Sustainability **2015**, *7*, 12071-12105; doi:10.3390/su70912071

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Review

Sustainable Water Systems for the City of Tomorrow—A Conceptual Framework

Xin (Cissy) Ma [1,*], Xiaobo Xue [2,†], Alejandra González-Mejía [2], Jay Garland [3] and Jennifer Cashdollar [3]

[1] National Risk Management Research Laboratory, US Environmental Protection Agency, 26 W Martin Luther King Drive, Cincinnati, OH 45268, USA

[2] Oak Ridge Institute for Science and Engineering (ORISE) Post Doctoral Research Participant, National Risk Management Research Laboratory, US Environmental Protection Agency, 26 W Martin Luther King Drive, Cincinnati, OH 45268, USA; E-Mails: xue.xiaobo@epa.gov (X.X.); gonzalez.alejandra@epa.gov (A.G.-M.)

[3] National Exposure Research Laboratory, US Environmental Protection Agency, 26 W Martin Luther King Drive, Cincinnati, OH 45268, USA; E-Mails: garland.jay@epa.gov (J.G.); cashdollar.jennifer@epa.gov (J.C.)

† Current address: Department of Environmental Health Sciences, School of Public Health, University at Albany, State University of New York, 1 University Place, Rensselaer, NY 12144, USA; E-Mail: xxue@albany.edu.

* Author to whom correspondence should be addressed; E-Mail: ma.cissy@epa.gov; Tel.: +1-513-569-7828; Fax: +1-513-569-7111.

Academic Editor: Marc A. Rosen

Received: 19 December 2014 / Accepted: 24 August 2015 / Published: 1 September 2015

Abstract: Urban water systems are an example of complex, dynamic human–environment coupled systems which exhibit emergent behaviors that transcend individual scientific disciplines. While previous siloed approaches to water services (*i.e.*, water resources, drinking water, wastewater, and stormwater) have led to great improvements in public health protection, sustainable solutions for a growing global population facing increased resource constraints demand a paradigm shift based on holistic management to maximize the use and recovery of water, energy, nutrients, and materials. The objective of this review paper is to highlight the issues in traditional water systems including water demand and use, centralized configuration, sewer collection systems, characteristics of mixed wastewater, and to explore alternative solutions such as decentralized water systems, fit for purpose and water reuse, natural/green infrastructure, vacuum sewer collection systems, and nutrient/energy recovery. This review also emphasizes a system thinking approach for evaluating alternatives that should include sustainability indicators and metrics such as emergy to assess global system efficiency. An example paradigm shift design for urban water system is presented, not as the recommended solution for all environments, but to emphasize the framework of system-level analysis and the need to visualize water services as an organic whole. When water systems are designed to maximize the resources and optimum efficiency, they are more prevailing and sustainable than siloed management because a system is more than the sum of its parts.

Keywords: urban water systems; paradigm shift; system-based analysis; resource recovery; energy recovery; nutrient recovery; fit-for-purpose; dual water quality; system efficiency; emergy synthesis

1. Introduction

In the words of Ecologist Eugene Odum: "Water is more critical than energy. We have alternative sources of energy. But with water, there is no other choice." [1]. Water usage is growing at twice the rate of population increase in the last century [2]. The rapidly accelerating pressures on this resource arising from constant changing quality and availability of freshwater exposes mankind to significant risk expected to worsen with climate change-induced intensification of the global hydrological cycle [3–6].

Traditional water management approaches categorize water into four types: water resource (surface water/groundwater), drinking water, wastewater and stormwater. Different engineering designs and management instruments are used to target specific "water" issues with an open-ended approach; for example, all domestic water uses are treated to drinking water standards and water is used only once and then disposed of. The wastewater is treated as waste to be eliminated with the investment of large amount of energy and materials, regardless of the potential value of wastewater constituents. For instance, even though phosphorus fertilizer production from easily accessible phosphate rock could be depleted in 50–100 years and cause global food security issues [7,8], expensive treatment technologies are used to remove phosphorus as waste from wastewater to reduce eutrophication in receiving water [9–13]. Emerging chemical and biological contaminants from wastewater and eroded sediments penetrate into the source water, making the treatment of drinking water more technically and financially challenging [14–16]. These vicious cycles worsen with the growth of cities, the concentration of agricultural practices, and intensifying material flows. Water-related infrastructure in some cities is at a breaking point, costing trillions of dollars (euros, *etc.*) just to fix it. Even so under the current paradigm, the ecological goals of the Clean Water Act in US will still not be met [17].

Many current developments are still piecemeal efforts rather than an integrated effort of the entire system which can provide interconnected functioning ecosystem and engineering services to urban populations [18,19]. The complex water issues are intertwined and cannot be sustainably solved by the traditional siloed water management approaches. Changes on the edge do not reach the center of the issues. Only when all of these players are evaluated inclusively will the sustainability of any whole water system with balanced economic activities and ecological services be possible.

Although the ultimate goals are to integrate the monitoring, modeling, assessment and management of water resources, drinking water, wastewater, and stormwater using a systems approach and watershed perspective, as an initial effort, it is important to understand the historical background of current urban water systems, analyze their various issues as components of a larger system, and lay out the argument for a conceptual framework and potential tools for such comprehensive analysis. Urban water systems have been studied extensively regarding separate issues such as pollution degradation [20–22], nutrient removal [23–25], disinfection by-product and emerging contaminants' detection and removal [26–28], microbial risk [29–31], water scarcity [32,33], stormwater management [34,35], and financial issues [36–38] among others. However, it is worth re-examining them in the context of holistic analysis and explore new integrated solutions that break the traditional barriers. For proposed future systems for the City of Tomorrow, many technological components such as resource recovery [39], green infrastructure [40], wetlands [41], and dual-water [42] quality concepts have not been studied with a system thinking approach or they are in their nascent phases of application. Without better understanding of these alternative technologies, it is difficult to confidently design and assess entire future sustainable systems. There are also knowledge gaps about advantages, disadvantages, and opportunities to manage centralized (traditional) and decentralized (alternative) water systems in a sustainability context (*i.e.*, integrates social, economic, and environmental components).

Here, we review the historical context of current urban water systems and major issues such as, water quantity, quality, energy use, wastewater contamination, system configuration, costs, and some cultural aspects. Further, we present a conceptual framework of transformative alternatives, as well as a potential tool used for a system analysis. When the system dynamics and its underlying forces are better understood, it would be possible to provide more insights on the tradeoffs and a sustainable system design.

2. Traditional Water Systems

2.1. Water Demand and Water Use

The issues and concerns surrounding the urban water systems like water quality, energy use, water scarcity, and wastewater contamination may trace back to initial water demand and water use by customers.

Of the 3.4×10^{10} gallons of drinking water produced annually by public water systems in the US, approximately 63% is used for residential purposes (indoor and outdoor) [43]. Of that, 42% of annual residential use was for indoor purposes and 58% for outdoor purposes (without taking into account firefighting allocation) based on the evaluation of 1188 homes from 14 cities across six regions of the US. Of the indoor use, 17% is for human consumption or related use (faucet use and dishwasher); 19% is for human contact (shower and bath); 64% is for non-human ingestion or contact uses (toilet, clothes washers, leaks and other) [43,44]. Although there are regional differences, one fact that remains is that potable water is only a minor portion of the total demand.

Activities other than human consumption and contact such as outdoor non-potable landscape irrigation and firefighting (58%) still require the entire water infrastructure to provide water of a quality acceptable for human consumption [44] (Figure 1, Table 1). The standby fire flow provision requires adequate capacity and pressure [44,45]. The standards governed by the National Fire Protection Association require fire-flows to sustain from three to eight hours [46]. In order to satisfy this need for adequate standby capacity and pressure, most distribution systems use standpipes, elevated tanks, and large storage reservoirs. Generally, up to 75% of the capacity of a typical drinking water distribution system is devoted to firefighting [47] (Figure 1, Table 1). Treating this large amount of water and moving it over long distances is energy- and material-intensive, mostly fossil fuel-driven. Additionally, there is a growing concern that such designs in most urban areas result in water quality degradation during transmission due to long water residence time which provide optimum conditions for the formation of disinfection by-products (DBPs) and the regrowth of microorganisms, a trade-off between public health and public safety [48,49]. The current flushing programs are costly and largely ineffective, resulting in wasted treated drinking water.

Table 1. Total residential drinking water demand of study.

Assumptions:		
Population (P)	100,000	Inhabitants
	gal/year	fraction
U.S. Drinking water provision [44]	3.40×10^{10}	
Residential	2.14×10^{10}	1
Residential indoor use		0.42
Human consumption or related use (faucet, dishwasher)		0.07
Human contact (shower and bath)		0.08
Nonhuman ingestion or contact (toilet, clothes, leaks)		0.27
Residential outdoor use		0.58
Water demands [50]	gpcd min	gpcd max
Residential	75	130
Firefighting demand based on population [50]		
The American Insurance Association recommends:	(P in thousands)	
$Q(\mathrm{gpm}) = 1020\sqrt{P}(1 - 0.01\sqrt{P})$		
Calculated Q =	9.68×10^3	qpm
	13.93	mgd
Calculations:		
Total drinking water demand of study (average residential per capita)	102.5	gpcd
	10.25	mgd
According U.S. drinking water provision fractions:		
Consumption for 100,000 inhabitants	mgd	
Residential indoor use	**4.31**	18%
Human consumption or related use (faucet, dishwasher)	0.74	3%
Human contact (shower and bath)	0.80	3%
Nonhuman ingestion or contact (toilet, clothes, leaks)	2.77	11%
Residential outdoor use	**5.95**	25%
Firefighting demand	**13.93**	58%
Total residential demand	**24.18**	100%

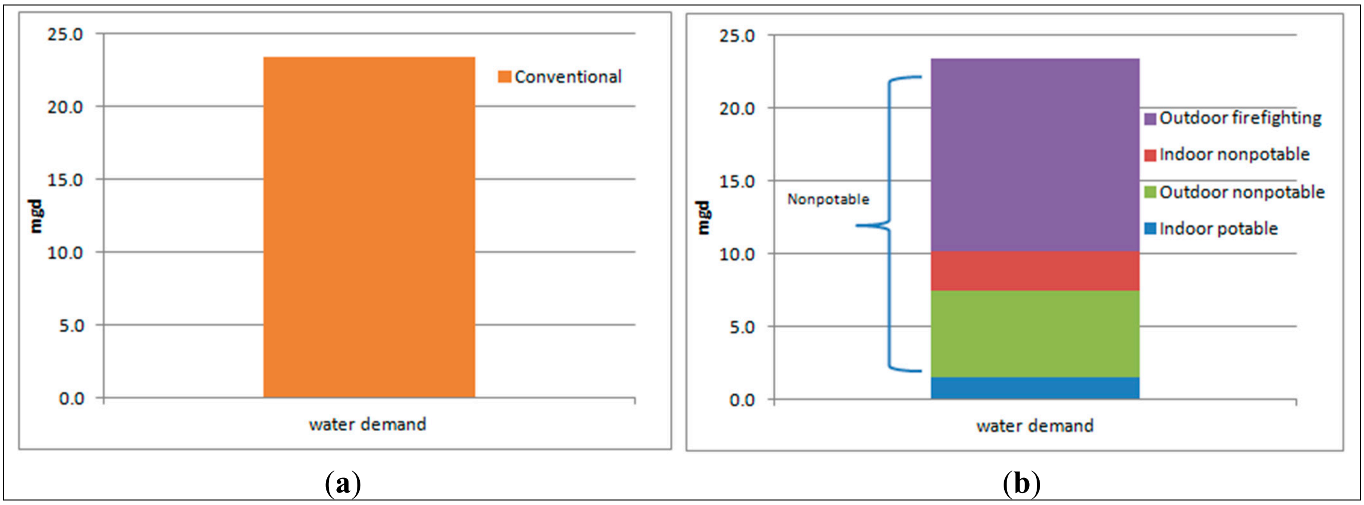

Figure 1. The demonstration of water demand and water use in a city with a population of 100,000. (**a**) Conventional water system with centralized water and wastewater facilities. All water demands are satisfied by potable water; (**b**) Dual water supply systems with potable from drinking water and non-potable from clean water, which accounts for 93% of the demand (see detail below).

2.2. Centralized Water Systems

Ancient Rome represents an example in the history of urban freshwater supply, hygiene and sanitation on a large scale [51]. However, with the rapid urban growth of early industrialization, the sanitary and freshwater-supply condition worsened in the early nineteenth century. The mid-nineteenth century sanitary crisis was an early sign of an inherent dilemma in the industrial market economy: it had no automatic, internal mechanism to restore a healthy equilibrium to natural ecosystems polluted by the unwanted by-products of growth, even though such environmental sustainability was a necessary condition of its continued productive expansion. The Great Stink in England in 1858 and the two cholera pandemics with the death of 25,000 Londoners in the previous decade was the final trigger to the sanitation revolution. A sophisticated network of intercepting sewers was built under London to reroute the waste far downstream from central London [51]. The Sanitary Awakening and acceptance of the germ theory of disease spurred England to take important actions to ensure water supply was both ample and clean. London was never again afflicted with cholera. England's sanitary revolution triggered a virtuous cycle of competition among industrial countries to improve water supplies and public health. By 1920, residents of almost all the world's rich industrial cities in Europe and North America enjoyed abundant and clean freshwater. At the beginning of the twentieth century, most of the largest American cities had municipality-run water supply systems [52]. Chicago achieved a most ambitious civil engineering project—the reversal of the flow of the Chicago River. The river no longer evacuated sewage into the city's Lake Michigan drinking supply; instead it was carried downstream to be diluted in the Illinois and Mississippi Rivers. The sanitary revolution played a pivotal role in sustaining the urban ecosystems at the heart of industrial civilization [51].

