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Urban Stormwater to Enhance Water Supply

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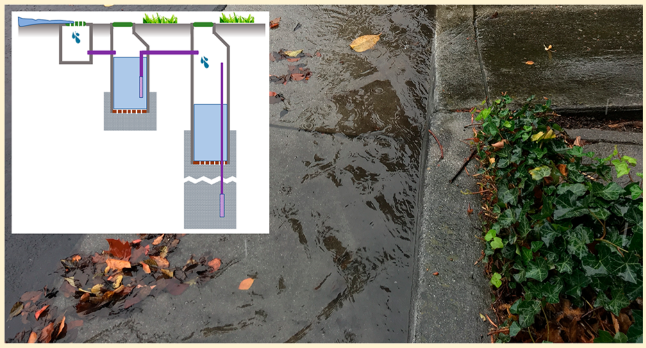
ABSTRACT: The capture, treatment, and recharge of urban runoff can augment water supplies for water-scarce cities. This article describes trends in urban stormwater capture for potable water supply using examples from the U.S. and Australia. In water-limited climates, water supply potential exists for large scale stormwater harvesting and recharge, such as neighborhood-scale and larger projects. The beneficial use of urban stormwater to meet nonpotable water demands has been successfully demonstrated in the U.S. and internationally. However, in terms of potable water use in the U.S., the lack of a regulatory framework and uncertainty in treatment and water quality targets are barriers to wide-scale adoption of urban stormwater for recharge, which is not so evident in Australia. More data on urban stormwater quality, particularly with respect to pathogens and polar organic contaminants, are needed to better inform treatment requirements. New technologies hold promise for improved operation and treatment, but must be demonstrated in field trials. Stormwater treatment systems may be needed for large-scale recharge in highly urbanized areas where source control is challenging. The co-benefits of water supply, urban amenities, and pollution reduction are important for financing, public acceptance and implementation—but are rarely quantified.



INTRODUCTION

Many cities, including those in Australia and the U.S. west and southeast, experience chronic or episodic water supply shortages. Water shortages in semi-arid regions are ever more evident in the 21st Century due to population growth, economic development, and impacts of climate change.[1] These same cities face challenges with managing urban runoff to control nutrient loads and pollution. This incongruity of not enough water for urban supply and yet environmental degradation due to runoff has changed thinking on stormwater management. Harvesting urban stormwater for water supply is being viewed as a resource that may alleviate local water shortages and benefit receiving water quality.[2] However, there remain unknowns on risks and benefits for use of urban stormwater as a new water supply that limit acceptance of this practice in the U.S. This feature examines trends in urban stormwater capture for potable water supply and irrigation, via aquifer recharge, and discusses acceptance, treatment, regulations, and risk. The focus is on larger-scale systems, such as neighborhood-scale and larger, to make an impact on the water supply from urban runoff in dry climates for water-scarce cities. Current U.S. and Australian examples are used to demonstrate what has been done, how risks are managed, and opportunities for innovation.

Stormwater infrastructure is designed foremost for flood protection, and this priority drove major stormwater infrastructure investments in the 20th Century. Los Angeles, for example, with its Mediterranean climate is prone to flooding, and the city's extensive stormwater network was designed to route runoff to the ocean as quickly and efficiently as possible. While effective for flood control, this conveys polluted stormwater runoff that impacts coastal water quality.[3] This need for environmental protection along with the challenge of becoming more self-reliant for water supplies is changing how we manage and use stormwater in the 21st Century.[4]

Community knowledge about water lends support for water-related projects such as stormwater use. Surveys in Australia show that greater water knowledge is associated with conservation and support for alternative water sources.[5] Similarly bond measures in northern and southern California pass by two-thirds majority when the voters understand the benefits of improvements to water quality and supply, and environmental protection.

Changing Perspective on Stormwater Management. Water rights may constrain what is feasible for stormwater capture. For inland areas like much of the western U.S. and Australia, stormwater capture and use may impinge on downstream water rights dependent on that runoff. In Colorado, for example, it is only recently that rainwater from rooftop gutters was allowed for nonpotable outdoor uses—and

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Figure 1. National Park Service constructed large stormwater cisterns under the National Mall for turf irrigation (center photo). Stormwater is processed through microscreens and ultraviolet light disinfection (right photo). On-site stormwater use is attractive where rainfall is more uniform throughout the year. (Right and left photos by the authors, center photo National Park Service).

only with rain barrels with a combined capacity of 110 gallons. For coastal cities the capture of stormwater does not impinge on water rights, since the water would otherwise have been discharged to the ocean. Some coastal cities, for example, San Diego, lack aquifers and sufficient rainfall for stormwater capture to significantly impact water supply.

Thus, depending on water law and local conditions, beneficial use of urban stormwater will help drought-proof cities by reducing dependence on imported water or unsustainable groundwater withdrawals. The specter of water-scarce cities in the U.S., Australia, and elsewhere highlight the need for long-term conservation measures and regional drought planning to achieve resilience to future droughts and climate change. Conservation, water reuse, desalination, water banking, and stormwater use will help diversify water supplies for cities. Among these options, stormwater is now viewed in a new light—less as solely a flood control problem and more as an opportunity for water supply augmentation and greening semi-arid urban areas.

