peace and security, and poverty eradication.—UN Water [1]

1.1. Definitions

Sustainable development is commonly defined by the Brundtland Report [2] as meeting the needs of the present generation without compromising the ability of future generations to meet their own needs. “Needs” include economic, environmental and ecosystem service delivery, and cultural goals including identity and subjectively defined values. Together, these are commonly referred to as the sustainability triple bottom line. Sustainable development is the combination of sustaining the natural environment, resources, and community, and development of the economy and societal goals.

Sustainable water management (SWM) is a critical component of sustainable development, and accounts for similar issues as sustainability. Mays [3] defines SWM as meeting current water demand for all water users without impairing future supply. More specifically, SWM should contribute to the objectives of society and maintain ecological, environmental, and hydrologic integrity [4]. The definition proposed by Alley *et al.* [5] for groundwater management cites protection of the components in the sustainability triple bottom line: environment, economy, and society. A more holistic objective is provided in Agenda 21 [6] which ensures that “*adequate supplies of water of good quality are maintained for the entire population of the planet, while preserving the hydrological, biological and chemical functions of ecosystems, adapting human activities within the capacity limits of nature and to combat vectors of water-related diseases.*”

Definitions of SWM present challenges for adoption because of the widespread use of subjective language and lack of detail. Most definitions offer only a broad conceptualization of the sectors or environments to consider. The language in most SWM definitions is usually qualitative and often normative. For example, sustainability entails “*the design of human and industrial systems to ensure that humankind’s use of natural resources and cycles does not lead to diminished quality of life due either to losses in future economic opportunities, or to adverse impacts on social conditions, human health, and the environment*” [7]. This definition uses “diminished quality of...” and “adverse impacts on...” to describe thresholds of sustainable system effects, which are difficult to interpret for management purposes. With respect to sustainable urban water management in Agenda 21 from the United Nations, Larsen & Gujer [8] assert that no concept proposed is applicable in practice. The normative guidance of most sustainability definitions is especially problematic for policy makers and water managers who are motivated to adopt sustainable practices, but have little tangible support.

1.2. Integration of Sustainable Development and Sustainable Water Management

Sustainable development and SWM are inherently related due to the requirement of water for development [9,10]. Water is a fundamental requirement for human life and well-being, thus proper management of water is a means to improve food production, reduce poverty and water-related diseases. SWM involves allocating water between competing purposes and users. This allocation can be represented as a hierarchy, similar to Maslow's hierarchy of human needs (Table 1) [11]. The framework asserts that the foundational biophysical needs must be met before effort can be dedicated to fulfilling higher needs. The second level of Maslow's hierarchy is "safety", which translates to security of domestic water and agricultural production at the local level. The third and fourth levels of needs in this hierarchy, "social" and "esteem", correspond to broader community water services and a focus on maintenance, justice, and responsibility, respectively. The two hierarchies share commonalities from levels 1 to 4, and seemingly end at the fifth level. Maslow's inward-looking "self-fulfillment" contrasts with resource sustainability, which emphasizes an outward-looking perspective including the fulfillment of other users both now and in the future. The greatest challenge for developing countries is promoting SWM, the fifth and final need, while still working to address their foundational needs.

Table 1. Comparison of Maslow's hierarchy of human needs and the hierarchy of water management needs. Adapted from Melloul and Collin [11].

Level	Maslow's Hierarchy of Human Needs	Hierarchy of Water Management Needs
5	Self-fulfillment	Water resource sustainability
4	Esteem (status, recognition)	National water projects (supply, remediation, public awareness)
3	Social (family, community)	Regional water projects (supply, treatment plants)
2	Safety (security, stability, law, order)	Local development (agriculture, domestic water, water quality standards)
1	Physiological for survival (Air, water, food, shelter, procreation)	Biophysical individual needs (water for survival)

This review explores urban, agricultural, and natural water system management in developing and developed nations. We aim to address the following questions: (1) How is SWM defined and evaluated? (2) What are the challenges associated with sustainable development in each sector? (3) What are the areas of greatest potential improvement in urban and agricultural systems? And (4) What role does country development status have in SWM? The first question is addressed generally in Sections 1 and 2, and more specifically with examples in Section 3. Questions (2)–(4) are addressed in Sections 3 and 4, and are summarized in Tables 2–4. Limitations to this review are discussed in Section 4.3. Rather than providing exhaustive discussion on all aspects of water management, the objective of this study is to conceptualize the dialogue around what constitutes SWM practices according to three sectors: urban, agricultural, and natural systems. Municipal and agricultural water use account for over 80% of global human water use, and higher in many developing nations [12]. The number of people experiencing perennial water shortages in urban areas is expected to increase from 150 million (*ca.* 2000) to 993 million by 2050, and those experiencing seasonal water shortages will rise from 1 to 3.1 billion,

respectively [13]. Agricultural water use accounts for 70% of global water consumption, and can exceed 90% in developing nations. Water management of natural systems is a key requirement of sustainable urban and agricultural management practices. These three sectors represent the majority of water use globally, but may not constitute the majority of water use in a specific region or country (e.g., Canada, Russia, and the United Kingdom). Therefore, a more detailed study of SWM should be completed at the regional scale to provide the most relevant information for management and policy purposes.