Currently, there are about 2 million miles of pipelines in US. These systems of engineering marvels, with some in the ground for over 100 years provide a critical public health function and are essential for economic development and growth. However, the "hard path" with massive infrastructure in the forms of dams, aqueducts, pipelines, and centralized treatment plants have substantial unexpected social, economic, and environmental cost [53]. Many of the systems were installed at the turn of the 20th century. Due to age, wear, and tear, many are not functioning well. The U.S. EPA 2002 gap analysis shows there is a $540 billion infrastructure needs and funding gap for clean water and drinking water alone for the next 20 years [54]. In 2013, the American Society of Civil Engineers rated both drinking water and wastewater infrastructures as D, indicating a significant backlog of overdue maintenance and a pressing need for modernization [55]. There are 240,000 water main breaks per year and 75% of wastewater capital needs are for pipe repair. The capital investment needs for the wastewater and stormwater systems alone are estimated to total $298 billion over the next 20 years.

The topology of the centralized infrastructure was a result of the strong economies of scale: large centralized infrastructures may still be found to be cost-effective to a certain degree, due to efficiency-boosting features that can be cost effectively added only when the utilities become very large [44,56]. Infrastructures were located strategically to be close to water resource or water receiving bodies. Currently, 35% of a typical U.S. municipal energy budget is associated with water and wastewater utilities [57]. Electricity use accounts for approximately 80% of drinking water treatment and distribution cost and 25%–40% of the operating budgets for wastewater facilities. However, when cities grow bigger, the longer the distance to transport water, the higher the energy demand.

2.3. Current Wastewater Collection Infrastructure

One of the features in urban development is the land use shift from vegetated surfaces to impervious surfaces, creating more frequent and higher peak flows of stormwater. According to the U.S. EPA, over 700 cities in the US with early infrastructure have combined sewer systems (CSS) collecting stormwater in sewer systems that occasionally discharge overflow wastewater directly into water bodies [58]. The untreated sewage from these overflows can contaminate our waters, causing serious water quality problems.

Besides the potential health risk, the current sewer system is designed to accommodate the infiltration from groundwater due to cracks and poor joints (e.g., 10% of the average domestic rate) and inflow from stormwater sources. The sewer systems should be sized to carry peak flow as a gravity flow according to Recommended Standards for Sewage Works ("Ten States' Standards") [59]. Although pumping is not as significant a portion of the load for wastewater as for drinking water in transporting water because of reliance upon gravity, the large-piping system, deep trench and extensive lift stations inherently consume a lot of labor and material in construction and energy in operation. About 150 kWh/million gallons of electricity on average are required to collect sewer [60]. In smaller communities, it was found that the cost of conventional gravity collection systems was up to four times higher than the cost of treatment and disposal because of the lift stations required to service less densely populated areas [61].

2.4. Mixed Wastewater

Human excreta in pre-industrial societies such as the Chinese, Indian, Egyptian, and Amazonian Indians have been used in agriculture and soil enrichment for over 2000 years [51,62]. Not until the industrial revolution, with its urban population explosions, did human waste in cities become a serious problem and health hazard, and so was considered as waste. The engineering infrastructures of sewer networks have been used to effectively convey the waste to water bodies like rivers or the sea in early times, and much later to the municipality-controlled wastewater treatment facilities [51,63]. Although the sanitary revolution made the rapid immigration from the countryside to the industrial cities possible and sustained the urban ecosystem, the one-directional waste transport and treatment solutions have given rise to new and more complex problems like eutrophication, loss of aqueous habitat, and increased financial burden. The technologies for meeting low levels of the key nutrients are very expensive to install and dramatically increase costs for the utility [64]. The "waste" transported away from urban areas actually removes valuable elements. Not until recent times when water pollution has become prevalent, energy costs have increased, and finite mineral resources are depleting, has wastewater begun to be reconsidered as a resource [65–69]. In fact, there is no such thing as waste in nature, only wasted resources [70]. To be more efficient and sustainable in the long run, human society should mimic natural processes.

Human waste comes from the metabolites of food digestion. The main compositions in wastewater are carbon, nitrogen, phosphorus and potassium. Currently, the primary and secondary treatments in the municipal wastewater treatment plants (WWTPs) effectively remove carbon as measured by biochemical oxygen demand and chemical oxygen demand (COD). Additional biological nutrient removal (BNR) treatments are needed to further remove nitrogen and phosphorus before discharging to the receiving body to avoid eutrophication. The removing processes are highly energy intensive even though many "free" microbes are employed along the treatment train. The in-plant pumping and aeration in common primary and secondary treatment often consists of more than 60% of the total plant electricity use [64]. The further sludge treatment and disposal is also energy-intensive because of dewatering, although the biosolids produced can be turned into fertilizer or soil amendment. If not treated effectively, the effluents from WWTPs are often the major sources contributing to eutrophication due to the excess carbon and nutrient release.

3. Alternative Solutions

3.1. Decentralized Water Systems

When populations in cities grow bigger, it is not only expensive to aggregate the services over a large region and size the systems to accommodate future demand, but also requires considerable pumping energy to transport water over longer distances and the systems are more vulnerable to contaminant transport like salt loads, drought or legal constraints [71]. A decentralized system, on the other hand, is a distributed control where localized, networked interactions between components (such as stormwater management, drinking water supply, firefighting water demand, and energy recovery) establish order and coordination based on local specific information. Decentralized wastewater management systems are stand-alone systems in which small wastewater flows are collected, treated and dispersed at or near the point of generation [72]. The U.S. EPA has formed the National Decentralized Water Resources Capacity Development Project (www.ndwrcdp.org) to support research and development in this area. It was found that the primary drivers for the uptake of decentralized systems in Australia were identified as (1) Overcoming limitations of local water and wastewater services; (2) Deferring infrastructure upgrade; (3) Environmental Protection; (4) Showcasing sustainability; (5) Water conservation;

(6) Enhancement of local amenity; (7) Technology showcase [73]. Decentralized water systems have less conveyance energy and more integrated resource management such as local system-wide reuse opportunities [38]. There is more flexibility, more utility optimization and community independence. Decentralized systems allow the communities to phase-in added sewer capacity as growth occurs, for example, and avoid the upfront financial burden of long-term demand projections in centralized systems where the current users bear the cost of future use [61]. The "soft path" approaches of small-scale decentralized facilities improve the productivity of water use and whole system efficiency, resulting in lower cost community-scale systems [53,74]. The investment risks are also far fewer than those of the "hard path" approaches found in centralized facilities [3]. In addition, the networks of decentralized subsystems provide the necessary redundancy and flexibility responsive to potential weather changes or other system disruptions. When one decentralized system fails, the other ones provide the auxiliary connections and can redirect resources in the event of an emergency. This will increase resource exchange among systems, optimal resource throughput and minimization of wastes. It is also easier to reach an equilibrium point between water, energy, and land use where improvements in one aspect does not signify cost in others [75]. The tradeoff of decentralized systems is the increased complexity within the clusters of independent, yet interconnected networks. In centralized systems, the system configuration and operations are much simpler, but costly. The efficiency of decentralized systems is achieved through complex information management that allows system exchange, and more diverse technology to achieve resource recovery and sharing, instead of extensive energy-driven technologies. The modern development of digital and communications technology can provide systematic communication between decentralized water systems like smart grid technology in electricity networks. Networks such as the Smart Water System use the automated and integrated remote sensing network to provide better efficiency, reliability and security, resulting in a more resilient system [76,77]. For example in an extreme weather event, the watershed management teams can automatically share stormwater modeling information with potential flooding zones and times based on predictive precipitation intelligence and develop corresponding timely emergency responses [78]. The emergence of localized systems will encourage more innovations and new market opportunities resembling those seen in the clean energy initiative such as nitrogen trading programs in nutrient management or "centralized operations of decentralized units" contracting business model [79]. This in turn can provide significant social, economic, and environmental benefits. As the high risk of the total system failure from critical centralized infrastructure is alleviated, so does the financial burden decrease.

Compared with a wealth of knowledge about conventional systems, decentralized systems have been shown conceptually promising. Although significant progress has been made [52,56,73,80–83], the decentralization concept is still in its relative infancy [72,84]. It is not a simple downscale of the centralized version, otherwise the economy of scale in microeconomics would determine that the cost generally decreases with increasing scale [38]. It should be effectively linked to other alternative options such as dual water quality, energy and material recovery, fit-for-purpose, *etc.* In reality, new system architectures can be configured in different designs, including hybrid systems which "tweak" the current systems and incorporate centralized and decentralized elements [72,84–86] and transformative systems that overcome the system inertia with new system designs [87]. The focus of system optimization certainly involves a general matter of scale that deserves more research [52,56].

3.2. Fit for Purpose and Greywater/Rainwater Reuse

The current distribution systems were designed for fire protection centuries ago and driven entirely by the need for large flows througout systems. Few structural standards are concerned with drinking water quality. The drinking water problems now inherent in all systems will not be addressed by continuing the same design practice [45]. Alternatively, dual systems in which separate pipe networks can be constructed for potable and non-potable water have the potential to improve water safety and reduce cost of drinking water distribution infrastructure, ultimately achieving maximum resource recovery from wastewater [88]. Dual water systems for dual water quality are not new. AWWA published the first edition of its *Manual of Practice: Dual Water Systems* in 1983 [89]. The original intention was to conserve high-quality natural waters for drinking and use reclaimed wastewater for nonpotable purposes. Dual systems in a new community/system would be built simultaneously. Such dual systems have been developed and are operating in a large suburb of Sydney, Australia serving 250,000 since the 1990s [90]. All houses are provided with reclaimed water lines inside for toilet flushing and with potable lines. For existing systems, dual systems can be retrofitted a new drinking water system (smaller pipes) and rely on the existing system (larger pipes) to serve as the non-potable supply [45].

If the majority of the domestic water use (e.g., 93% as in the case in Figure 1) is for non-potable purposes, the treatment strategy should adopt "fit-for-purpose" practice, in which the treated water, called "clean water", is for non-potable use, like toilet flush, clothes washing, firefighting and landscape irrigation. The City of St. Petersburg, FL develped the first major dual system in 1969 in US [90,91]. There are approximately 335 dual distribution systems in the U.S., mainly in Florida, California, Arizona, and Texas with reclaimed water [88]. The national mileage of pipes in dual systems is between 10,000 and 20,000 miles. However, most current dual systems do not serve residential users and the reclaimed water is only 1% to up to 60% of total water delivery. The survey of current dual water systems showed no major public health problems from the use of reclaimed water in US [88]. U.S. EPA's 2012 manual includes water reuse projects, state standards, regulations, and recommendations [92].

The source of clean water can be treated greywater and rainwater, in which the water quality standard is not as high as drinking water, but safe for its purpose. Unlike blackwater, *i.e.*, feces without urine, which is rich in organic matter, greywater is domestic non-sewage water which generates larger volumes with lower concentrations of contaminants, such as that from showers, sinks, and laundry.

Due to the evaporation and condensation processes as parts of the water cycle, rainwater is generally considered clean and the quality is better than surface water. It is when rainwater comes in to contact with the catchment area such as roof and road surfaces, contaminants like pathogens, VOC and road salts are introduced. The harvested rainwater can serve as an independent water source for clean water as well as for storage and other purposes such as landscape irrigation [93].

The treatment of combined greywater and stormwater can employ less energy-intensive technology and with lower capital expenditure [94]. Constructed wetlands can serve as one such option. The natural wetland system is one of the most productive primary production systems on terrestrial biomes. Although wetlands occupy only about 2% of the global surface area, they contain 10%–14% of the carbon [95]. Wetland soils, such as histosols, may contain up to 20% carbon by weight. The peats are even more carboniferous. The aerobic-anaerobic stratification of wetland sediment columns involving vegetation, microbial and soil community is uniquely important in the global cycling of sulfur, nitrogen, and phosphorus as well as carbon [96]. An open-water wetland with land area of 6 × 10^4 m^2 (15 ha) can achieve 90% removal of most compounds in nitrified wastewater effluent receiving 3.8 × 10^3 m^3/d (1 million gallon per day (mgd) flow) [97]. The treatment efficiency would be higher for lower strength greywater and stormwater. This efficient ecological and evolutionary machinery from natural systems provides enormous natural capitals that often are not appreciated by market capitals. Moreover, the benefits beyond water purification can be food chain support, biodiversity conservation, stormwater and erosion control, flood conveyance, water storage and buffering, local climate control, reduction of wild fire, and downstream ecosystem improvement. Constructed wetlands are designed to simulate natural wetlands and use renewable energy to replace fossil fuel energy used in conventional treatment technologies to achieve the same water purification purpose.