Water scarcity and pollutants in runoff from municipal separate stormwater sewer systems (MS 4s) led California to define stormwater as a water resource with the goal of increasing the use of stormwater over 2007 levels by one million acre-ft/yr (1.2 B m^3) by 2030.[6] Some information is available on the costs, benefits, and risks of urban stormwater use, but in general such practical information beyond the simplest applications is limited. Urban stormwater for groundwater recharge poses risk of groundwater contamination and requires robust data, careful design and appropriate operation and maintenance to mitigate those risks.[7,8]

Project Size and Storage. Stormwater capture projects can be divided into three main categories depending on size and use.[9] Centralized recharge projects capture stormwater in large infrastructure systems, such as spreading basins. Distributed, or neighborhood, stormwater recharge systems include green streets, park retrofits, and dry wells. Distributed systems for direct on-site use employ tanks or cisterns.

For stormwater systems with frequent events throughout the year, detention storage requirements may be small and can be addressed using tanks and small impoundments.[2] For stormwater systems with seasonal or intermittent flows, large storage is required by dams or aquifer recharge. Subsurface storage in shallow aquifers, if they are available, is preferred because storage capacity already exists and it only has to be accessed. While stormwater yields are climate-dependent, coupling stormwater with aquifer recharge may give reliable and resilient supplies.[10] Cities that already have overdrafted aquifers that contain potable water would have a significant cost advantage for storing and recovering treated stormwater.[2]

Impact of Future Stormwater Capture on a City's Water Supply. Examples from Southern California and Southern Australia are illustrative of the potential impact of urban stormwater capture on future water supplies. Currently the City of Los Angeles captures about 64 000 acre-ft/yr (79 M m^3/yr) of stormwater through existing centralized capture and incidental distributed recharge.[11] This number could increase by an additional 115 000−194 000 acre-ft/yr (142−239 M m^3/yr) under the City's long-term Stormwater Capture Master Plan—a 2- to 4-fold increase from today's value. Whether or not these goals are achieved depends on technical and financial feasibility, managing and preventing groundwater contamination, assumptions about land use, and sustained political will. Considering that Los Angeles' water needs are estimated at about 711 000 acre-ft/yr (880 M m^3/yr) in 2035, it is clear that stormwater capture could play an important role

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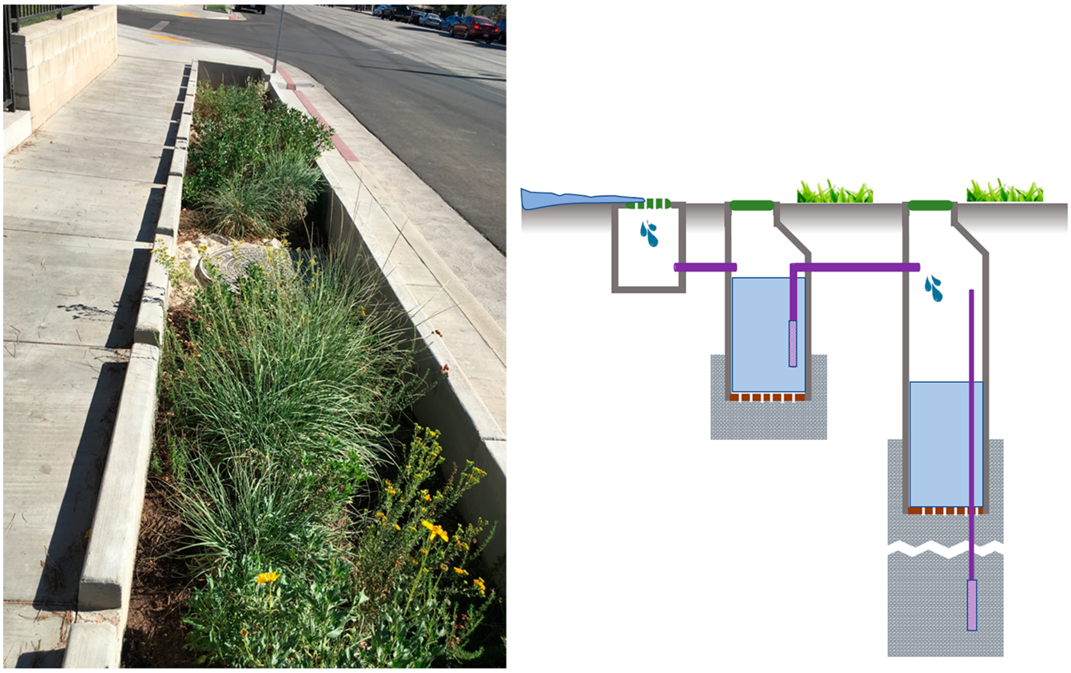

Figure 2. Curbside dry well installation with vegetation in Los Angeles. The system comprises three chambers—one for particle settling with the second and third chambers allowing percolation from the base into crushed rock or by an overflow pipe in the third chamber set into crushed rock. (photo by the authors).

in diversifying the city's water supply and reducing the need for imported water.