Table 2. Primary sustainable water management objectives.

Sector	Developing Areas	Developed Areas
Urban	<ul style="list-style-type: none"> • Equitable delivery • Reliability • System flexibility with growth 	<ul style="list-style-type: none"> • Supporting demand • Infrastructure longevity • Recycling and reuse • Environmental protection
Agriculture	<ul style="list-style-type: none"> • Food security • Expansion of irrigated area • Supplemental irrigation • Crop water productivity 	<ul style="list-style-type: none"> • Crop water productivity • Environmental protection • Resource conservation
Ecosystem	<ul style="list-style-type: none"> • Protection of valued ecosystem services 	<ul style="list-style-type: none"> • Protection and/or restoration of natural functions within development constraints

Table 3. Developing country challenges and solutions for sustainable water management in urban, agricultural, and natural systems.

Sector	Challenges	Examples ⁺
Urban	<ul style="list-style-type: none"> • Intermittent operation • Lost or stolen water • Rapid urban growth • Political conflict 	<ul style="list-style-type: none"> • India [14], Ethiopia [15] • Palestine [16] • China [17] • <i>Mid East</i> [16,18,19]
Agriculture	<ul style="list-style-type: none"> • Irrigation infrastructure cost • Subsidies promoting irresponsible use • Low water use efficiency 	<ul style="list-style-type: none"> • <i>Sub-Saharan Africa</i> [20] • India [21] • <i>N Africa</i> [22]; China, Pakistan [23]
Ecosystem	<ul style="list-style-type: none"> • Economic development priorities 	<ul style="list-style-type: none"> • India [24]
Sector	Solutions	Examples
Urban	<ul style="list-style-type: none"> • Institutional improvements • Low-tech water capture and treatment * • Graywater reuse * • Cooperation, sharing riparian rights • Stakeholder engagement 	<ul style="list-style-type: none"> • Algeria [25]; Palestine [26] • Greece [27] • Jordan [28] • <i>Mid East</i> [29]; <i>World</i> [30] • Mexico [31]; <i>World</i> [32]
Agriculture	<ul style="list-style-type: none"> • Optimize water productivity * • Improve subsidy/pricing structure • Supplemental irrigation with rainwater harvesting 	<ul style="list-style-type: none"> • <i>World</i> [33,34] • India [35]; <i>Mid East</i> [36]; <i>World</i> [37] • <i>Sub-Saharan Africa</i> [38,39]; Burkina Faso [40]; <i>Drylands</i> [41]
Ecosystem	<ul style="list-style-type: none"> • Communication of ecosystem service value 	<ul style="list-style-type: none"> • <i>Africa</i> [42,43]; Ethiopia [44]

Notes: ⁺ Regions and non-country area descriptions are in *italics*; * Topics covered in the discussion.

Table 4. Developed country challenges and solutions for sustainable water management in urban, agricultural, and natural systems.

Sector	Challenges	Examples ⁺
Urban	<ul style="list-style-type: none"> • Demand management • Cost of adopting new technology 	<ul style="list-style-type: none"> • Australia [45]; USA [46] • <i>World</i> [47]
Agriculture	<ul style="list-style-type: none"> • Over-allocation of water resources • Cost of new technology vs. low cost of water 	<ul style="list-style-type: none"> • S Africa [48] • USA [49,50]
Ecosystem	<ul style="list-style-type: none"> • Development priorities 	<ul style="list-style-type: none"> • <i>World</i> [51]
Sector	Solutions	Examples
Urban	<ul style="list-style-type: none"> • Conservation education • Water reuse and recycling * • Stormwater management, green infrastructure * 	<ul style="list-style-type: none"> • S Africa [52]; Australia [53] • <i>World</i> [54]; UK [55] • UK [56]; Denmark [57]
Agriculture	<ul style="list-style-type: none"> • Improve water allocation, irrigation management • Affordable precision agriculture methods * 	<ul style="list-style-type: none"> • Greece [58]; Spain [59] • USA [49]
Ecosystem	<ul style="list-style-type: none"> • Identification and protection of most valuable resources • Definition of a degradation tolerance level 	<ul style="list-style-type: none"> • USA [60] • <i>World</i> [61]

Notes: ⁺ Regions and non-country area descriptions are in *italics*; * Topics covered in the discussion.

2. Evaluation Tools and Models

Sustainable systems are especially apt to compare favorably with conventional systems when the comparison includes a full cost accounting of the environmental and public health harms and benefits of each system.—Horrigan *et al.* [62]

SWM evaluation requires accounting for real costs, opportunity costs, and competing requirements among and within water use sectors. These sometimes include vague political and socio-economic components, which often do not translate easily to the quantitative values necessary for planning, decision-making, and rigorous monitoring and assessment. Evaluation models range from generic indices used to compare management practices across multiple agencies and environments, to site-specific modeling analyses that enable individual managers and governments to assess progress toward or away from sustainable practices [63].