The carbon sequestration of wetlands is not limited to simply carbon fixation by photosynthesis within the wetland. It is also the sinks of carbon from inflow water such as greywater from domestic use. The aquatic vegetation and organisms in wetlands also play an active role in taking up nitrogen, phosphorus and other compounds from inflow water. Over time, the peat production from the wetland can be used for soil conditioning and potting soil. Twenty-three states produced about 900,000 tons of peat worth about $20 million in 1988 [98].

The rising temperature and imbalanced water cycle has been and will continue to result in more severe climatological events [3,5]. It has been estimated that the frequency of such severe events has increased by 20% in the US since the beginning of the century [98]. In the areas with decreased precipitation, constructed wetland and its storage function will provide additional supply during summer months or drought periods because of its relative constant flow from domestic water use. In the areas with increased precipitation, the constructed wetland will provide water quality buffering, stormwater runoff treatment and erosion control. The integration of constructed wetland with urban living as a part of aesthetic co-design of water functioning services and urban landscape will not only provide a financially viable option (because the water purification is done by natural capital instead of market capital), but also offers numerous ecological services as mentioned above and additional urban design function such as more public spaces to promote social interactions, physical health and fitness, diminished crime and increased wellness, resulting in improving the quality of life within the livable, regenerative community (rather than the conventional mentality NIMBY-Not In My Back Yard) [99]. For example, hiking trails, and nature parks around the wetlands can offer public recreational space and increase aesthetic and property values [100].

Although the wetland treatment efficiency for lower strength greywater and stormwater would be higher than for traditional wastewater, the technology still requires extensive land occupation that captures renewable energy in the form of vegetation, soil and microbes to treat wastewater. In areas where land is not available such as in the densely populated communities, the treatment can instead employ technologies with smaller footprint, but driven by purchased inputs and fossil fuels to treat greywater and stormwater. Even so, the overall system efficiency may still outweigh the ones in centralized systems.

3.3. Natural/Green Infrastructure

To develop effective stormwater management and build cost-effective solutions with physical and operational resilience, it is suggested that hard urban surfaces are replaced by vegetated or permeable surfaces to retain runoff and natural shoreline features such as wetlands and sand dunes to mitigate the effects of storm surges [101]. Green infrastructure incorporates natural capitals like vegetation and soil to manage rainwater near where it falls [102]. Instead of diverting stormwater outside the watershed as much and as fast as possible with extensive piping system and transport energy, the available potential energy from the rain should be used to encourage maximum productivity and native biodiversity within the watershed [103].

Water system management should also collaborate with city zoning and land use management. Most metropolitan cities in US and around the world have experienced the massive flooding in severe storm and urban heat island (UHI) effects in hot summer due to the replacement of natural open and vegetated land surfaces with artificial concrete infrastructure and impermeable, dry surfaces [104,105]. Solar energy is converted to more sensible heat, rather than latent heat. Excess water is disposed as quick as possible before it returns to its natural cycle through evapotranspiration (ET) and infiltration. To overcome these issues, cities should implement strategies that encourage more ET and infiltration with urban forests, urban agriculture, trees and vegetation, green roof and cool roof, and cool and permeable pavements and surfaces [102]. The study of ecohydrologic effects of urbanization on ET showed that loamy soils can sustain vegetation transpiration more than sandy soils; mature tree covers with deep root structures have higher annual ET rates than shallow rooted covers such as grass, which may reduce runoff and mitigate against UHI effects [106]. Although urbanization necessarily comes with a certain degree of impervious surface at the expense of vegetated cover, it was shown that impacts to annual ET fluxes can be mitigated by strategies like eliminating directly connected impervious area [34]. The natural ground cover would only have 10% runoff with 40% via ET and 50% through infiltration while the impervious cover would have 55% runoff with 30% ET and 15% infiltration [107]. The basic principle of low-impact development (LID) practices as stormwater management alternative is to mimic pre-development hydrologic regime and detain runoff close to its source [108]. At the watershed level, if the efforts are focused on targeting the fundamental problem by making acyclic hydrologic process become more cyclic and restoring natural hydrologic cycle [109], the stormwater runoff will be alleviated and the more balanced natural hydrologic cycle will in turn provide resilient support for urban water systems in the long run.

Constructed wetlands will also increase ET and potentially infiltration. Large bodies of water greatly moderate land climates because of the high latent heat of evaporation and melting characteristic of water [109]. If possible and necessary, other underground and above-ground water storage bodies, like quarry reservoirs, can serve as water bank and environmental buffer to store excess water for later use, flood control, energy storage of potential hydroelectric power, emergency water supply and groundwater recharge, *etc.* [71]. For example, the Stone Quarry Reservoir in Carrboro, North Carolina stores up to 200 million gallons of water [110]. Regionally, Southern Nevada Water Bank program has stored over 104 billion gallons of water in the local hydrographical basins [111].

3.4. Vacuum Sewer Collection Systems

Unless there are onsite collection and treatment units like composting toilets or septic systems, the sewage generated must be connected to a common collection system and transferred to a treatment facility. The conventional gravity sewer is considered as the standard operation. However, one of the alternative systems, vacuum sewer, may provide an option for decentralized urban sewer transport replacement when blackwater transport is considered (see Section 3.5).

Vacuum sewer systems collect wastewater in a valve pit where sewage is drained from the house by gravity and then conveys the sewage by vacuum. When a pneumatically controlled valve on a service line is opened to atmospheric pressure, wastewater and air are "pulled" into the system. The vacuum valves do not need an onsite electricity source to operate. Therefore, a single vacuum valve pit can serve two or three equivalent dwelling units (EDUs) with no electricity sharing issues. The wastewater that enters with the air forms a "plug" in the line, and air pressure pushes the wastes toward the vacuum station. When the vacuum valves closes, atmospheric pressure is restored inside the valve pit by a central vacuum station. Cumulative kinetic energy moves the sewage toward the central vacuum station and break up the larger suspended solids during transport. This energy from the air pressure difference offsets the fossil fuel-driven energy needed to achieve the same sewage flow transport. However, due to the reference atmosphere pressure, vacuum sewers have a limited capacity to pull water uphill. The maximum expected lift is between 4.5 and 6 m (15–20 ft) under flat terrain [61]. Otherwise, lifts are needed to bring the vacuum line to a shallow elevation. Each vacuum station can serve approximately 1200 EDUs with a length of 3000 m (10,000 ft) service radius in a modest housing density and flat terrain. Vacuum stations are the centers of the vacuum sewer system. When sewage arrives in vacuum stations, it is stored in a large vacuum collection tank and then conveyed by sewage pump through a force main to the treatment facility.

The periodic air influx through valve openings encourages the aeration process so there are less anaerobic conditions in sewage flow. Vacuum sewers are "closed" systems and inherently watertight since any air leakage into the system reduces the available vacuum and the pipe breakage leads to the operation failure. This immediate "alert" feature will prevent any prolonged leakage without notice, unlike in a gravity system where the leak detection may take days to run a camera in the sewer main to locate the leak. The sewage in a vacuum line remains in the pipe if a break does occur due to the negative pressure in the piping system. Exfiltration rarely occurs and the impact of sewage contamination is greatly reduced. Another benefit is odor containment. Unlike gravity sewers with many places where odors can escape, vacuum mains tend to self-clean due to the scouring ability of the high speed of the wastewater in the line.

The pipe size for a vacuum sewer is smaller than those used in gravity sewers due to less infiltration. There is no need for large, deep trench installations, which reduces the excavation cost and community disruption. The shallow burial depth also simplifies the finding and repairing of leaks which reduces the long-term operational and maintenance cost. To convey more viscous blackwater, which is not mixed with urine and greywater and is mainly "dry" feces, vacuum sewer systems will work better than gravity sewer because of the negative pressure in the line. It has been proven to be 24% cheaper than gravity sewer [112].

3.5. Resource Recovery

In municipal solid waste management, source separation has been long advocated, in which compostable organic wastes, recyclable materials such as paper, glass and metal are diverted from other waste streams at the source for separate collection [113]. The view that the organic fraction of the waste stream is a resource to produce renewable energy and compost should apply in wastewater management. Instead of the extensive energy and chemical expenditures required to separate carbon and other nutrients in wastewater treatment processes, source separation at the user phase has been regarded as resource efficient to treat concentrated, unmixed solutions [114,115].

The challenge for source separation has prompted researchers to design urine diversion toilets, in which urine and feces are separately collected [63,116]. The toilet bowl has two openings, one toward the front for urine and one toward the back for feces. Since 2010, the Bill & Melinda Gates Foundation has awarded more than 50 grants for designing "next-generation sanitation" to maximize the recovery of nutrients and energy [116].

3.5.1. Nutrient Recovery

In the nitrification process in traditional BNR treatment, ammonia is converted to nitrate, followed by denitrification, reducing nitrate to nitrogen gas. Nitrogen gas is then released to the atmosphere as a part of the nitrogen biogeochemical cycle. To sustain all forms of life, nitrogen fixation is essential to convert nitrogen gas in the atmosphere into ammonium and nitrate forms which are the most readily used by plants. Nitrogen fixation is especially energy expensive because so much energy is required to break the triple bond of molecular $N\equiv N$ so that it can be converted (with addition of hydrogen from water) to two molecules of ammonia. Free living biofixers are less efficient and may require up to 100 g of glucose to fix 1 g of nitrogen (1% efficiency) [117]. In the fertilizer industry, the most common nitrogen fixation process, the Haber-Bosch process requires a lot of fossil fuel energy in industrial fixation. In fact, 3%–5% of the world's natural gas production is used in the Haber-Bosch process [118]. This is the reason that nitrogen fertilizer is more expensive than most other fertilizers [109].

Phosphorus removal during BNR treatment may involve biological accumulation in biomass and chemical precipitation. The phosphate-rich sludge can be resold as fertilizers or soil conditioner. The great reservoir of phosphorus is not the air, however, but the rocks and other deposits formed in past geological ages. Much of the eroding and dissolved phosphate ends up in the sea. The returned phosphorus to the land (like extensive uplifting of sediments) is inadequate to compensate the loss [109]. Human activities have hastened the rate of phosphorus loss [119]. Phosphorus is one of the scarcest minerals in terms of its relative abundance in the available pools on the earth's surface [109]. Phosphate rock is predicted to be depleted in 50–100 years which puts global food security at risk [7,8]. Ultimately, phosphorus will have to be recycled on a large scale to avoid the collapse of agriculture [120].

Urine is an important source of minerals, especially nitrogen, phosphorus, and potassium. These minerals are also the feedstock ingredients for commercial fertilizer. Nitrogen in urine is already in the forms of ammonia and urea. If the two industrial processes are connected and minerals in urine are used directly, the high energy spent to nitrify ammonia and denitrify nitrate in wastewater, and fix the nitrogen gas in synthetic fertilizer can be offset. Technologies such as struvite crystallization (magnesium ammonium phosphate hexahydrate, $MgNH_4PO_4 \cdot 6H_2O$) provide such promising potential. The struvite process occurs spontaneously in wastewater processes and it often clogs the pipes. The crystallization process can selectively extract phosphate and ammonia-nitrogen from the mixed wastewater stream and produce slow release pellets for fertilizer use [121–123]. The struvite product is thought to be more bioavailable. Therefore, less quantity is needed than the commercial one to achieve the same nutrient needs for plants and less unused nutrients will end up in the water ways. The same technology can be used in urine where the target constituents are more pure and concentrated. Therefore, higher efficiency would be expected for the crystallization from urine than from mixed wastewater. The theoretical potential has been estimated to be 67,000 tons of P_2O_5 fertilizer per year from the UK alone and 270,000 tons from Western Europe [124]. The nutrient recovery from urine will, at larger scale, make material acyclic processes become more cyclic, which is what natural biogeochemical cycles do.

3.5.2. Energy Recovery

When nutrients are diverted from the feces (and since greywater is also diverted) at the source, the more concentrated organic materials (mostly carbon) that are left, named blackwater, can be further processed to more efficiently recover embedded energy. In conventional wastewater, the suspended solids are settled in the form of sludge which is further digested to methane (CH_4). The soluble organic fraction has been treated with aerobic processes effectively, but with relatively high energy input and little financial advantage. One promising technology to capture the energy potential of the dissolved organic fraction is microbial fuel cells (MFCs) [125]. MFCs convert direct biological energy to electricity. Currently, only 30%–40% of the CH_4 energy is converted. More improvements such as less voltage loss and higher transfer efficiency are needed for this process to be competitive with complete anaerobic biological conversion to biogas, a renewable fuel used in electricity generation [68,125].