The Millennium Drought in Australia caused a shift in attitude about stormwater management and new thinking on how to capture and store urban stormwater.[12,13] For Greater Adelaide, a city with a Mediterranean climate, the plan is to triple the amount of stormwater harvesting from 16 000 acre-ft/yr (20 M m^3/yr) in 2013 to 48 000 acre-ft/yr (60 M m^3/yr) in 2050.[14] This increase could accommodate about half the growth in water demand expected by 2050.[14] Seawater desalination has also been initiated at Adelaide with a plant capacity of 72 MGD (100 M m^3/yr) installed for potable supplies. But, managed aquifer recharge with stormwater can produce irrigation and potable water at one-third and one-half the costs, respectively, of the optimum cost of desalination.[15] During the Millennium Drought, desalination was implemented very quickly at Adelaide and the plant is now operated at minimal capacity to keep it in a functioning condition as a backup measure for drought security.

Given the range in climatic and geographic conditions across California and Australia, cities with different challenges respond differently to water scarcity. A comparison point is San Diego and Perth. Both have embraced seawater desalination and water recycling for augmenting potable water supplies.[1,4,16] But Perth has also developed stormwater harvesting for nonpotable use.

Examples of Stormwater Capture for Use. Stormwater capture in large cisterns may be practical in locales where rainfall and demand are more uniform throughout the year. One example is Washington, DC. where the National Park Service built a stormwater capture system on the National Mall for turf irrigation (Figure 1). Four 250 000-gallon cisterns (totaling 3800 m^3) collect runoff from the Mall's turf and walkways. The stormwater capture and treatment system is the primary water source for irrigation, reducing potable water demand and harmful stormwater discharges.[2,17,18] The stormwater is treated in underground facilities using microscreens (25 μm) and ultraviolet disinfection. The microscreens prevent fouling of the irrigation system, while the UV disinfection system is deemed important to reduce health risk to the large number of visitors that frequent the National Mall.

Similarly, stormwater harvesting in Royal Park, Melbourne, Australia employs a cistern. The runoff passes through a sediment trap, wetlands, and open-water storage, followed by UV disinfection and holding in a 1.3 M gal (5000 m^3) underground tank prior to use for irrigation. The water is applied through spray irrigation at night to minimize human health risks.[19]

In arid regions with Mediterranean climate, cisterns are impractical owing to the asynchronous nature of rainfall and water demand, which requires storing large amounts of water for six to eight months during the dry season. In this case urban aquifers can store stormwater by infiltration. In Los Angeles, CA, U.S., for example, the Rory M. Shaw Wetlands Park in the Sun Valley neighborhood is being built to capture up to 900 acre-ft/yr (1.1 M m^3/yr) of urban runoff.[3,20] The collected stormwater will be pumped to an adjacent infiltration system that takes advantage of the permeable media in this area. This neighborhood-scale project contributes to water supply while converting a blighted landscape into 46 acres (19 Ha) of green space and recreation.

Dry wells, also called vadose zone wells or leaky wells, are vertical pipe-like devices with coarse media and an open bottom and holes in the walls that percolate water to the surrounding soil (Figure 2). The only treatment may be a sediment trap to remove debris or a geotextile fabric to further prevent clogging.[21] In California, dry wells are used with caution due to the concern that they provide a conduit for contaminants to enter the groundwater.[22] Dry wells in New Jersey are prohibited in industrial or other areas where toxic chemicals might be used, whereas in Pennsylvania dry wells are permitted in industrial areas with restrictions, but not along

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roadways. Some newer designs consist of three parts: a vegetated pretreatment feature, a structural pretreatment sedimentation well, and the dry well itself, which contains layers of sand or gravel. The goal of this design is to maximize the removal of particle-associated pollutants, reduce clogging of the dry well, and promote efficient infiltration. These types of designs are implemented in Los Angeles in the San Fernando Valley, as shown in Figure 2.[23,24] However, data on actual water volume infiltrated and water quality in such dry wells are lacking.

A water partnership in South Australia undertook a multiyear research project that evaluated the quality of stormwater, treatment requirements, risk management, and public acceptance of various stormwater use options. The primary case study was in Salisbury, a suburb of Adelaide.[15] Focus groups cited "equality" and "trust" as being of prime importance for public acceptance followed by the environmental benefits of stormwater harvesting to mitigate beach and marine impacts.