Inputs to the evaluation should be quantifiable, independent from each other, unambiguous, and representative. Quantitative evaluations allow for assessing conditions and comparing management options. Following the definitions for sustainable development, many tools aim to evaluate environmental, social, and economic aspects of the system [64,65]. While many such tools quantify environmental impact and resource utilization, we continue to lack robust quantitative evaluation methods for social-cultural criteria, and the interconnected impacts of social, biological, and physical components of complex systems [66,67].

In addition to having a quantitative framework that bridges a complex system, evaluation models must account for the time and place dependent conditions of sustainability. Time is relevant within the lifecycle of a specific action or management practice, and also in the subsequent impacts on the environment. The spatial scale of evaluation governs what resources are assumed to be available for a given location, ranging from household to village to watershed to country to multinational region.

The spatial extents of the region, including quantity of available water resources and competing users, will influence analysis of existing and potential development. Accounting for local conditions and perspectives in the evaluation method has particular utility when assessing policy impacts over time or when advocating for specific policy changes [25].

There are three primary evaluation methods for SWM: (1) indicators and indices; (2) product related assessment; and (3) integrated assessment [64]. Water indicators and indices should simplify, quantify, and communicate information [68]. The classification, weighting, and method of index aggregation varies by model [68], making the processes somewhat arbitrary. However, the advantage of the indicator method is a simple numerical result that provides comparative capability across cases. Common indices which address water in sustainable development include the Water Poverty Index [69], the Canadian Water Sustainability Index [70], the Environmental Performance Index [71], and the Watershed Sustainability Index [72]. Water management indicators typically include water infrastructure, environmental quality, economics and finance, institutions and society, human health, and technology [4]. Other indices which specifically address some of the socio-economic dilemmas mentioned previously include accessibility of data, institutional schemes to resolve water conflict, and democratic water-related decision making [3].

Product related assessments, or life cycle assessments (LCA), can provide information about land, water, and energy requirements for a physical system or supply chain. The LCA framework can be used to inventory a set of sustainability indicators across the supply chain of a water system. Examples such as the Ecological Footprint [73] and its hydrologic corollary, the Water Footprint [74], translate biophysical assets into progress measurements. These tools are resource accounting mechanisms that enable integrated quantitative assessments of land and water resources in terms of current and potential demand, and regenerative probability at national and global scales.

Integrated assessments tend to be holistic assessments completed using system dynamics models, risk analysis, cost-benefit analysis, and impact assessments. Integrated assessments provide a systems perspective, often incorporating more robust quantification than the indicator method alone. Information theory can be used to study how efficiently human systems are using resources, and the resilience of those systems [75]. A systems dynamics modeling approach can be used with a framework based on viability loops to monitor water system acceptance, use, and economics [76]. Chung and Lee [77] demonstrate the value of coupling a hydrologic model and a multi-criteria decision model (MCDM) to evaluate alternatives for sustainable development. Many of the integrated assessment methods can include a Monte Carlo method to test for uncertainty and sensitivity.

Beyond the three typical evaluation types, groundwater use is often evaluated by comparing extraction to the aquifer safe yield. Historically, groundwater extraction sustainability was based only on groundwater recharge, which over-simplified subsurface dynamics. Early definitions of safe yield preclude pumping that is “dangerous” [78] or produces an “undesirable result” [79], including rapid declines in groundwater levels. More recent studies have called into question both the value and the sustainability of safe yield [80–82]. Evaluations of groundwater development sustainability account for natural groundwater recharge rates, as well as capture which includes induced recharge and decreases in natural discharge [5,83,84]. Advances in numerical and statistical models are improving our estimates and projections of groundwater use sustainability.

The diversity of evaluation methods described above provides water users and managers a wide array of tools to assess the sustainability of water use and allocation in specific water systems at a variety of scales. These tools reflect the complexity of evaluating sustainability within the physical and social world. Local variations, data availability, and socio-political objectives may lead to selection of different water quantity sustainability evaluation methods. This is particularly relevant for setting estimates of thresholds for sustainable use and allocation. Future work will improve evaluation frameworks in terms of measuring and assessing SWM including spatial and temporal efficiency, supply longevity, and equitable distribution.

3. Sector Reviews

3.1. *Developing Countries: Practices, Challenges, and Solutions*

3.1.1. Urban Water Development

Access to potable water is among the most important prerequisites for healthy and productive development. Water and socioeconomic development are integrally connected—either creating a vicious downward spiral or reinforcing positive development practices [85]. Sustainable development in urban areas requires reliable, equitable, and easily accessible water (Table 2). Providing water to the rapidly growing urban populations in developing nations creates a complex logistic and economic problem. This is exacerbated in areas where urban expansion is largely informal and unplanned, as demand is difficult to project and consumption is difficult to monitor.