Anaerobic treatment has been considered as the core technology for energy recovery [126]. Anaerobic digestion is the biological degradation of organic matters in the absence of oxgen and converts the embedded chemical energy in organic carbon to biogas. The biogas can further be tranformed into other forms of energy such as electricity, heat, or compressed fuel. Anaerobic biological processes involve facultative hydrolysis and acidogenesis and strictly anaerobic acetogenesis and methanogenesis. Anaerobic organisms particularly methanogens are slow growers and respond slowly to changes. The common method for anaerobic processes in wastewater systems uses continuous feed with a single-stage system, resulting in lower capital costs. The temperature-phased digester has two reactors to separate microbial processes to optimize parameters with higher biogas and CH_4 production, although the cost of construction and materials increase with the separation of these processes [127].

Anaerobic digestion has been used for wastewater sludge treatment and reduction, agricultural manure management, and food waste management. In all cases, the organic carbon embeded in the waste is anaerobically converted into biogas. The higher the organic content, the more biogas. For blackwater stream where the organic concentration is at least 10 times higher than conventional mixed wastewater [128,129], up to 97% of total COD can be removed and 60% converted to CH_4 [127,129,130]. The diversion of urine prevents the inhibition of methanogensis from high levels of ammonium and improves the efficiency of digestion and energy recovery. Other configurations are being investigated to improve the efficiency of the biodegration of the organics, reduce the hydraulic and solid retention time and recover the dissolved methane loss to the effluent in processes such as ananerobic membrane bioreactors [68,129,130], anaerobic fludized bed reactors [68,131,132], upflow anaerobic sludge blankets [129,133,134], and the combination of MFCs and anaerobic membrane bioreactor [135]. In addition, since organics in human feces are mostly metabolized low molecular weight carbons, co-digestion with food waste which contains higher molecular weight carbons can double the biogas production [127,129]. In response to a European Union Directive requiring diversion of 65% of the 1995 levels of organic wastes from landfills, there were 127 operational food waste anaerobic digesters, with a capacity of 4.6 million tons, installed as of 2006 in Europe [127]. Among the 16,000 municipal wasteater treatment facilities operating in the US, only 544 facilities employ anaerobic digestion, and only 106 of these now utilize the biogas produced to generate eletricitiy and/or thermal energy [136]. The potential of co-digestion to maximize the biogas production is huge.

Biogas is comprised of 60%–70% CH_4 and 30%–40% CO_2 and other trace gasses. Common applications for utilizing biogas include heat, power or combined heat and power (CHP). A portion of the generated biogas (approximately 10%) is the feedback of self-maintaining temperature and energy demands for the digestion process [127]. Remaining energy is available for electricity generation or direct combustion for heating purposes. Biogas can also provide space heating and compressing biogas for fleet vehicles [127]. An eco-village in Jenfelder Au, Germany with 2000 residents developed by HAMBURG WASSER intends to provide renewable energy supplies from locally CHP generated biogas from blackwater and organic waste (30%), geothermal energy (40%) and solar heat (10%) to achieve decentralized, energy self-sufficient cities of the future [128].

Besides the chemical energy embeded in organics, the thermal energy in the form of heat in wastewater is at least 2.5 time higher assuming 6 °C change in water temperature [68]. Heat pumps can use sewage water as heat source and extract heat for building heating [137]. Other technologies like hybrid pressure retarded osmosis-membrane distillation (PRO-MD) are being developed to capture the enoumous low-grade waste heat (<80 °C) for electricity generation, although technology gaps still exist [138]. Such energy recovery from blackwater, together with energy consumption reduction from other alternative strategies would greatly contribute to overall low carbon urban development [39,139].

4. The Sustainable Urban Water Systems Case Study: The City of Tomorrow

Each city has its unique socio-political and bio-physical characteristics [140]. There are no one-size-fits-all solutions. Many institutions and organizations around the world have been part of the efforts of promoting paradigm shift. The International Water Association (IWA) Cities of the Future program (http://www.iwa-network.org/) aspires to help cities create robust and resilient responses to various changes cities are facing and promote rethinking water management. Numerous cases under Global Water Partnership have applied different toolbox in dealing with various water challenges around the world [141]. While it is critical to gain experience of how a tool has worked in a given situation and with local context, the details from real world often not only focus on one aspect of water issues that specific community faces but also may mask or distract the higher level of understanding and core questions: how do different parts of water system interact and how can urban water system as a whole be more efficient and sustainable? Similar to the studies of process mechanisms under laboratory controlled environment before the field experiments, with the understanding of the potential alternative options for each sector within the water system and its complex intertwined nature, a specific urban development setting is required to clearly explore how these players can be evaluated inclusively and the system reorganization can achieve global system efficiency.

Thus, it is indispensable to combine system thinking approaches with sustainability indicators or metrics for assessing holistically this global system efficiency. Some examples of these tools are metrics that evaluate particular dimensions such as: human health with risk assessment [31], and economic and environmental dimensions with footprints (e.g., ecological, water, and carbon), life cycle impact assessments, triple bottom line reporting, and benefit-cost analysis [142,143]. There is a plethora of publications about footprints (89,976 approximately) and life cycle assessment of water systems (21,316 approximately), but less about studies about integrated water systems such as: sustainability indicators (1434 approximately), benefit-cost analysis (531 approximately) and triple bottom (166 approximately), which indicates a gap of knowledge needed for holistic analysis of water systems (number of citations obtained from [144]).

One of these system tools is emergy, which incorporates all dimensions into one for a complete sustainability analysis. There have been attempts to evaluate separately each unit of the water system with emergy, *i.e.*, drinking water [145,146] and wastewater systems [147]. However, a more comprehensive study that assesses the current system configuration and sustainable alternatives is still needed.

4.1. System-Based Tool: Emergy Synthesis

While integrated measures are needed to provide a holistic view of sustainability, they require a "common currency" to compare different units and scales [148]. One such system-based method is emergy synthesis, a process previously used for various systems at multiple scales to incorporate environmental, social, and economic aspects into a common unit of nonmonetary measure (equivalent solar energy joule, sej). Emergy is defined as the available energy of one kind previously used up directly and indirectly to make a service or product [149]. It is based on the observation of the energy flow patterns in ecosystems and economic systems during self-organization. The theory states that the functions of all systems (ecological, social and economic) are derived from the transformation of available energy. Such transformation also defines the relative energy quality in a hierarchical order. For example, the transformity values for wind energy, electricity and phosphate fertilizer are 1.5×10^3, 2.0×10^5, and 1.0×10^7 sej/J [149]. It means that the processes for generating phosphate fertilizer require a lot more upstream energy investment than what it takes to regenerate wind energy, due to the geological sedimentary cycle for phosphorus rock to regenerate and the fossil fuels needed in mining and concentrating into the appropriate form as fertilizer. In other words, phosphate fertilizer has higher "energy quality". The unique concept of energy quality in emergy analysis has the capability to value natural resources such as rain or soil that are often considered as "free" in the economic market. Many other integrated tools including life cycle analysis or "footprint" analysis often limit the analyses within technosphere from unit processes and overlook the biophysical supports from natural capitals. Instead, emergy analysis can provide a more inclusive evaluation of water systems that not only satisfy the urban water services, but also serve as driving forces in shaping the landscape and sustaining the ecological services.

Such energy quality term can be easily used to clarify the misunderstanding that upstream reduction in demand does not produce *new* water because non-consumptive water used inefficiently will be used by downstream users [150]. It is not just water quantity, but also energy quality of water that matters. With such a conversion factor to a common measuring unit, all energy, material, and information flows with completely different qualities in a system can be holistically assessed. Therefore, the behavior of a system as a whole and the interactions between subcomponents can be observed and optimized and its sustainability can be assessed. This applies to water systems with components like wastewater, stormwater, drinking water, surface/groundwater, water in natural systems and associated infrastructures.

Emergy theory asserts that prevailing systems are those whose designs maximize available energy by reinforcing resource intake at the optimum efficiency. This includes maximizing the resource intake *and* the operation at the optimum efficiency for maximum power. In other words, both *intake* and its best *use* are maximized [149]. The beneficial organization increases intake energy (first priority) and its efficient use (second priority) on all scales (not just maximizing levels with more energy, and not maximizing some levels at the expense of others) [151]. The same holds for water systems, particularly for urban water services. It is not a self-contained unit, economically or ecologically. Its future depends as much on the external life-support environment as on the activities within the city limits ([109,152,153]). If the hydrological cycle can be maintained and repaired, and if the acyclic processes driven by human activities become more cyclic, enabling a feedback loop, there is a better chance for sustainably managing urban water systems.

Emergy analysis of the urban water system finds that the drinking water and wastewater treatment processes are high energy-, chemical-, intensive processes. For example, it was found 5.87×10^{11} sej/m^3 for potable water [146] and 3.15×10^{11} sej/m^3 for activated sludge-treated wastewater [147] (global baseline adjusted to 15.2×10^{24} sej/year [154]). The high emergy values for drinking water come from chemicals and electricity for supreme quality of water and for wastewater come from the embedded emergy in raw materials in food (such as fertilizers, soil organic matter, *etc.*) and from modern agricultural processing and food distribution system inputs. This is why when the urbanization of the modern community creates large population centers that generate concentrated wastewater, a large expenditure on wastewater treatment has to be invested to make a modern city function without human and environmental health problems. Society relies on systems with technological energies rather than on systems with natural energies resulting in "systems being energy intensive rather than land-intensive" [155]. There is a reciprocity between the amount of resources used in the concentration of nutrients (the food support system) and the resources that have to be spent on dispersion (the WWTP system) [149,155,156]. The resources for treating the wastewater could either be drawn from local resources by the expropriation of large land areas (or less land for longer period time), or by the use of high technologies and large amounts of purchased inputs from other places or other time periods such as importing chemicals and materials from outside systems, or utilizing the higher emergy quality products like electricity driven by fossil fuels concentrated through prior geological times. Since concentrated wastewater is inherent to a modern city and requires certain emergy expenditure to disperse it, the more sustainable water system would maximize its available energy by reinforcing resource intake such as water, energy and nutrient recovery, and operating at the optimum efficiency by using more renewable emergy intake such as natural/green infrastructure to provide the same services.

4.2. The Alternative System for the City of Tomorrow

In order to become a more sustainable city, and to overcome the numerous drawbacks in the base-case scenario, the City of Tomorrow could employ various alternative approaches and design a more integrated system that breaks the invisible boundaries. Non-traditional strategies like fit-for-purpose treatment and source separation could be adopted, in which water services and qualities are delivered to match users' needs, less wasteful energy expenditure is spent and productivity of water use is maximized, rather than continuing to seek sources of new supply [53]. In the decentralized setting proposed herein (Figure 2), a dual water supply system is exploited at the community level. The drinking water supplies only for potable water needs. Only 2.07×10^6 m^3/year (1.5 mgd) is withdrawn from groundwater, a 93% reduction from the conventional practice (Figure 1). If only 7% of the potable water demand is supplied by high quality groundwater, the treatment and distribution cost will be greatly reduced. Shorter residence time is also expected. Smaller size piping, possibly stainless steel, requires fewer joints [88]. It will greatly decrease, if not eliminate, DBPs and pathogen risks. The high potable water quality is easier to achieve to protect public health and secure public safety, even with future population growth, and ensure long-term water resource sustainablity.

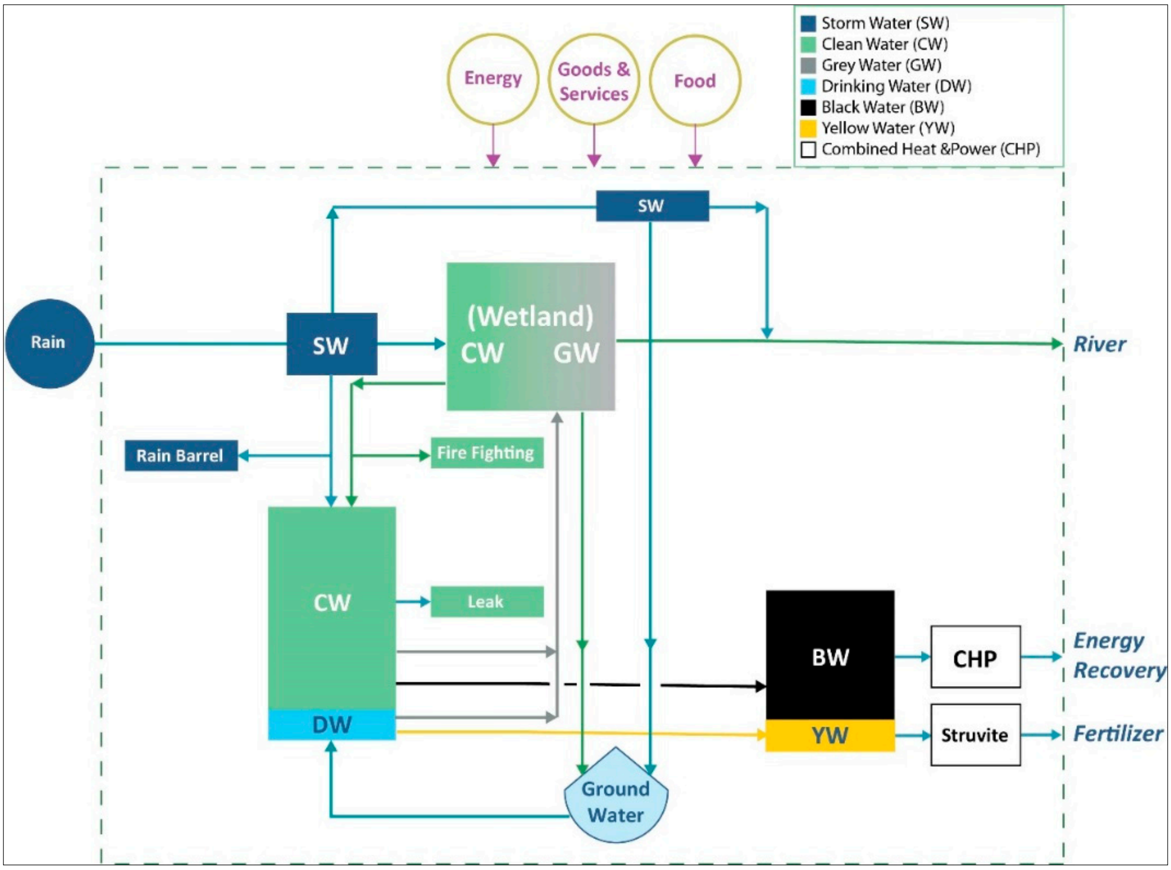

Figure 2. Sustainable alternative urban water system.