Costs and Benefits. Unit costs of stormwater capture projects are highly variable. Among the least expensive options in terms of cost-per-volume captured are retrofitting centralized spreading basins where the land is already available for this purpose. Unit costs increase for distributed projects because they involve more infrastructure to capture smaller flow volumes. This is illustrated by data compiled by the Southern California Stormwater Coalition.[25] The group surveyed agencies across Southern California to get a better understanding of actual capture volumes, costs, and benefits. Projects that may capture about 600 acre-ft/yr cost less than \$1200/AF. Median costs for distributed projects are \$25,000 per acre-foot, new centralized projects are \$6,900 per acre-foot, and retrofit projects are \$600 per acre-ft. Similar costs exist in Australia for larger stormwater recharge projects,[26] where stormwater harvesting is very cost competitive—especially compared to desalination. As space for large projects is increasingly scarce, decentralized projects at parks, schools, and roadways become affordable options.

Based on Los Angeles' projections for water import costs, the estimated economic value of recharged water may be \$1100 per acre-ft (\$0.89/m^3) or more based on lifecycle analysis.[11,27] Projects with costs below these values are economically viable based solely on the water supply benefit, and cities are more likely to pursue these projects without seeking funds from external partners. However, caution must be exercised in comparison with cost of current water supplies, as much of those costs were heavily subsidized in the past and there really is not new water to be had at the old rates. Stormwater capture and use project costs can be notably less than or greater than costs for current supplies.[25]

Many projects lack flow meters and do not include monitoring, in which case yields are estimated or modeled. Distributed projects offer multiple benefits, such as green space, walkways, recreation, and downstream water quality improvements. Although co-benefits are difficult to monetize, co-benefits can create partnerships, coalitions, and political momentum to bring projects to fruition.[2,15]

Microbial Risk and Treatment. While regulatory frameworks and water quality requirements do exist for roof runoff capture in the U.S.,[2] regulations for beneficial use of stormwater at a larger scale are sparse (Table 1). The only state that has a regulation for such projects is Minnesota. The Cities of Los Angeles, CA and San Francisco, CA and the District of Columbia have developed programs to allow for beneficial use of stormwater. These programs focus on collection of stormwater in cisterns or tanks for storage and subsequent use. These state and local programs for beneficial use of stormwater have enabled projects to move forward that serve as viable demonstrations (e.g., the National Mall). However, water quality requirements, particularly for pathogens, are highly variable. Three of the four programs allowing use of stormwater have water quality requirements for *E. coli* in treated stormwater, and those requirements range from 2.2−4615 CFU/100 mL for unrestricted irrigation and 2.2−50 000 CFU/100 mL for indoor use (toilet flushing and laundry; Table I). This large range of water quality requirements and approaches for regulating treated stormwater quality for various end uses is indicative of lack of guidance to develop a risk based approach for beneficial use of stormwater in the U.S. Lack of data on pathogen concentrations in stormwater and high variability in observed pathogen concentrations[2,28] contribute to the ambiguity around setting treatment targets and water quality standards for end uses of treated stormwater.

Between 2006 and 2009, a set of four national guidelines for water recycling were published by the Council of Australian Governments within the National Water Quality Management Strategy, and using common principles. These cover water recycling for nonpotable use,[29] and recycling for augmenting potable supplies,[30] stormwater harvesting and use,[31] and managed aquifer recharge.[7] For stormwater use for irrigation with no access restrictions, treatment requirements are specified for disinfection, turbidity, and iron. Disinfection criteria suggest >1.6 log reduction of virus and bacteria and >0.8 log reduction of protozoa,[15,31,32] which are less strict than the log reductions required for stormwater use for irrigation in San Francisco referenced in Table I.

For managed aquifer recharge in Australia, a risk assessment[32] and management plan[33] are undertaken to account for source water quality and its variability, native groundwater quality, and changes in water quality that occur during passage through the subsurface, such as pathogen inactivation and biodegradation of organic chemicals, as well as mobilization of metals.[7] Some data are available on the maximum inactivation times in aerobic and anoxic aquifers for *E. coli*, salmonella and bacteriophage MS2 that can serve as a basis for precommissioning estimation of reduction of pathogens.[7] However, more data are needed on pathogen attenuation rates under varying aquifer conditions. Thus, validation that includes in situ chamber decay studies is recommended to provide site-specific decay rates of pathogens.

To support the development of a risk based approach for use of nonpotable water in the U.S., the Water Reuse Foundation assembled a panel to outline a risk based framework for decentralized nonpotable water systems that included stormwater.[34] The framework proposed is similar to the Australian guidelines previously mentioned. The approach moves away from end point analysis of water quality and toward designing systems to achieve log reduction targets (LRTs). The City of San Francisco adopted this approach and includes this in regulating LRTs for virus, bacteria, and protozoa for different end uses of stormwater (Table I).

With respect to risk from pathogens, the LRTs provided by Sharvelle et al. for stormwater can serve as a basis for design of stormwater treatment systems for captured water.[34] A treatment system including 50 μm filtration and 150 mJ/cm^2 UV dose can achieve health risk based-targets for unrestricted

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access irrigation (i.e., 3, 3.5, 6-log reduction of virus, bacteria, and protozoa, respectively). Addition of slow sand filtration would increase performance[35] and lower the required UV dose.