Indicator methods are commonly used for evaluating urban water management. Developing successful indicator methods requires continued efforts to quantify the relationships between urban water management and environmental sustainability, which groups including the UN Centre for Human Settlements and the UN Environmental Program are currently pursuing. Monitoring and evaluation of urban water systems in developing regions will help improve current conditions and inform future development. One assessment evaluated 25 indicators in four criteria groups: technical, social/environmental, financial, and institutional [86]. They found that technical (design flow and the functionality of the system) and social criteria (status of use, equity, decision making in operations and maintenance) are more crucial to sustaining a water system than financial and institutional criteria, although all are necessary.

Urban water system sustainability faces challenges emerging from physical resource, infrastructure, and socioeconomic conditions (Table 3). In water rich regions, water distribution systems are optimized to meet a specified minimum pressure, whereas in water stressed regions equal water distribution among users is the goal. In the latter case, distribution systems should be designed with the expectation of intermittent operation rather than assuming continuous supply, thus reducing pressure problems and inequities in distribution [14]. Both water rich and poor regions are faced with the infrastructure design and water supply challenges of meeting demands associated with population growth [17]. Infrastructure and operation problems include leaking pipes and “stolen” water in water scarce regions. Material and construction failures, electricity supply or operation and maintenance issues all affect water distribution. Thirty percent of water supply systems serving rural sub-Saharan communities are non-functioning at

any given time [15]. Challenges include infrastructure issues, however their origins may include socio-institutional problems involving responsibility, knowledge, and coordination [87].

Regional conflict presents a significant challenge to SWM, especially in countries with differing development levels. Melloul and Collin [11] give an example where two factions of a local population are at different stages of the Water Management Hierarchy of Needs (Table 1). These disparities led to conflicts concerning resource allocation and development plans. Political conflict often leads to increased water stress, and vice versa. The UN has numerous programs involved in assessment and management of water resources, including transboundary integrated water resources management and urban water supply [88]. Recent evaluations of cooperation and competition in transboundary water management show a clear preference for cooperation rather than conflict among riparian neighbors [29,30].

Increasingly, sustainability solutions include participatory planning and water capture and reuse. Sustaining a water system requires personnel training, monitoring, health and safety regulations, and communication with users [25]. Sustainable water utilities should involve the population which they serve, and utilize the local knowledge of water resources and traditional management practices [89]. The inclusion of women in water management decisions is particularly important in cultural contexts where women are traditionally charged with collecting water for domestic consumption and use, as water management can have immediate and long-term impacts on gender equality [85,90].

Water capture, storage, and reuse are becoming common aspects of SWM systems [91]. While traditional capture and treatment systems may be cost-prohibitive for many developing regions, there are low-cost, low-technology treatment systems including constructed wetlands or layering with indigenous rock materials which can be effective for treating water for reuse [27,92,93]. Local conditions and capacity for operation require evaluation to determine the feasibility on a site by site basis [94]. Reuse of graywater in urban areas is becoming more common in water stressed, developing regions [28]. Decentralized systems are recommended at the household or neighborhood scale for producing recycled water for gardening or domestic reuse.

3.1.2. Agricultural Water Development

Food production is an integral part of sustainable human development. Sustainable agricultural water management objectives include attaining food security and maximizing food water productivity in rainfed and irrigated agriculture (Table 2). A majority of global population growth is occurring in developing countries, some of which rely heavily on rainfed agriculture. Therefore, rainfed agriculture must expand and/or see increased productivity to feed the growing population [95]. Irrigation provides a water supply buffer during dry periods, reducing the risks to purely rainfed agriculture. Though irrigation led to notable production gains in India and China over the past decades, it was coupled with increased dependency on unrenowable water resources in many regions.

Quantification of agricultural practice impact on water resources will help prevent these negative impacts under future development. Pereira *et al.* [34] present case studies for Tunisia and China using an indicator method for evaluating agricultural management strategies. Their framework accounts for water reuse and crop production economics. Dixon and Wood [44] used optimization of social, environmental, and economic benefits to define agricultural plans. While leaving natural areas uncultivated was environmentally sustainable, it provided little support for human development.

The optimization method recommended mixed use: leaving part of the land in its natural condition, and converting part of it for cultivation. Despite the demonstrated success, optimizing agricultural development and environmental water resources is not typical.

Few of the Green Revolution nations prioritized sustainable agricultural water use with increasing yields and meeting food security goals. Therefore, while the Green Revolution more than doubled crop yields, resulting in greater food security, lower food prices, and improved social and economic conditions [96], it also had many unintended environmental consequences. Government subsidies for water and energy (for pumping water) have led to wider adoption of irrigation and higher crop yields, however the low costs provide little incentive for farmers to conserve water and adopt more efficient irrigation methods. In many agricultural regions, greater than 100% of the renewable water resources are used for irrigation each year [97]. These regions must assess alternative irrigation support policies and agricultural water management strategies in order to sustain production in the future [21].