The non-potable demand cannot be solely satisfied from greywater generated. Rainwater/stormwater serves as an additional supply. The non-potable water sources (clean water from wetland-treated greywater and rainwater) provide water for non-potable demands (Figure 2). Smart land use strategies are used to further reduce stormwater runoff and encourage more evapotranspiration (40%) and water storage and recharge (50%) [107], for example, promote the growth of more mature tree with deep root structures [106]. With the same precipitation, the water intake from natural resources in the alternative system is only 7% of the conventional practices. Most of the water is retained and recycled within the system. Only 20% of the water coming into the system is discharged. In a conventional system, the efficiency is much less with over 77% discharged (Figure 3). Instead of being lost as runoff, the flow of geopotential energy and chemical potential energy of water is dispersed in the watersheds and maximizes the biological productivity and other contributions [149].

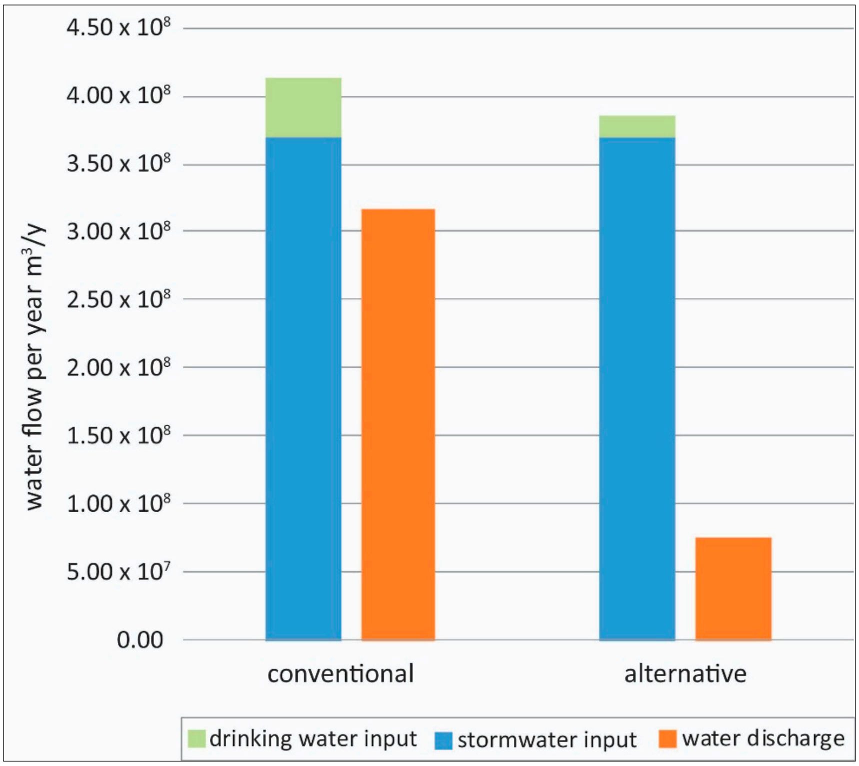

Figure 3. Whole system water flow balance for a city of 100,000 population. With the same rain precipitation (blue part), the difference in water inputs between two systems is the reduction of water withdrawal from groundwater (green part). Water input from natural resources in the alternative system is only 7% of the conventional system since most of the water is retained and recycled within the system. Only 20% of the water coming in the system is discharged in the alternative system. In the conventional system, the system efficiency is much less, with over 77% discharged.

Greywater, blackwater and yellow water are collected separately and treated at the neighborhood level for maximum energy and nutrient recovery. The greywater and blackwater are collected by separate vacuum sewer systems. Rainwater from roof and domestic greywater is drained into constructed wetland and treated for clean water use. Additional treatments such as filtration, and disinfection may be used for final polishing. Clean water is reused for non-potable indoor domestic uses (toilet flushing and clothes washing) and firefighting needs (68% of total demand). On-site containment of rainwater like rain barrels satisfies the outdoor needs (25% of total demand).

Since greywater (~57% of total) is diverted from the wastewater mixture, the volume of the waste stream is greatly reduced, so is the energy needed to convey the wastewater. The concentrated blackwater is anaerobically digested and the biogas generated undergoes further energy recovery through CHP. The energy generated will not only self-sustain the anaerobic digestion and CHP processes, but will also aid in production of struvite fertilizer. The remaining energy can feed back to the smart grid and generate revenue for the city. Another revenue source is the struvite fertilizer through yellowwater processing. Instead of transporting all the fertilizer outside the city and losing potential local productivity, the community should encourage networks of urban or peri-urban agriculture, urban forestry, community gardens, local horticulture, *etc.* to support urban self-sufficiency in food production, improve food security, food safety and local employment.

Due to the internal looping, the majority of the water (greywater and rainwater/stormwater) is mainly treated with wetland systems. The energy thermodynamically needed to disperse organics and minerals is derived from renewable energy synergistically provided by plants, the microbial community and the soil matrix, instead of the fossil fuel-driven intensive centralized treatment. Less dependence on fossil fuel means more energy independence and more resiliency for the community. Additionally, the smart land use and green infrastructure applications will support the restoration of the natural hydrologic cycle by encouraging ET and infiltration. This will have long-term buffer effects on the imminent climate change of the local region and will alleviate impacts like Urban Heat Island (UHI), drought and flooding. It will provide a more sustainable external life-support environment for the urban community.

Further study needs to be done to characterize the performance and emergy expenditure in the alternative system with the non-traditional strategies, although some technologies might be still in the nascent phase and the integration of different new technologies may present the sizeable challenges at the beginning.

4.3. Centralized and Decentralized Water Systems Challenges

Centralized systems are inherently large and experience inertia in making any big changes. Nonetheless, they reduce opportunities for innovation development and implementation because of perceived financial, organizational, system operations and technical risks. If a community wants to implement alternative technologies and practices such as: collection and storage of rainwater in existing ponds or wetlands, rainwater reuse, anaerobic digesters for generating energy that can supply homes and business; it would be more likely implemented in smaller systems. While such innovative options might not be easily carried out in the scale of centralized system; the advantage of these systems is its uniformity that assures meeting the water demand and quality standards in an economy of scale (Table 1). Nonetheless, smaller systems can only become competitive if they can meet the demand and standards in terms of the cost–benefit relations that must be controlled by experts [77].

The advantage of decentralized systems is diversity, choosing the technologies to achieve maximum system efficiency such as the system described in Section 4.2. In the event of interruption, energy blackout or water outbreak, decentralized systems are more insulated from the events because of their relative independence. It is true that decentralized systems need more community participation and management. This is the stakeholder involvement process. Whenever there are stakeholder involvements, the communities will be more likely develop the objectives suitable for their own interests and collectively find more balanced solutions. This rootedness option is better than a one-size-fit-for-all centralized system. Nevertheless, the research and the demonstration of various decentralized systems is still not sufficient. More is needed to fill the gap (Table 2).

Table 2. Comparison of the traditional and the alternative water systems.

	Traditional Water Systems		References	Alternative Solutions		References
	Advantages	**Disadvantages/Opportunities**		**Advantages**	**Disadvantages/ Opportunities**	
Water quantity	Centralized control and assurance to meet demand and standards.	Drinking standard applied to potable and non-potable increases demand. Vulnerable to failures in service that will impact the whole system.	[43,44,48,49,71,150]	Decrease in demand of potable water for non-potable uses (fit for purpose). More resilient system.	Paradigm shift towards a new revenue model not based on water consumption.	[45,52,72,90,91]
Water quality		A critical event (e.g., algae bloom or spill) can impact the whole system. For larger systems is difficult to attain at the end of the distribution.		New methods are needed for monitoring, modeling, assessing, and managing water resources using a systems approach, and watershed perspective.		
Energy use	More research is needed Energy recovery	Intensive, mostly fossil fuel-driven	[61,64,157,158]	Potential use of renewable sources Energy recovery	More research is needed	[66,68]
Wastewater contamination	Centralized control and assurance to meet standards Resource recovery	CSS that discharge overflow directly into water bodies Infiltration to groundwater due to cracks and poor joints	[58,59,101]	Mimic natural processes Resource recovery	More research is needed	[69,115,159]

Table 2. *Cont.*

	Traditional Water Systems		References	Alternative Solutions		References
	Advantages	**Disadvantages/Opportunities**		**Advantages**	**Disadvantages/ Opportunities**	
Direct cost	Economies of scale	Huge infrastructure needs to modernize systems Intensive labor and material in construction and operation	[53–55]	Lower cost community-scale systems New markets for nutrients and energy generated in the system	More research is needed	[38,56,63,64,67,75]
Indirect cost	More research is needed	Water scarcity, eutrophication, loss of aqueous habitat		Watershed and ecosystem conservation	More research is needed	
Cultural	More research is need. Less community engagement.		[77,87]	More research is need. High community engagement.		[73,79,99,100]

The research of decentralization is still in its relative infancy. Decentralization is not solely referring to downscaling to the degree of individual homes. It should be effectively linked to other alternative options such as dual water quality, energy and material recovery, and fit-for-purpose. This is exactly why we need more in depth research and demonstration in this area. Nevertheless, more needs to be done to demonstrate reliable performances and gain more experiences in its applications. Theoretical modeling and calculations provide bases for such explorations. Without trial and error, we will not be able to confidently know if it is better or worst. However, one thing we know for sure is that the current centralized system is not sustainable. One example of a non-sustainable condition of a centralized approach is the high initial investment, maintenance and update, which is a burden on the local economy [77].

Future-oriented neighborhood should be built not only considering environmental sustainability which is characterized by a water-energy self-sufficient community, but also social sustainability in terms of public spaces (e.g., central park with water feature, communal garden with locally generated fertilizer and walkable green space with more mature trees) that promote social wellness and stability for a resilient community.

5. Moving Forward

The water system for the City of Tomorrow is fundamentally different from the conventional water systems. It may represent an ideal scenario for an urban water system, however, it by no means is the best or the only alternative. It also does not discredit other means that are not included here such as water conservation or efficiency improvement. In reality, a variety of factors affect the selection of the optimum configuration for a particular urban area, including local hydrology, water resource availability, water demands, local energy and nutrient-management situations, existing infrastructure, and utility governance structure [160]. There is no one-size-fits-all solution. The effort here is to demonstrate a holistic method that potentially resolves trade-offs across spatial, temporal scales based on thermodynamic principles to address various issues facing urban systems, no matter how the system designs would be. The example design of a future system here reveals how system thinking can be realized in transformative water systems and how the sub-components can be integrated based on system optimization. Nevertheless, such a paradigm shift is no easy task. The current standards, practices, codes, and municipal requirements that guide engineering practice result in the institutional inertia [88].

There are no test models, policy playbooks or historical data to confidently guide investors and decision-makers. The transformative changes may initially seem to be unrealistic or mission impossible. What is clear, however, is that even with plenty of evidence demonstrating the ineffectiveness of the conventional systems, more evidences of the effectiveness of new, alternative options are needed before abandoning faith in an institutional belief that has significantly supported markets and practices in the past centuries. Most importantly, it has to demonstrate that holistic analysis is not just an environmental, sustainable practice, but also has substantial economic gains for the community in the long run [3]. Prevailing systems are those whose designs maximize the productivity at the optimum efficiency [161].

The new water system will also require a new operating structure and governance framework to accommodate complexity and uncertainty [162]. Drinking water, wastewater and stormwater professionals are no longer separated in different institutions or departments. A truly integrated collaboration and management is required to achieve holistic system-wide planning and operation. A new revenue model is needed that is not solely based on the flow and water usage, but rather on whole system efficiency such as energy and nutrient recovery. The economic appeal to those public utilities that struggle financially may be the main driving force for transformative changes [3,17]. More research and testing are needed for the new technologies, such as scale-up anaerobic digestion of blackwater, membrane reactors, struvite crystallization, constructed wetland and green infrastructure practices and to validate whether the new technologies provide the same protection for the public health and the ecosystem. New integrated tool and metrics such as emergy accounting are needed to explore the holistic analysis in water systems [148,149,163,164].