While the LRTs recommended by Sharvelle et al.[34] provide a basis for treatment requirements for on-site use of stormwater, there was large uncertainty in those values. Due to limited data on pathogen concentrations characterized by large variability,[28] the approach adopted by Sharvelle et al.[34] to estimate LRTs for stormwater use for various end uses was to consider dilution with raw sewage. Thus, LRTs were provided for stormwater with a 10^{-1} and 10^{-3} dilution of sewage water. The basis for these dilutions was observed concentration of pathogens in stormwater.[28] The LRTs for stormwater based on sewage dilution were intended to provide decision makers with the range of likely impacts from human contamination based on age of infrastructure, potential for leaky sewers, and measurement of pathogens or indicator organisms in collected stormwater. The recommended LRTs provide a path to enable projects designed to meet human health targets to move forward. However, the LRTs should be better informed by more data on pathogens in stormwater and the reduction targets may be overly conservative, resulting in stormwater treatment systems that are costlier and more energy intensive than needed to provide an acceptable level of risk.

Chemical Contaminants in Urban Runoff. Pollutants most frequently detected in urban runoff include metals, bacteria, nutrients, salts, and petroleum hydrocarbons.[36,37] This reflects the fact that most stormwater monitoring programs have focused on regulated contaminants for protection of aquatic ecosystems and beach water quality. Although found in urban stormwater runoff, these contaminants are not necessarily a threat to the underlying groundwater because they are often removed as they percolate into the ground.[36,38,39] In contrast, recent studies report the presence of unregulated moderately polar trace organic contaminants (e.g., flame retardants, biocides, plastic additives, perfluorinated compounds) in stormwater runoff.[40,41] Some of these chemical contaminants could pose larger threats to drinking water than the contaminants that have driven discharge permits, that is, total maximum daily loads (TMDLs). For example, widely used urban insecticides (e.g., fipronil) have been detected in urban residential runoff,[40,42] and found in dry wells (e.g., bifenthrin), and predicted to migrate in time through the vadose zone under dry wells.[43]

Australia provides guidelines for design and operation of large stormwater infiltration via managed aquifer recharge.[7] However, where the aquifer is relied on for contaminant removal, in situ or laboratory studies are required to confirm attenuation of microbial and chemical contaminants. Standard design criteria do not exist in the U.S. or Australia due to limited data on chemical and microbial contaminant attenuation in aquifers, which depends on environmental conditions, such as temperature and redox state, presence of nutrients and cometabolites, and aquifer materials[2,44,45] Additional treatment beyond what is achieved in the aquifer may be needed for uses outside of low exposure irrigation and industrial uses.[15]

At the spreading grounds in Los Angeles County the inflow is monitored for suspended solids and the flow is bypassed if the suspended solids exceed 500 mg/L. This is done to prevent clogging but may also divert the so-called first-flush that is expected to contain the highest pollution levels. While runoff quality from upper watershed areas may rightly focus on

Table I. Summary of Treatment Targets and Water Quality Requirements for Beneficial Use of Stormwater in the U.S. (NS, Not Specified)

water quality parameter	unrestricted irrigation				indoor use (toilet flushing or laundry)		
	state of MN[a]	District of Columbia[b]	Los Angeles, CA[cd]	San Francisco, CA[e]	District of Columbia[b]	Los Angeles, CA[cd]	San Francisco, CA[e]
BOD_5	NS	NS	10 mg/L	NS	NS	10 mg/L	
turbidity	3 NTU	NS	2 NTU	2 NTU	NS	2 NTU	2 NTU
TSS	5 mg/L	NS	10 mg/L	NS	NS	10 mg/L	NS
pH	6–9	NS	6–9	NS	NS	6–9	NS
chloride	500 mg/L	NS	NS	NS	NS	NS	NS
zinc	2 mg/L (long-term); 10 mg/L (short-term)	15 mg/L	NS	NS	160 mg/L	NS	NS
copper	0.2 mg/L (long-term); 5 mg/L (short-term)	NS	NS	NS	NS	NS	NS
pathogens/ indicators	*E. coli*: 126 CFU/ 100 mL	*E. coli*: 4615 CFU/100 mL*Crypto.*: 0.033 oocysts/L	*E. coli*: 2.2 CFU/ 100 mL	*Virus*: 3.0-log reduction*Protozoa*: 2.5-log reduction*Bacteria*: 2.0- log reduction	*E. coli*: 50 000 CFU/100 mL*Crypto.*: 0.320 oocysts/L	*E. coli*: 2.2 CFU/ 100 mL	*Virus*: 3.5-log reduction*Protozoa*: 3.5-log reduction*Bacteria*: 3.0- log reduction

[a]Minnesota Pollution Control Agency, 2017. [b]DDOE, 2013. [c]Can also treat to CA Title 22 water quality equivalence. [d]Los Angeles County Department of Public Health, 2016. [e]City and County of San Francisco, 2017.