Solutions include improving water productivity and reducing risk in rainfed crops by using supplemental irrigation (Table 3). Postel [33] suggests a transition from Green Revolution to Blue Revolution, where productivity is measured in crop production per unit water. In much of the developing world, irrigation systems are less than 50% efficient. Increasing irrigation productivity requires improvements to technical, managerial, institutional, and agronomic methods. In rainfed agricultural regions, improvements in rainwater capture, selection of drought-resistant crops, and alternate tillage practices will be critical to feeding growing populations [22]. Using rainwater harvesting for supplemental irrigation to mitigate the impact of dry spells, combined with soil fertility management, can more than double rainfed crop yields [38,40]. Though the practice is not broadly used, there is widespread potential for water harvesting for supplemental irrigation in many rainfed agricultural regions [39,98].

3.1.3. Environmental Protection

Evaluation of environmental sustainability is required concurrently with development planning to protect ecosystem services (Table 2). Integrated modeling is a common approach for evaluating impacts between the human and natural environments. For example, integrated modeling can be used to assess the impact of rainwater harvesting and storage on downstream hydrology and environmental conditions [99]. Application of this model can reduce conflicts between upstream and downstream water stakeholders, while maintaining environmental flow requirements. A case study in northern India demonstrates a progressive water resource development plan to evaluate conservation of land, water, and forest resources [24]. Their proposed plan considers ecological sustainability, socio-economic options and user requirements. An important and uncommon component of their proposed plan is ensuring income generation where land use change will affect employment options. This is critical given the emphasis on land conservation and restoration in an area where 77% of the population depends on agriculture for income, similar to much of the rural developing world.

An effective method to encourage conservation and land protection is communicating the economic value of natural resources [42,44], thus allowing a community to make the optimal development decision (Table 3). Communities that depend heavily on the natural environment for their livelihoods innately place a high priority on sustainable use of resources and protection of the environment [43]. Quantifying

ecosystem value makes it simple to determine whether a use scenario protecting water resources is most beneficial for stakeholders.

Relatively few studies explore sustainable human development and water in the natural environment in developing countries, with the exceptions of the examples above, the Millennium Ecosystem Assessment report [10], and the bi-annual release of the Environmental Performance Index [71]. The priority for many developing regions is meeting present basic needs, which, according to the Water Management Hierarchy (Table 1), must be addressed prior to planning for a sustainable future. Generally, protection of the environment is not integrated into policy as it is considered anti-development. To reduce the risks of this policy omission, the Southern African Development Community has adopted the fundamental assumption that, “*strategies to reduce poverty should not lead to further degradation of water resources or ecological functions and services.*” They hope to move mainstream sustainability criteria into water resources policy and management, especially in developing nations.

3.2. Developed Countries: Practices, Challenges, and Solutions

3.2.1. Urban Water Development

Every human being has a right to clean water. For urban areas, our vision is water management where water and its constituents can be safely used, reused and returned to nature.—Hellström et al. [67]

The primary functions of urban water management include meeting hygiene (supply and sanitation), drinking water, drainage, urban agriculture, and recreational needs. Meeting these needs while protecting natural resources and human health, especially if water is scarce, is key to sustainable development [100]. Challenges include water demand management, and the cost of adopting sustainable, innovative technologies (Table 4).

Indicator methods were most common for evaluating sustainable urban water management, similar to the developing country studies. The Sustainable Urban Water Management Program in Sweden uses five categories of sustainability criteria. The criteria include: nontoxic environment, health and hygiene, human resources, natural resources, financial resources, functionally robust and flexible, adaptable to local conditions, and easy to understand to encourage responsible user behavior [67]. The structure of the evaluation framework is modular so it can be used to evaluate cities, structures, and scenarios. Several cities have developed their own sustainability evaluation models, including the Sustainable Index for Taipei and Sustainable Seattle, with 51 and 40 indicators, respectively. Unfortunately, development often leads to some level of environmental or resource degradation. “Sustainable” practices in these cases may be defined as having the least detrimental environmental, economic, and social impacts. For example, to account for continued development in the water-scarce western United States, proposed water policy would use a hierarchical tree of environmental values to direct damage to the least valuable resource [60].

In developed countries where water demand far exceeds sustenance requirements, water demand management becomes relevant. The need for conservation and demand management is a function of resource availability, population growth, and climate change. In addition to technology innovation and pricing incentives, education and awareness are critical to achieving conservation goals. One case study concluded that 50% of time and resources need to be spent on user education and awareness [52].

Marlow *et al.* [47] review sustainable urban water management methods, and discuss probable barriers including the uncertainty and challenges of innovative technology adoption, financial considerations, and institutional bias or advocacy. Innovative systems may require experimentation and carry inherent risk, so as more cities adopt sustainable practices, sharing experiences and results is required to broaden adoption. The cost of infrastructure and technology improvements may be offset by water prices which reflect its true value.