Finally, public perception and acceptance will be a critical factor to roll out these new ideas. The public may not be receptive to new ideas such as dual water quality, urine diversion toilets, or reclaimed water. Risk perception for most people is not from a scientific, mathematical calculation, but a gut feeling [165]. To win people over involves the delicate work of overcoming deep-rooted psychological barriers and cultural taboos surrounding water use [165]. The "yuck factor" has scuttled proposed wastewater recycling projects in San Diego, Los Angeles and elsewhere [165]. However, from a psychological perspective, when the public is being educated and communicated and the ideas are reframed differently such as reuse projects in the context of the urban water cycle and water as a reusable resource, the public is more willing to accept the ideas. In Singapore, the government has been successfully educating the public and 98% of the people now believe that reclaimed water is safe to drink [166,167].

It is encouraging to find that many communities around the world are taking steps towards more sustainable solutions [141,168]. Jenfelder Au in Hamburg, Germany is rethinking wastewater management by implementing an integrated concept for decentralized wastewater treatment, stormwater/greywater treatment, and energy recovery [169]. The city of San Francisco's non-potable water program currently aims to expand the recycled water reuse on the district-scale. The city of San Jose in northern California has been operating a dual distribution network since 1997 over 1.6 km (100 miles) and 1.4×10^6 m^3/year (10 mgd) serving over 690 customers [90]. Their current goal is to recycle 1.4×10^7 m^3/year (100 mgd) wastewater by 2022. In 2013, the city of Chicago announced the construction of the world's largest nutrient recovery facility with the potential capacity of 10,000–15,000 tons of fertilizer per year. To increase public acceptance, communities, government agencies, academics and other stakeholders should all work together and carry out more real world applications like "test beds" and "demo villages" such as those to help implement the needed changes at a faster pace. A thousand mile journey begins by taking the first step. As communities are taking incremental steps towards a more sustainable future, the City of Tomorrow will soon become the City of Today.

Acknowledgments

This research was part of the Safe and Sustainable Water Resources National Research Program in the EPA's Office of Research and Development and was supported in part by the appointments of Xiaobo Xue and Alejandra González-Mejía to the ORISE participant research program.

Author Contributions

Xin (Cissy) Ma conceptualized the design of urban water systems for the City of Tomorrow, conducted the emergy calculations and conceived the need for this review paper. Xin (Cissy) Ma drafted the earlier versions of the manuscript. Xiaobo Xue contributed to the discussions and literature review of the conventional systems. Alejandra González-Mejía contributed to the review of resource recovery, critical review and edition of the manuscript. Jay Garland and Jennifer Cashdollar provided constructive suggestions for the reorganization of the manuscript and critically reviewed the draft. All authors have read and approved the final manuscript.

Conflicts of Interest

The views expressed in this article are those of the authors and do not necessarily reflect the views or policies of the Environmental Protection Agency.

References

1. Miller, R.W.; Donahue, R.L. *Soils in Our Environment*, 7th ed.; Prentice-Hall Inc.: Eaglewood Cliffs, NJ, USA, 1990; p. 649.
2. United Nations Environment Programme. *Status Report on the Application of Integrated Approaches to Water Resources Management*; United Nations Environment Programme: Nairobi, Kenya, 2012; p. 119.
3. Bloomberg, M.; Paulson, H.; Steyer, T. Risky Business: The Economic Risks of Climate Change in the United States. Available online: http://riskybusiness.org/ (accessed on 26 June 2014).
4. Bates, B.C.; Kundzewicz, Z.W.; Wu, S.; Palutikof, J.P. *Climate Change and Water*; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2008; p. 210.
5. Melillo, J.M.; Richmond, T.C.; Yohe, G.W. *Climate Change Impacts in the United States: The Third National Climate Assessment*; U.S. Global Change Research Program: Washington, DC, USA, 2014; p. 841.
6. Schnoor, J.L. When the well runs dry. *Environ. Sci. Technol.* **2014**, *48*, 5351–5351.
7. Cordell, D.; Drangert, J.-O.; White, S. The story of phosphorus: Global food security and food for thought. *Global Environ. Chang.* **2009**, *19*, 292–305.
8. Jasinski, S.M. Phosphate rock. Mineral Commodity Summaries. U.S. Geological Survey. Available online: http://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/index.html (accessed on 17 December 2012).
9. Mino, T.; van Loosdrecht, M.C.M.; Heijnen, J.J. Review paper: Microbiology and biochemistry of the enhanced biological phosphate removal process. *Water Res.* **1998**, *32*, 3193–3207.
10. Britton, A.; Koch, F.A.; Mavinic, D.S.; Adnan, A.; Oldham, W.K.; Udala, B. Pilot-scale struvite recovery from anaerobic digester supernatant at an enhanced biological phosphorus removal wastewater treatment plant. *J. Environ. Eng. Sci.* **2005**, *4*, 265–277.
11. Oguz, E.; Gurses, A.; Canpolat, N. Removal of phosphate from wastewaters. *Cement Concr. Res.* **2003**, *33*, 1109–1113.

12. Zeng, L.; Li, X.; Liu, J. Adsorptive removal of phosphate from aqueous solutions using iron oxide tailings. *Water Res.* **2004**, *38*, 1318–1327.
13. Metson, G.S.; Iwaniec, D.M.; Baker, L.A.; Bennett, E.M.; Childers, D.L.; Cordell, D.; Grimm, N.B.; Grove, J.M.; Nidzgorski, D.A.; White, S. Urban phosphorus sustainability: Systemically incorporating social, ecological, and technological factors into phosphorus flow analysis. *Environ. Sci. Policy* **2015**, *47*, 1–11.
14. Da Silva, A.K.; Amador, J.; Cherchi, C.; Miller, S.M.; Morse, A.N.; Pellegrin, M.L.; Wells, M.J.M. Emerging pollutants—Part i: Occurrence, fate and transport. *Water Environ. Res.* **2013**, *85*, 1978–2021.
15. Bell, K.Y.; Bandy, J.; Beck, S.; Keen, O.; Kolankowsky, N.; Parker, A.M.; Linden, K. Emerging pollutants—Part ii: Treatment. *Water Environ. Res.* **2012**, *84*, 1909–1940.
16. Brookes, J.D.; Carey, C.C.; Hamilton, D.P.; Ho, L.; van der Linden, L.; Renner, R.; Rigosi, A. Emerging challenges for the drinking water industry. *Environ. Sci. Technol.* **2014**, *48*, 2099–2101.
17. Novotny, V.; Ahern, J.; Brown, P. *Water Centric Sustainable Communities*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2010.
18. Sedlak, D.L.; Schnoor, J.L. The challenge of water sustainability. *Environ. Sci. Technol.* **2013**, *47*, 5517.
19. Hill, K. Urban ecological design and urban ecology: An assessment of the state of current knowledge and a suggested research agenda. In *Cities of the Future: Towards Integrated Sustainable Water and Landscape Management*; Novotny, V., Brown, P., Eds.; IWA Publishing: London, UK, 2007; pp. 251–266.
20. Arceivala, S.J. *Wastewater Treatment and Disposal: Engineering and Ecology in Pollution Control*; Marcel Dekker, Inc.: New York, NY, USA, 1981.
21. Walsh, C. Urban impacts on the ecology of receiving waters: A framework for assessment, conservation and restoration. *Hydrobiologia* **2000**, *431*, 107–114.
22. Sirés, I.; Brillas, E. Remediation of water pollution caused by pharmaceutical residues based on electrochemical separation and degradation technologies: A review. *Environ. Int.* **2012**, *40*, 212–229.
23. Kishida, N.; Kim, J.; Tsuneda, S.; Sudo, R. Anaerobic/oxic/anoxic granular sludge process as an effective nutrient removal process utilizing denitrifying polyphosphate-accumulating organisms. *Water Res.* **2006**, *40*, 2303–2310.
24. Sakadevan, K.; Bavor, H.J. Nutrient removal mechanisms in constructed wetlands and sustainable water management. *Water Sci. Technol.* **1999**, *40*, 121–128.
25. Van Loosdrecht, M.C.M.; Brandse, F.A.; de Vries, A.C. Upgrading of waste water treatment processes for integrated nutrient removal—The BCFS® process. *Water Sci. Technol.* **1998**, *37*, 209–217.
26. Boyer, T.H.; Singer, P.C. Bench-scale testing of a magnetic ion exchange resin for removal of disinfection by-product precursors. *Water Res.* **2005**, *39*, 1265–1276.
27. Petrović, M.; Gonzalez, S.; Barceló, D. Analysis and removal of emerging contaminants in wastewater and drinking water. *TrAC Trends Anal. Chem.* **2003**, *22*, 685–696.
28. Bolong, N.; Ismail, A.F.; Salim, M.R.; Matsuura, T. A review of the effects of emerging contaminants in wastewater and options for their removal. *Desalination* **2009**, *239*, 229–246.

29. Macler, B.A.; Regli, S. Use of microbial risk assessment in setting us drinking water standards. *Int. J. Food Microbiol.* **1993**, *18*, 245–256.
30. Ashbolt, N.J.; Schoen, M.E.; Soller, J.A.; Roser, D.J. Predicting pathogen risks to aid beach management: The real value of quantitative microbial risk assessment (QMRA). *Water Res.* **2010**, *44*, 4692–4703.
31. Schoen, M.E.; Xue, X.; Hawkins, T.R.; Ashbolt, N.J. Comparative human health risk analysis of coastal community water and waste service options. *Environ. Sci. Technol.* **2014**, *48*, 9728–9736.
32. Brown, A.; Matlock, M.D. *A Review of Water Scarcity Indices and Methodologies*; White Paper #106; The Sustainability Consortium: Fayetteville, AR, USA, 2011; p. 19.
33. Schewe, J.; Heinke, J.; Gerten, D.; Haddeland, I.; Arnell, N.W.; Clark, D.B.; Dankers, R.; Eisner, S.; Fekete, B.M.; Colón-González, F.J.; *et al.* Multimodel assessment of water scarcity under climate change. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 3245–3250.
34. Lubick, N. Using nature's design to stem urban storm-water problems. *Environ. Sci. Technol.* **2006**, *40*, 5832–5833.
35. Jang, S.; Cho, M.; Yoon, J.; Yoon, Y.; Kim, S.; Kim, G.; Kim, L.; Aksoy, H. Using swmm as a tool for hydrologic impact assessment. *Desalination* **2007**, *212*, 344–356.
36. Bos, J.J.; Gijzen, H.J.; Hilderink, H.B.M.; Moussa, M.; de Ruyter van Steveninck, E.D. *Quick Scan Health Benefits and Costs of Water Supply and Sanitation*; National Institute for Public Health and the Environment: Bilthoven, The Netherlands, 2004.
37. Brown, M.T.; Martínez, A.; Uche, J. Emergy analysis applied to the estimation of the recovery of costs for water services under the european water framework directive. *Ecol. Model.* **2010**, *221*, 2123–2132.
38. Maurer, M. Full costs, (dis-)economies of scale and the price of uncertainty. In *Source Separation and Decentralization for Wastewater Management*; Larsent, T.A., Udert, K.M., Lienert, J., Eds.; IWA Publishing: London, UK, 2013; pp. 85–100.
39. Guest, J.; Skerlos, S.; Barnard, J.; Beck, M.; Daigger, G.; Hilger, H.; Jackson, S.; Karvazy, K.; Kelly, L.; Macpherson, L.; *et al.* A new planning and design paradigm to achieve sustainable resource recovery from wastewater. *Environ. Sci. Technol.* **2009**, *43*, 6126–6130.
40. Tzoulas, K.; Korpela, K.; Venn, S.; Yli-Pelkonen, V.; Kaźmierczak, A.; Niemela, J.; James, P. Promoting ecosystem and human health in urban areas using green infrastructure: A literature review. *Landsc. Urban Plan.* **2007**, *81*, 167–178.
41. Solano, M.L.; Soriano, P.; Ciria, M.P. Constructed wetlands as a sustainable solution for wastewater treatment in small villages. *Biosyst. Eng.* **2004**, *87*, 109–118.
42. Hurlimann, A.C.; McKay, J.M. What attributes of recycled water make it fit for residential purposes? The mawson lakes experience. *Desalination* **2006**, *187*, 167–177.
43. Mayer, P.; DeOreo, W.B.; Opitz, E.M.; Kiefer, J.C.; Davis, W.Y.; Dziegielewski, B.; Nelson, J.O. *Resiential end Uses of Water*; American Water Works Association Research Foundation: Denver, CO, USA, 1999.
44. National Research Council of the National Academies. *Drinking Water Distribution Systems: Assessing and Reducing Risks*; National Academies Press: Washington, DC, USA, 2006; p. 404.
45. Okun, D.A. Letter to the editor: Designing future water distribution systems. *J. Amer. Water Works Assoc.* **2005**, *6*, 99–101.