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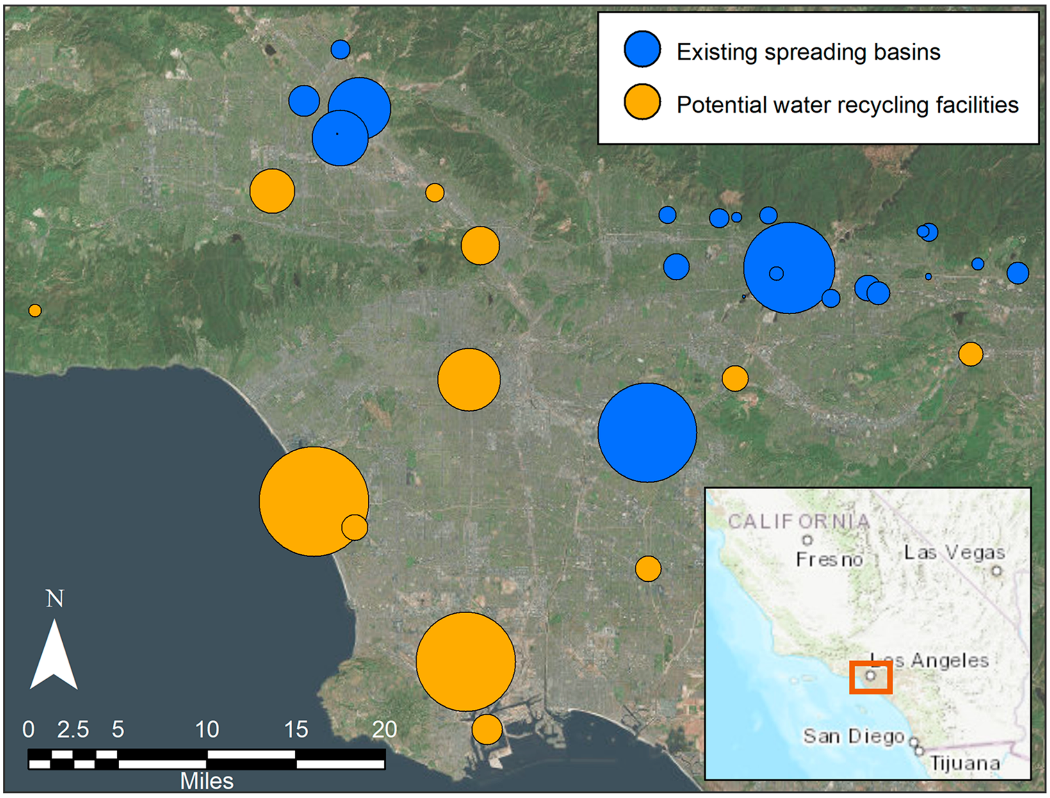

Figure 3. Cost-effective opportunities exist to enhance urban water supplies by joining stormwater and recycled water for groundwater recharge through spreading basins that receive intermittent stormwater deliveries.[27,61] Assessment of regional multisupply groundwater recharge projects benefit from optimization and planning tools to evaluate system costs and trade-offs, and dynamic control. (courtesy J. Bradshaw from LADWP and LACFCD sources).

suspended solids, the capture and recharge of urban runoff introduces other concerns. The urban stormwater recharge project in the Sun Valley neighborhood of Los Angeles, for example, employs hydrodynamic swirl-type separators with a filter to remove suspended solids, oils, and metals.[46] In Australia design practices for stormwater harvesting rely on general stormwater pollution control technologies like sediment traps, swales, wetlands, and ponds,[47] and for managed aquifer recharge further engineered treatments or controls are applied as required to meet the water quality requirements for use of recovered water.[7]

Because dry wells provide shorter contaminant residence times through the vadose zone, concerns have been raised about the safety and use of these engineered subsurface infiltration systems.[39] Dry wells that penetrate a significant thickness of the vadose zone could compromise water quality by bypassing natural contaminant attenuation processes and could be vulnerable to point source illicit discharges.[48]

Opportunities for Improved Design and Management. Better monitoring and implementation of new technologies for urban runoff capture and infiltration practices are necessary to protect local drinking water supplies, while increasing the confidence of regulatory agencies.[8,49−52] As we look ahead toward evermore urban stormwater capture and recharge for water supply, we can invoke advancements in monitoring, performance assessment, and innovation.

Improved monitoring should focus on temporal variability, including the degree to which dry-weather versus wet weather flows contain higher levels of pesticides, automotive, and commercial chemicals. Polar and moderately soluble organic contaminants need greater attention, as these contaminants are more likely to affect groundwater quality. Passive samplers for polar trace organic measurements may offer considerable advantages for spatial and temporal resolution and correlating with land use.[42,53]

New treatment technologies, such as low-cost biochar filters,[54] reactive media, or solar-powered oxidative processes could be incorporated into designs to enhance pollutant removal. Mixed-media filters show promise. For example, field tests in Sonoma, CA demonstrated that the combination of woodchips and biochar is very effective for managing nitrate, metals, and trace organic contaminants.[55] Aged woodchip reactors with 33% weight biochar removed trace organic contaminants. Under conditions expected in stormwater treatment systems, breakthrough of the most polar trace organic contaminants (i.e., 2,4-D) would take many years based on reasonable assumptions about land area devoted to capture basins, number of bed volumes that may be treated, and maintenance for control of clogging.[55] Further research on costs and performance leading to scientifically informed standards are fundamental to improved watershed-scale stormwater management.[56]