Future solutions for sustainable urban water management include broader adoption of water reuse and green infrastructure practices. Approaches for improving sustainable water reuse can be categorized into two groups: (1) Substitution (e.g., rainwater capture and reuse of graywater); and (2) regeneration (e.g., potable reuse and wastewater reuse) [54]. Public awareness of treatment practices and cooperation for how treated water can safely be used are key to developing successful reuse programs [53]. In addition to treating and reusing wastewater, stormwater runoff should be viewed as a potential water source, rather than water that needs to be treated and routed away [91]. Ellis [56] advocates for a wider green infrastructure framework including green roofs, downspout disconnection, and canopy cover of 25%–30% in riparian corridors. These broader sustainability practices can improve urban water management, while also reducing energy consumption, and benefiting local ecosystem services.

3.2.2. Agricultural Water Development

Agricultural water use accounts for 70% of worldwide consumption. Irrigation is broadly adopted in developed regions because it supports higher crop yields with lower risk [101]. Similar to developing regions where irrigation is occurring, many aspects of industrial agriculture in the first world are unsustainable [62]. Evaluation of water management in agricultural development must account for inevitable negative impacts on the environment [80,102]. Evaluating the sustainability of irrigation practices requires determining the degree of environmental degradation that people are willing to accept. Metrics for evaluating irrigation systems and on-farm water use practices must account for off-farm (or downstream) consequences. SWAGMAN is a tool that integrates hydrologic, agricultural, environmental, and economic models [103]. The SWAGMAN model helps determine crop types and irrigation methods which increase agricultural value while improving environmental conditions relative to business as usual. Sustainable irrigation practices will always be site specific, depending on local climate, soil, topography, and water source. For example, areas with shallow water tables will need different strategies compared to areas with deep water tables. For the former, water logging and soil salinization may be primary concerns, while energy costs and groundwater depletion are issues for the latter.

Negative environmental impacts due to agriculture are inevitable, but they can be minimized by increasing the efficiency of nutrient additions and water use [104]. There are clear opportunities for improving water productivity in the agricultural sector. Two primary areas include: (1) improving water allocation; and (2) improving application efficiency (Table 4). Improving allocation requires selection of crops which require less irrigation per unit of production, given the local climate and growing conditions. For example, reducing beef production, which requires 100 times the water required to produce equal protein from grains [105], would improve water productivity. Broad improvements in crop water productivity requires a better understanding of the biological, biogeochemical, and ecological processes active in agricultural settings. Improved farm management practices include no-till farming,

drip or other efficient irrigation technologies, and soil tensiometers or moisture sensors. Many farms in developed nations can afford to use irrigation, though only ~10% of farmers in the Western U.S. improve their irrigation application timing by using soil monitoring technology which informs irrigation scheduling based on actual conditions and plant requirements [49]. The low adoption rate of precision agricultural technologies is evidence of the cost and implementation barriers faced by farmers. However, as aquifers become depleted, the cost of pumping water from deep aquifers will increase which may make conservation technologies relatively affordable. The solution requires efficient irrigation technologies which are economically preferable to current water use costs.

3.2.3. Environmental Protection

Water management must balance development needs with environmental protection or restoration (Table 2). Multiple methods for ecosystem or environmental evaluation have been developed in both applied and academic literatures (e.g., [105–107]). Typical water-related evaluation criteria include stream discharge, groundwater elevation, lake stage, and rates of flow between surface, soil, and groundwater. Some of these criteria have single thresholds for defining sustainable hydrologic behavior, while others have more complicated dynamic requirements. Numerous models can be used for estimating the sustainability of riverine systems in developed watersheds. The framework Ecological Limits of Hydrologic Alteration (ELOHA) is based on the requirement of natural flow variation, *i.e.*, that a single minimum flow threshold is insufficient [108]. The quantity of flow in the river, or the flow regime, can be characterized using look-up tables with hydrologic modeling [109]. In an effort to recreate natural flow variability on a controlled river, statistical methods can be used to compare current flow frequency distributions to a natural reference [110].

Several integrated models aim to identify natural water system vulnerability and value under human development scenarios to help prioritize protection and management (Table 4). Given the natural or desired streamflow regime, the impact of population growth and development can be modeled and used to inform water management practices [111]. When applied over multiple watersheds, results can identify locations where water and growth management strategies are most needed, and where they will provide the greatest benefit. Alternatively, modeling can identify incompatibilities between human and ecosystem requirements, which are then used to develop and test new management strategies [107]. The timing and frequency of incompatibilities must be assessed using both within-year and among multiple year analyses to account for seasonal and long term trends in water supply and demand.