46. National Fire Protection Association (NFPA). *Fire Protection Handbook*; National Fire Protection Association (NFPA): Batterymarch Park Quincy, MA, USA, 1986.
47. Walski, T.M.; Chase, D.V.; Savic, D.A. *Water Distribution Modeling*, 1st ed.; Haestad Press: Waterbury, CT, USA, 2001.
48. Clark, R.M.; Grayman, W.M. Distribution system quality: A trade-off between public health and public safety. *J. Am. Water Works Assoc.* **1992**, *84*, 18.
49. Brandt, M.J. *Managing Distribution Retention Time to Improve Water Quality—Phase ii: Guidance Manual*; AWWRF Report 91121F; American Water Works Association Research Foundation: London, UK, 2007.
50. Lindeburg, M.R. Water supply treatment and distribution. In *Environmental Engineering Reference Manual for the PE Exam*, 2nd ed.; Professional Publications Inc.: Belmont, CA, USA, 2003; pp. 2418–2419.
51. Solomon, S. *Water: The Epic Struggle for Wealth, Power, and Civilization*; HarperCollins Publishers: New York, NY, USA, 2010.
52. Gikas, P.; Tchobanoglous, G. The role of satellite and decentralized strategies in water resources management. *J. Environ. Manag.* **2009**, *90*, 144–152.
53. Gleick, P.H. Global freshwater resources: Soft-path solutions for the 21st century. *Science* **2003**, *302*, 1524–1528.
54. U.S. Environmental Protection Agency. The Clean Water and Drinking Water Infrastructure Gap Analysis. Available online: http://www.epa.gov/ogwdw/gapreport.pdf (accessed on 9 April 2014).
55. American Society of Civil Engineers. *2013 Report Card for America's Infrastructure*; American Society of Civil Engineers: Reston, VA, USA, 2013.
56. Libralato, G.; Ghirardini, A.V.; Avezzu, F. To centralize or to decentralize: An overview of the most recent trends in wastewater treatment management. *J. Environ. Manag.* **2012**, *94*, 61–68.
57. U.S. Environmental Protection Agency. Energy Efficiency in Water and Wastewater Facilities. A Guide to Developing and Implementing Greenhouse Gas Reduction Programs. Local Government Climate and Energy Strategy Guides. Available online: www.epa.gov/statelocalclimate/resources/strategy-guides.html (accessed on 10 February 2015).
58. U.S. Environmental Protection Agency. Combined Sewer Overflows. Available online: http://cfpub.epa.gov/npdes/home.cfm (Accessed on 9 April 2014).
59. The Great Lakes—Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers. *Recommended Standards for Water Works*; The Great Lakes—Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers: Albany, NY, USA, 2012.
60. Klein, G. *California's Water–Energy Relationship*; California Energy Commission: Sacramento, CA, USA, 2005; p. 174.
61. Water Environment Federation. *Alternative Sewer Systems: Manual of Practice No. Fd-12*, 2nd ed.; WEF Press: Alexandria, VA, USA, 2008.
62. Factura, H.; Bettendorf, T.; Buzie, C.; Pieplow, H.; Reckin, J.; Otterpohl, R. Terra preta sanitation: Re-discovered from an ancient amazonian civilisation—Integrating sanitation, bio-waste management and agriculture. *Water Sci. Technol.* **2010**, *61*, 2673–2679.

63. Stichting Toegepas t Onder zoek Waterbeheer (STOWA). *Separate Urine Collection and Treatment: Options for Sustainable Wastewater Systems and Mineral Recovery*; STOWA: Amersfoort, The Netherlands, 2001.
64. The National Association of Clean Water Agencies (NACWA). *2008 Nacwa Financial Survey Summary: Highlighting Challenges in Utility Financing and Management*; NACWA: Washington, DC, USA, 2008.
65. Hering, J.G.; Waite, T.D.; Luthy, R.G.; Drewes, J.E.; Sedlak, D.L. A changing framework for urban water systems. *Environ. Sci. Technol.* **2013**, *47*, 10721–10726.
66. Heidrich, E.S.; Curtis, T.P.; Dolfing, J. Determination of the internal chemical energy of wastewater. *Environ. Sci. Technol.* **2011**, *45*, 827–832.
67. Grant, S.B.; Saphores, J.-D.; Feldman, D.L.; Hamilton, A.J.; Fletcher, T.D.; Cook, P.L.M.; Stewardson, M.; Sanders, B.F.; Levin, L.A.; Ambrose, R.F.; *et al.* Taking the "waste" out of "wastewater" for human water security and ecosystem sustainability. *Science* **2012**, *337*, 681–686.
68. McCarty, P.L.; Bae, J.; Kim, J. Domestic wastewater treatment as a net energy producer—Can this be achieved? *Environ. Sci. Technol.* **2011**, *45*, 7100–7106.
69. Otterpohl, R.; Grottker, M.; Lange, J. Sustainable water and waste management in urban areas. *Water Sci. Technol.* **1997**, *35*, 121–133.
70. Pennisi, E. Water reclamation going green. *Science* **2012**, *337*, 674–676.
71. Raucher, R.; Tchobanoglous, G. *The Opportunities and Economics of Direct Potable Reuse*; WaterReuse Research Foundation: Alexandria, VA, USA, 2014.
72. Tchobanoglous, G.; Leverenz, H. The rationale for decentralization of wastewater infrastructure. In *Source Separation and Decentralization for Wastewater Management*; Larsen, T.A., Udert, K.M., Lienert, J., Eds.; IWA Publishing: London, UK, 2013; pp. 101–115.
73. Gardner, T.; Sharma, A. Development of decentralized systems in Australia. In *Source Separation and Decentralization for Wastewater Management*; Larsen, T.A., Udert, K.M., Lienert, J., Eds.; IWA Publishing: London, UK, 2013; pp. 511–520.
74. Lee, E.J.; Criddle, C.S.; Bobel, P.; Freyberg, D.L. Assessing the scale of resource recovery for centralized and satellite wastewater treatment. *Environ. Sci. Technol.* **2013**, *47*, 10762–10770.
75. Makropoulos, C.; Butler, D. Distributed water infrastructure for sustainable communities. *Water Resour. Manag.* **2010**, *24*, 2795–2816.
76. Strother, N. Smart Water Making Gains beyond the U.S. Available online: http://www.smartgridnews.com/artman/publish/Technologies_Smart_Water/Smart-water-making-gains-beyond-the-U-S-6155.html (accessed on 3 June 2014).
77. Wilderer, P.A.; Schreff, D. Decentralised and centralised wastewater management: A challenge for developers. *Water Sci. Technol.* **2000**, *41*, 1–8.
78. Anderson, J.; Leinmiller, M. Why Smart Grid and Smart Water are Essential to A Smart City. Available online: http://www.smartgridnews.com/artman/publish/Technologies_Smart_Water/Why-smart-grid-and-smart-water-are-essential-to-a-smart-city-6365.html (accessed on 3 June 2014).
79. Hiessl, H. Alternative Scenarios of Urban Water Infrasturcture Systems. In Proceedings of the OECD Expert Meeting on "Sustainable Financing for Affordable Water Services: From Theory to Practice", Paris, France, 14–15 November 2007.

80. Larsen, T.A.; Gujer, W. Implementation of source separation and decentralization in cities. In *Source Separation and Decentralization for Wastewater Management*; Larsen, T.A., Udert, K.M., Lienert, J., Eds.; IWA Publishing: London, UK, 2013; pp. 135–150.
81. Boller, M. Source control and source separation: The Swiss experience. In *Source Separation and Decentralization for Wastewater Management*; Larsen, T.A., Udert, K.M., Lienert, J., Eds.; IWA Publishing: London, UK, 2013; pp. 439–446.
82. Londong, J. Practical experience with source separation in Germany. In *Source Separation and Decentralization for Wastewater Management*; Larsen, T.A., Udert, K.M., Lienert, J., Eds.; IWA Publishing: London, UK, 2013; pp. 423–430.
83. Sharma, A.; Grant, A.; Tjandraatmadja, G.; Grant, T.; Opray, L.; Pamminger, F. Towards sustainable water and sewerage servicing options for a multi-story infill development. In *Water Management Challenges in Global Change: Proceedings of the 9th Computing and Control for the Water Industry (CCWI 2007) and the Sustainable Urban Water Management (SUWM 2007) Conferences*; Ulanicki, B., Vairavamoorthy, K., Butler, D., Bounds, P., Memon, F., Eds.; Taylor & Francis: London, UK, 2007; pp. 507–513.
84. Weber, J.W. Optimal uses of advanced technologies for water and wastewater treatment in urban environments. *Water Supply* **2004**, *4*, 7–12.
85. Weber, J.W. Distributed optimal technology networks: A concept and strategy for potable water sustainability. *Water Sci. Technol.* **2002**, *46*, 241–246.
86. Davis, C.; Nikolic, I.; Dijkema, G.P.J. Integration of life cycle assessment into agent-based modeling. *J. Ind. Ecol.* **2009**, *13*, 306–325.
87. Childers, D.L.; Pickett, S.T.A.; Grove, J.M.; Ogden, L.; Whitmer, A. Advancing urban sustainability theory and action: Challenges and opportunities. *Landsc. Urban Plan.* **2014**, *125*, 320–328.
88. Grigg, N.; Rogers, P.; Edmiston, S. *Dual Water Systems: Characterization and Performance for Distribution of Reclaimed Water*; Web Report #4333; Water Research Foundation: Denver, CO, USA, 2013.
89. American Water Works Association (AWWA). *Planning for the Distribution of Reclaimed Water*; AWWA: Denver, CO, USA, 2009.
90. Okun, D.A. Distribuing reclaimed water through dual systems. *J. Amer. Water Works Assoc.* **1997**, *89*, 52–64.
91. National Research Council. *Water Conservation, Reuse, and Recycling: Proceedings of an Iranian-American Workshop*; The National Academies Press: Washington, DC, USA, 2005.
92. U.S. Environmental Protection Agency. *Guidelines for Water Reuse*; EPA/600/R-12/618; U.S. Environmental Protection Agency: Washington, DC, USA, 2012.
93. Grant, S.B.; Fletcher, T.D.; Feldman, D.; Saphores, J.-D.; Cook, P.L.M.; Stewardson, M.; Low, K.; Burry, K.; Hamilton, A.J. Adapting urban water systems to a changing climate: Lessons from the millennium drought in southeast Australia. *Environ. Sci. Technol.* **2013**, *47*, 10727–10734.
94. Mohanty, S.K.; Torkelson, A.A.; Dodd, H.; Nelson, K.L.; Boehm, A.B. Engineering solutions to improve the removal of fecal indicator bacteria by bioinfiltration systems during intermittent flow of stormwater. *Environ. Sci. Technol.* **2013**, *47*, 10791–10798.

95. Armentano, T.V. Drainage of organic soils as a factor in the world carbon cycle. *BioScience* **1980**, *30*, 825–830.
96. Odum, E.P.; Barrett, G.W. *Fundamental of Ecology*, 5th ed.; Brooks/Cole: Belmont, CA, USA, 2005.
97. Jasper, J.T.; Sedlak, D.L. Phototransformation of wastewater-derived trace organic contaminants in open-water unit process treatment wetlands. *Environ. Sci. Technol.* **2013**, *47*, 10781–10790.
98. Kusler, J. Common questions: Wetlands, climate change, and carbon sequestering. Available online: http://aswm.org/pdf_lib/11_carbon_6_26_06.pdf (accessed on 9 April 2014).
99. Wendel, H.E.W.; Downs, J.A.; Mihelcic, J.R. Assessing equitable access to urban green space: The role of engineered water infrastructure. *Environ. Sci. Technol.* **2011**, *45*, 6728–6734.
100. Mazzotta, M.J.; Besedin, E.; Speers, A.E. A meta-analysis of hedonic studies to assess the property value effects of low impact development. *Resources* **2014**, *3*, 31–61.
101. The National Association of Clean Water Agencies (NACWA); The Water Environment Research Foundation (WERF); The Water Environment Federation (WEF). *The Water Resources Utility of the Future: A Blueprint for Action*; NACWA: Washington, DC, USA; WERF: Washington, DC, USA; WEF: Washington, DC, USA, 2013; p. 48.
102. U.S. Environmental Protection Agency. Reducing urban heat islands: Compendium of strategies. Available online: http://www.epa.gov/heatisland/resources/compendium.htm (accessed on 30 May 2014).
103. Romitelli, M.S. *Energy Analysis of Watersheds*; University of Florida: Gainsville, FL, USA, 1997.
104. Peng, S.; Piao, S.; Ciais, P.; Friedlingstein, P.; Ottle, C.; Bréon, F.-M.; Nan, H.; Zhou, L.; Myneni, R.B. Surface urban heat island across 419 global big cities. *Environ. Sci. Technol.* **2011**, *46*, 696–703.
105. Shepherd, J.M. A review of current investigations of urban-induced rainfall and recommendations for the future. *Earth Interact.* **2005**, *9*, 1–27.
106. Arden, S.; Ma, X.; Brown, M. Ecohydrologic effects of urbanization on evapotranspiration in shallow groundwater table environments. *Water Sci. Technol.* **2014**, *70*, 1789–1797.
107. U.S. Environmental Protection Agency. *Protecting Water Quality from Urban Runoff*; EPA 841-F-03-003; U.S. Environmental Protection Agency: Washington, DC, USA, 2003.
108. Coffman, L. Low-impact development design strategies, an integrated design approach. Prince George's County, Maryand. Available online: http://water.epa.gov/polwaste/green/upload/lidnatl.pdf (accessed on 25 June 2014).
109. Odum, E.P. *Basic Ecology*; Saunders College Pub.: Philadelphia, PA, USA, 1983.
110. Saddleback Educational Publishing. *Water Conservation*; Saddleback Educational Publishing: Costa Mesa, CA, USA, 2009.
111. Southern Nevada Water Authority. Water Banking. Available online: http://www.snwa.com/ws/future_banking.html (accessed on 25 June 2014).
112. Panfil, C.; Mirel, I.; Szigyarto, I.; Isacu, M. Technical, economical, social and ecological characteristics of vacuum sewage system. *Environ. Eng. Manag. J.* **2013**, *12*, 1017–1022.
113. U.S. Environmental Protection Agency. *Composting Yard Trimmings and Municipal Solid Waste*; EPA530-R-94-003; U.S. Environmental Protection Agency: Washington, DC, USA, 1994.