It is only recently that stormwater management is beginning to catch up with other sectors on the “internet of things.” A systemic challenge with urban stormwater management is that current approaches are essentially static solutions to a dynamic problem. But, advances in sensing and forecasting can make stormwater capture more dynamic through interconnectivity and real-time decision making.[57] Wireless communications, low-cost sensors and controllers can proactively control such

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systems in response to changing conditions wherein stormwater treatment and infiltration can be coupled with weather forecasting. In this way control decisions can be made in real time for more efficient treatment considering anticipated flows,[58] such as by draining or filling detention basins. Longer holding times in detention basins have shown improvements in water quality through sedimentation and increased exposure to sunlight.[59] In drought-prone regions where stormwater capture can contribute to water supply, real-time control can improve both the quality and quantity of water recharged.[57]

Regardless of the approach, side-by-side field studies are needed to benchmark efficiencies under real-world conditions to gauge how installed facilities perform and to quantify the benefits of technology improvements.[60] Conditioning with actual stormwater is an essential experimental protocol for the evaluation of long-term robustness in a range of urban environments. Laboratory experiments are useful in understanding the mechanisms behind the removal of contaminants, and such tests with field-aging is the best approach to mimic field conditions because materials change following exposure to stormwater and microbes.

Synergies with Other Urban Water Supply Trends. As semi-arid cities rethink how they manage water in all its forms, stormwater capture will play a significant role to ensure sustainable water supplies (e.g., Hagekhalil et al.;[3] Luthy and Sedlak[1]). However, two emerging strategies for increasing water supplies—collecting stormwater runoff and recycling treated wastewater—are usually viewed separately, which can create costly and under-utilized infrastructure. Instead, considering these strategies together offers opportunities for significant synergies. For example, systems that deliver recycled water to existing stormwater spreading basins in Los Angeles would take advantage of both the spreading basins' significant unused capacity and the city's substantial potential to produce recycled water, thereby creating an integrated, cost-effective groundwater replenishment system.[27,61]

As illustrated in Figure 3, the complexity of these integrated systems in terms of capacity and location requires decision-support methods to evaluate various design options for bringing recycled water to underutilized stormwater spreading basins and to optimize these designs by engineering considerations such as infrastructure life cycle costs, energy use, and water quantity and quality. An example for the City of Los Angeles illustrates trade-offs between centralized and decentralized configurations and highlights the potential for decentralized inland systems to deliver up to 44 500 acre-ft/yr of recycled water to spreading basins at costs significantly less than a centralized system delivering recycled water from the coast.[61]

Outlook. Capturing and using urban stormwater runoff for water supply can help alleviate water scarcity in semi-arid regions. This is a new paradigm that views stormwater as a water source and not solely a flood or pollution problem. As illustrated by examples in the U.S. and Australia, significant water demand reduction potential exists for large-scale stormwater harvesting and use. This push is being driven also by compliance with municipal separate stormwater sewer TMDL regulations and parcel taxes to fund stormwater capture projects.[62] Aquifer recharge is attractive in regions with Mediterranean climates due to the need to store large quantities of water for long periods. While beneficial use of stormwater to meet nonpotable water demand has been successfully demonstrated, there is much less experience for large-scale urban stormwater infiltration for potable supply and designs are just emerging. The lack of a regulatory framework and uncertainty in treatment and water quality targets is a barrier to wide-scale adoption of stormwater use projects. More data on stormwater quality and system performance, particularly with respect to pathogens and polar organic contaminants, are needed to better inform treatment targets. New technologies for treatment and real-time control can help improve both the quantity and quality of recharged water. Successful neighborhood and larger-scale stormwater capture, treat, and recharge projects provide co-benefits of water security, urban amenities, and pollution reduction, which are important for public acceptance and financing.

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Notes

The authors declare no competing financial interest.

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REFERENCES

(1) Luthy, R. G.; Sedlak, D. L. Urban Water-Supply Reinvention. *Daedalus* **2015**, *144* (3), 72−82.

(2) National Academies of Sciences, E., and Medicine, *Using Graywater and Stormwater to Enhance Local Water Supplies: An Assessment of Risks, Costs, and Benefits*; The National Academies Press: Washington, DC, 2016; p 223.

(3) Hagekhalil, A.; Kharaghani, S.; Tam, W.; Haimann, R.; Susilo, K. Becoming the Green-Blue City. *Civil Engineering Magazine Archive* **2014**, *84* (11), 68−91.

(4) Lam, K. L.; Lant, P. A.; O'Brien, K. R.; Kenway, S. J. Comparison of water-energy trajectories of two major regions experiencing water shortage. *J. Environ. Manage.* **2016**, *181*, 403−412.