Given that urban and agricultural development will impact environmental systems, defining sustainability requires setting a tolerance level or acceptable pathway. Instead of setting a static goal, Chapin *et al.* [61] propose a method of ecosystem stewardship that maintains a trajectory which sustains social-ecological systems and ecosystem services. The trajectory may vary over time as conditions change, and actions should be taken to correct undesirable trajectories when they occur. The temporal variability of this method makes it perhaps more difficult to define, however the flexibility is valuable for accommodating population growth and climate change.

4. Discussion

4.1. Areas of Greatest Improvement in Urban and Agricultural Systems

4.1.1. Urban Systems: All Water is a (Re)Usable Resource

Meeting the challenges of water resources sustainability increasingly involves ... applying innovative approaches to conjunctive use of groundwater, surface water, artificial recharge, and water reuse.—Alley and Leake [80]

Managing water resource sustainability requires considering water in all states and forms as potential resources for use and reuse. Improving use efficiency, capture, and reuse of these non-traditional water resources is more critical in water stressed regions, and those which are expected to become stressed due to climate change or population growth. Treating wastewater is a key part of solving water scarcity [16]. As climate change makes dry regions drier [112,113], the need for water capture and reuse intensifies in areas with increasing water stress.

There are two key points when considering all water as resources; first, not all applications require the same quality water, and second, not all “used” water requires the same level of treatment before it can be reused. Treatment before and treatment after of the combined water stream uses unnecessary amounts of energy and effort [91]. Incentivizing a selective system of treatment and reuse requires that water be priced appropriately. Water must be considered an economic good to account for its competing uses [85], where the price depends on availability and quality. To encourage treatment and reuse, the value of water should equal the cost of treating source water to necessary standards.

Green infrastructure and stormwater capture are not fully utilized in both developing and developed regions. Excess water during rain events can be harvested and stored for use in dry periods [91]. Depending on the level of existing infrastructure and water application purposes, the scale of water capture and distribution can range from household to neighborhood to city. In many developing regions, small scale capture is recommended at the household level using storage tanks or infiltration ponds in conjunction with hand pumps for recovery [114]. Increased capture and use of all available water resources will significantly reduce water stress, especially during dry seasons and periods of drought.

4.1.2. Agricultural Systems: Crop Water Productivity

Improvements in crop water productivity can result in commensurately large decreases in water use because agriculture accounts for the largest quantity of water use. With water use efficiency ranging between 10% and 30% for rainfed and between 40% and 95% for irrigated agriculture [22,115,116], there is nearly always opportunity for improvement. Methods for improved on-farm agricultural water management include supplementing rainfed crops, irrigation scheduling, and efficient irrigation methods [117]. At the national or global scale, agricultural water use efficiency can be improved by growing more food in high water productivity regions and exporting to less productive regions [118]. Irrigation (or electricity) subsidies should target regions with sustainable water sources, or should couple incentives for high efficiency irrigation systems and low water-requirement crops. As water demands increase in the developing world, irrigation reliability is expect to decline from 0.79 (out of 1.0) in 2005

to 0.71 in 2025 [119]. In areas where groundwater use is unsustainable, improving efficiency (and decreasing total extraction) allows production to continue longer into the future [120].

The use of technology to inform irrigation scheduling can save water, and also increase crop yields compared to over-irrigation [121]. The estimated benefits of irrigation scheduling will vary by method and location. Methods for irrigation scheduling include using soil moisture sensors and incorporating weather forecast data. Soil moisture sensors or tensiometers indicate soil wetness conditions, and can be compared to plant moisture requirements. Sensor informed agriculture water savings range from 18% to 50% [122]. Crop water production can be further improved by combining irrigation scheduling with farm management techniques including mulching, reducing soil hydrophobicity, and the use of wastewater [123]. Instrument cost is a primary barrier in both developing and developed regions. The technology must be designed within the budget of the intended farmers, and/or should be subsidized by the government.

In regions where water is the limiting factor to production instead of land, increases in water use efficiency may allow farmers to irrigate more land. While this is arguably not a SWM solution because it does not reduce the total amount of water used for irrigation [124], it does increase the crop water productivity of the region. In cases where over-irrigation results in runoff and water supply for downstream users, irrigation reduction may in fact reduce water availability to these users, and should be considered in the overall management strategy [125].

4.2. Relevance of Country Development Status

This review highlights several differences as well as similarities between developing and developed nation SWM objectives (Table 2), challenges, and solutions (Tables 3 and 4). The differences lie in the context and level of development, and not in the definition of sustainability. The model selected for SWM evaluation typically varies to accommodate local infrastructure and economic conditions, but still maintains the objectives of sustainable development.

For urban water systems, equitable and reliable supply is the objective in developed and developing regions. Water stress and aging infrastructure are challenges faced around the world. Developing nations may face additional challenges including intermittent electricity and disparities in access to water delivery or built infrastructure. Indeed, the focus of SWM in developing countries is on providing equitable and reliable water supply, while developed nations may focus on water reuse and system longevity (Table 2). In addition, many developed regions now strive to have water systems that mimic natural ecosystems [75]. Water system evaluation may also include a demand management component in developed regions. Conversely, this metric is irrelevant in regions where people are not yet receiving the recommended amount of water, for example more than half of the population of the Middle East, as determined by the Islamic Network on Water Resources Development and Management [16].