114. Larsen, T.A.; Alder, A.C.; Eggen, R.I.L.; Maurer, M.; Lienert, J. Source separation: Will we see a paradigm shift in wastewater handling? *Environ. Sci. Technol.* **2009**, *43*, 6121–6125.
115. Otterpohl, R. Options for alternative types of sewerage and treatment systems directed to improvement of the overall performance. *Water Sci. Technol.* **2002**, *45*, 149–158.
116. Vogel, G. Finding a new way to go. *Science* **2012**, *337*, 673.
117. Gutschick, V. Energy and nitrogen fixation. *BioScience* **1978**, *28*, 571–575.
118. Smil, V. Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production; The MIT Press: Cambridge, MA, USA, 2004.
119. Metson, G.S.; Hale, R.L.; Iwaniec, D.; Cook, E.M.; Gorman, J.R.; Galletti, C.S.; Childers, D.L. Phosphorus in phoenix: A budget and spatial representation of phosphorus in an urban ecosystem. *Ecol. Appl.* **2012**, *22*, 705–721.
120. Childers, D.L.; Corman, J.; Edwards, M.; Elser, J.J. Sustainability challenges of phosphorus and food: Solutions from closing the human phosphorus cycle. *BioScience* **2011**, *61*, 117–124.
121. Rahman, M.M.; Salleh, M.A.M.; Rashid, U.; Ahsan, A.; Hossain, M.M.; Ra, C.S. Production of slow release crystal fertilizer from wastewaters through struvite crystallization—A review. *Arab. J. Chem.* **2014**, *7*, 139–155.
122. Mo, W.W.; Zhang, Q. Energy-nutrients-water nexus: Integrated resource recovery in municipal wastewater treatment plants. *J. Environ. Manag.* **2013**, *127*, 255–267.
123. De-Bashan, L.; Bashan, Y. Recent advances in removing phosphorus from wastewater and its future use as fertilizer (1997–2003). *Water Res.* **2004**, *38*, 4222–4246.
124. Gaterell, M.R.; Gay, R.; Wilson, R.; Gochin, R.J.; Lester, J.N. An economic and environmental evaluation of the opportunities for substituting phosphorus recovered from wastewater treatment works in existing UK fertiliser markets. *Environ. Technol.* **2000**, *21*, 1067–1084.
125. Logan, B.E.; Rabaey, K. Conversion of wastes into bioelectricity and chemicals by using microbial electrochemical technologies. *Science* **2012**, *337*, 686–690.
126. U.S. Environmental Protection Agency. Case study primer for participant discussion: Biodigesters and biogas. Available online: http://www.epa.gov/agstar/documents/biogas_primer.pdf (accessed on 9 April 2014).
127. Moriarty, K. Feasibility study of anaerobic digestion of food waste in st. Bernard, Louisiana. National Renewable Energy Laboratory. Available online: http://www.nrel.gov/docs/fy13osti/57082.pdf (accessed on 11 April 2014).
128. Augustin, K.; Skambraks, A.-K.; Li, Z.; Giese, T.; Rakelmann, U.; Meinzinger, F.; Schonlau, H.; Günner, C. Towards sustainable sanitation—The hamburg water cycle in the settlement jenfelder Au. *Water Sci. Technol.: Water Supply* **2014**, *14*, 13–21.
129. De Graaff, M.; Temmink, H.; Zeeman, G.; Buisman, C. Anaerobic treatment of concentrated black water in a uasb reactor at a short HRT. *Water* **2010**, *2*, 101–119.
130. Xu, S.N.; Wu, D.L.; Hu, Z.Q. Impact of hydraulic retention time on organic and nutrient removal in a membrane coupled sequencing batch reactor. *Water Res.* **2014**, *55*, 12–20.
131. Kim, J.; Kim, K.; Ye, H.; Lee, E.; Shin, C.; McCarty, P.L.; Bae, J. Anaerobic fluidized bed membrane bioreactor for wastewater treatment. *Environ. Sci. Technol.* **2010**, *45*, 576–581.

132. Shin, C.; McCarty, P.L.; Kim, J.; Bae, J. Pilot-scale temperate-climate treatment of domestic wastewater with a staged anaerobic fluidized membrane bioreactor (SAF-MBR). *Bioresour. Technol.* **2014**, *159*, 95–103.
133. Zeeman, G.; Kujawa, K.; de Mes, T.; Hernandez, L.; de Graaff, M.; Abu-Ghunmi, L.; Mels, A.; Meulman, B.; Temmink, H.; Buisman, C.; *et al.* Anaerobic treatment as a core technology for energy, nutrients and water recovery from source-separated domestic waste(water). *Water Sci. Technol.* **2008**, *57*, 1207–1212
134. Lettinga, G.; Roersma, R.; Grin, P. Anaerobic treatment of raw domestic sewage at ambient-temperatures using a granular bed UASB reactor. *Biotechnol. Bioeng.* **1983**, *25*, 1701–1723.
135. Ren, L.J.; Ahn, Y.; Logan, B.E. A two-stage microbial fuel cell and anaerobic fluidized bed membrane bioreactor (MFC-AFMBR) system for effective domestic wastewater treatment. *Environ. Sci. Technol.* **2014**, *48*, 4199–4206.
136. U.S. Environmental Protection Agency. *Opportunites for and Benefits of Combined Heat and Power at Wastewater Treatment Facilities*; EPA-430-R-07-003; U.S. Environmental Protection Agency: Washington, DC, USA, 2007.
137. Lindtrom, H.O. Experiences with a 3.3 MW heat pump using sewage water as heat source. *Heat Recovery Systems* **1985**, *5*, 33–38.
138. Lin, S.; Yip, N.Y.; Cath, T.Y.; Osuji, C.O.; Elimelech, M. Hybrid pressure retarded osmosis–membrane distillation system for power generation from low-grade heat: Thermodynamic analysis and energy efficiency. *Environ. Sci. Technol.* **2014**, *48*, 5306–5313.
139. Lehmann, S. *The Principles of Green Urbanism-Transforming the City for Sustainability*; Routledge: New York, NY, USA, 2010.
140. Brown, R.R.; Keath, N.; Wong, T.H.F. Urban water management in cities: Historical, current and future regimes. *Water Sci. Technol.* **2009**, *59*, 847–855.
141. Global Water Partnership. Toolbox: Case Studies. Available online: http://www.gwp.org/en/ToolBox/CASE-STUDIES/ (accessed on 8 October 2014).
142. Xue, X.; Schoen, M.E.; Ma, X.; Hawkins, T.R.; Ashbolt, N.J.; Cashdollar, J.; Garland, J. Critical insights for a sustainability framework to address integrated community water services: Technical metrics and approaches. *Water Res.* **2015**, *77*, 155–169.
143. Wood, A.; Blackhurst, M.; Hawkins, T.; Xue, X.; Ashbolt, N.; Garland, J. Cost-effectiveness of nitrogen mitigation by alternative household wastewater management technologies. *J. Environ. Manag.* **2015**, *150*, 344–354.
144. Thomson Reuters. Web of science [v.5.18] (search engine). Available online: http://thomsonreuters.com/en/products-services/scholarly-scientific-research/scholarly-search-and-discovery/web-of-science.html (accessed on 10 August 2015).
145. Fugaro, L.; Picchi, M.P.; Principi, I. *Application of Emergy Analysis to Sustainable Management of Water Resources*; A. A. Balkema Publishers: Leiden, The Netherlands, 2004; pp. 37–43.
146. Arbault, D.; Rugani, B.; Tiruta-Barna, L.; Benetto, E. Emergy evaluation of water treatment processes. *Ecol. Eng.* **2013**, *60*, 172–182.
147. Zhou, J.B.; Jiang, M.M.; Chen, B.; Chen, G.Q. Emergy evaluations for constructed wetland andconventional wastewater treatments. *Communications in Nonlinear Science and Numerical Simulation* **2009**, *14*, 1781–1789.

148. Hester, E.T.; Little, J.C. Measuring environmental sustainability of water in watersheds. *Environ. Sci. Technol.* **2013**, *47*, 8083–8090.
149. Odum, H.T. *Environmental Accounting*; John Wiley & Sons: New York, NY, USA, 1996.
150. Gleick, P. Water Use. *Annu. Rev. Environ. Resour* **2003**, *28*, 275–314.
151. Odum, H.T. Emergy evaluation. In *International Workshop on Advances in Energy Studies: Energy Flows in Ecology and Economy*; Biennial International Workshop Advances in Energy Studies: Porto Venere, Italy, 1998.
152. Prigogine, I.; Nicolis, G.; Babloyants, A. Thermodynamics of evolution (part i). *Phys. Today* **1972**, *25*, 23–28.
153. Prigogine, I.; Nicolis, G.; Babloyants, A. Thermodynamics of evolution (part ii). *Phys. Today* **1972**, *25*, 38–44.
154. Brown, M.T.; Ulgiati, S. Updated evaluation of exergy and emergy driving the geobiosphere: A review and refinement of the emergy baseline. *Ecol. Model.* **2010**, *221*, 2501–2508.
155. Björklund, J.; Geber, U.; Rydberg, T. Emergy analysis of municipal wastewater treatment and generation of electricity by digestion of sewage sludge. *Resour. Conserv. Recycl.* **2001**, *31*, 293–316.
156. Geber, U.; Bjo¨rklund, J. The relationship between ecosystem services and purchased input in swedish wastewater treatment systems—A case study. *Ecol. Eng.* **2002**, *19*, 97–117.
157. Griffiths-Sattenspiel, B.; Wilson, W. *The Carbon Footprint of Water*; River Network: Portland, OR, USA, 2009.
158. California Energy Commission. California's Water–Energy Relationship. Available online: http://www.energy.ca.gov/2005publications/CEC-700-2005-011/CEC-700-2005-011-SF.PDF (accessed on 24 August 2015).
159. Otterpohl, R.; Braun, U.; Oldenburg, M. Innovative technologies for decentralised water-, wastewater and biowaste management in urban and peri-urban areas. *Water Sci. Technol.* **2003**, *48*, 23–32.
160. Daigger, G.T. Evolving urban water and residuals management paradigms: Water reclamation and reuse, decentralization, resource recovery. *Wat. Env. Res* **2009**, *81*, 809–823.
161. Ulgiati, S.; Bargigli, S.; Raugei, M. An emergy evaluation of complexity, information and technology, towards maximum power and zero emissions. *J. Clean. Prod.* **2007**, *15*, 1359–1372.
162. Farrelly, M.; Brown, R. Rethinking urban water management: Experimentation as a way forward? *Global Environ. Chang.* **2011**, *21*, 721–732.
163. National Research Council. *Sustainability Concepts in Decision-Making: Tools and Approaches for the US Environmental Protection Agency*; National Research Council of the National Academies: Washington, DC, USA, 2014.
164. U.S. Environmental Protection Agency. *Sustainability Analytics: Assessment Tools & Approaches*; U.S. Environmental Protection Agency: Cincinnati, OH, USA, 2013; p. 166.
165. Miller, G. Getting minds out of the sewer. *Science* **2012**, *337*, 679–680.
166. Schnoor, J.L. Newater future? *Environ. Sci. Technol.* **2009**, *43*, 6441–6442.
167. Asian Development Bank (ADB). *Every Drop Counts: Learning from Good Practices in Eight Asian Cities*; ADB: Mandaluyong City, Philippines, 2010.

168. Bahri, A. *Integrated Urban Water Management*; Global Water Partnership: Stockholm, Sweden, 2012.
169. Skambraks, A.-K.; Augustin, K.; Meinzinger, F. Key Factors and Challenges for Implementing the Large-Scale Integrated Wastewater and Energy Generation Concept HAMBURG WATER Cycle® in the Settlement Jenfelder Au in Hamburg. In Proceedings of the International Water Week Conference, Amsterdam, The Netherland, 4–8 November 2013.