Evaluation models and opportunities in agriculture are most sensitive to whether the farm is rainfed or irrigated, and what technology and information the farmer has access to. In developing nations, increasing crop productivity and equitable water allocation is critical. However, as we have learned from the Green Revolution in South Asia, increasing productivity at the expense of natural resources is not a sustainable solution. In rainfed agriculture, methods for improving yields should include supplemental irrigation during critical growth periods, and on-farm management practices that improve soil moisture

holding capacity. In developed nations with high levels of food security, increasing resource use efficiency should be a priority. The use of soil and plant sensors to inform irrigation scheduling must be part of the solution, as well as switching to more efficient irrigation technologies.

The literature on environmental water management is dominated by developed region case studies and models where water management needs have been met and sustainability emerges as a priority. We note the presence of environmental objectives in both urban and agricultural development (Table 2). Conversely, in developing regions, the objectives for environmental water management are presented by two contrasting sides. The first follows the order of the Hierarchy of Water Management Needs (Table 1), asserting that until individual and community water needs are met, environmental sustainability is not a priority. Larsen and Gujer [8] stated “*sustainable development is only possible in the absence of extreme poverty ... In areas with a lack of safe drinking water, biological diversity and other ecosystem requirements will not be given any priority.*” In alignment with this thinking, meaningful protection of the environment is generally not integrated into developing nation policy because it is considered anti-development.

It is irresponsible to allow damage to resources that will ultimately be required for a population to continue developing. The second perspective, which is held by communities who depend heavily on the natural environment for their livelihoods, prioritizes sustainable resource use and protection of the environment regardless of economic development level. The Southern African Development Community is an example of a progressive group regarding environmental sustainability. They maintain that poverty reduction does not need to compromise environmental health and services. This perspective will grow as further evidence of economic and social development coupled with environmental protection is successfully documented. All regions can have the intent of SWM, while practices may vary with geography and economic capabilities.

4.3. Limitations

Limitations of this study include: (1) the exclusive scope of urban, agricultural, and natural systems; (2) the challenge of obtaining municipal and other types of non-peer reviewed documents; and (3) omission of relevance of country geography, climate, and other factors. While urban and agricultural systems account for over 80% of global water consumption, other water uses such as industrial and recreational can be significant in some countries or local regions. Future reviews of other water uses would be complementary to this one, and provide value in improving water management practices across sectors. Much of the relevant literature, especially for urban water management, may include white papers, municipal reports, and other documents which are not typically available in academic databases. This review likely overlooked numerous documents describing SWM assessments, practices, challenges, and solutions. Future reviews would benefit from a more thorough search for these reports. Lastly, the scope of this paper did not include a synthesis of how country geography, climate, and other factors affect SWM practices. Future studies may focus on a number of factors to illustrate why SWM practices can differ in proximal nations or be similar in distant nations; relevant endogenous factors may include in-country distribution of wealth and resources, socio-cultural traditions, and political stability, while exogenous factors may include climate, geology, and a more detailed look at historical and present inter-country conflict.

5. Conclusions

SWM of urban, agricultural, and environmental systems is integral to continued development. Numerous models and metrics exist for evaluating sustainable management practices. Improvements to these methods should focus on the interconnectedness of social and physical systems using robust *quantitative* metrics. Urban water management in developing regions faces challenges of equitable delivery, especially under rapid urban population growth. Sustainable management plans should focus on continued improvements in stakeholder involvement and infrastructure in developing regions, and on water reclamation and reuse in developed regions. Water reuse will reduce stress during drought periods, though technology adoption cost and risks are still barriers in both developing and developed nations. Improvements to crop water productivity can benefit all sectors of water users discussed in this article by reducing competition between the agricultural sector and urban and environmental users. Crop water production in irrigated areas can be improved with changes in crop water allocation and adoption of efficient irrigation and on-farm technologies, while rainfed agricultural areas will benefit from supplemental irrigation. Maintaining sustainable water supply in natural systems can be seen to conflict with development practices if only looking at the near-term future. Long-term economic development is clearly linked to environmental system health, evidenced by developed country focus on restoration and protection of water resources. In application, decisions informed by the estimated value of ecosystem services may be used to set thresholds for environmental degradation, in the context of social and economic development goals. SWM will vary with geography and economic capabilities, though all regions can manage water resources in a way that supports sustainable social, economic, and environmental development.

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Authors Contribution

Katherine Alfredo contributed expertise on the evaluation metrics, urban water management challenges and solutions, and water reuse. Joshua Fisher provided substantive input to synthesize the water-based measures and tools with existing sustainable development metrics, theories and toolkits.

Conflicts of Interest

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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