(5) Dean, A. J.; Fielding, K. S.; Newton, F. J., Community Knowledge about Water: Who Has Better Knowledge and Is This Associated with Water-Related Behaviors and Support for Water-Related Policies? *PLoS One* **2016**, *11*, (7).e0159063

(6) California Water Boards *Strategy to Optimize Resource Management of Storm Water*; Sacramento, CA, January 6, 2016.

(7) Natural Resource Management Ministerial Council; Environment Protection and Heritage Council; National Health and Medical Research Council *Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 2) Managed Aquifer Recharge*; 2009.

(8) Andres, A. S.; Ballestero, T. P.; Musick, M. L. Stormwater Management: When Is Green Not So Green? *Groundwater* **2018**, *56* (3), 357−358.

(9) Bureau of Reclamation; County of Los Angeles *Los Angeles Basin Study, Summary Report*; November 2016.

(10) Clark, R.; Gonzalez, D.; Dillon, P.; Charles, S.; Cresswell, D.; Naumann, B. Reliability of water supply from stormwater harvesting

DOI: 10.1021/acs.est.8b05913
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

and managed aquifer recharge with a brackish aquifer in an urbanising catchment and changing climate. *Environmental Modelling & Software* **2015**, 72, 117−125.
(11) Los Angeles Department of Water and Power *Stormwater Capture Master Plan*; Los Angeles, CA, August, 2015.
(12) Government of South Australia *Stormwater Strategy: The Future of Stormwater Management*; Department for Water: Adelaide, South Australia, 2011.
(13) Kretschmer, P. *Managed Aquifer Recharge Schemes in the Adelaide Metropolitan Area*; Government of South Australia, Department of Environment, Water and Natural Resources: Adelaide, South Australia, 2017.
(14) Government of South Australia *Water for Good: A Plan to Ensure our Water Future to 2050*; Office for Water Security: Adelaide, South Australia, June, 2010.
(15) Dillon, P.; Page, D.; Dandy, G.; Leonard, R.; Tjandraatmadja, G.; Vanderzalm, J.; Rouse, K.; Barry, K.; Gonzalez, D.; Myers, B. *Managed Aquifer Recharge and Urban Stormwater Use Options: Summary of Research Findings*; Goyder Institute for Water Research: Adelaide, South Australia, 2014.
(16) San Diego Water Authority Seawater Desalination. https://www.sdcwa.org/seawater-desalination (February 5, 2019).
(17) National Capital Planning Commission *The Mall: Irrigation, Drainage, Water Collection and Relandscaping, Preliminary and Final Review*; Washington, DC, April, 2013.
(18) Stachowicz, M. *Personal Communication*; National Park Service, Washington, DC, 2014, 2015.
(19) City of Melbourne *Royal Park Stormwater Harvesting Project*; March, 2013.
(20) Los Angeles County Flood Control District. *Sun Valley Watershed, Strathern Wetlands Park Project (Fact Sheet)*; Los Angeles, CA, 2012.
(21) Hunters Council. *Vegetated Drainage Devices, Practice Note #5*; Environment Division, Hunters Councils Inc.: New South Wales, Australia, 2013.
(22) California Office of Environmental Health Hazard Assessment *Dry Wells: Uses, Regulations, and Guidelines in California and Elsewhere [Fact Sheet]*; September 25, 2014.
(23) Los Angeles Department of Water and Power *Branford Street Dry Well Details, Sun Valley EDA Public Improvements Project*; Los Angeles, CA, 2015.
(24) Los Angeles Department of Water and Power. *Laurel Canyon Boulevard Green Street Project (Fact Sheet)*; Los Angeles, CA, 2015.
(25) Southern California Water Coalition. *Stormwater Capture: Enhancing Recharge & Direct Use Through Data Collection*; April, 2018.
(26) Dillon, P.; Pavelic, P.; Page, D.; Beringen, H.; Ward, J. *Managed Aquifer Recharge: An Introduction*; National Water Commission: Canberra, Australia, February, 2009.
(27) Bradshaw, J. L.; Osorio, M.; Schmitt, T. G.; Luthy, R. G., System modeling, optimization, and analysis of recycled water and dynamic stormwater deliveries to spreading basins for urban groundwater recharge. *Water Resour. Res.***2019**; in press. DOI: 10.1029/2018WR024411
(28) Schoen, M. E.; Ashbolt, N. J.; Jahne, M. A.; Garland, J. Risk-based enteric pathogen reduction targets for non-potable and direct potable use of roof runoff, stormwater, and greywater. *Microbial Risk Analysis* **2017**, *5*, 32−43.
(29) Natural Resource Management Ministerial Council; Environment Protection and Heritage Council; Australian Health Ministers Conference. *Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 1)*, 2006.
(30) Natural Resource Management Ministerial Council; Environment Protection and Heritage Council; National Health and Medical Research Council. *Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 2) Augmentation of Drinking Water Supplies*, 2008.
(31) Natural Resource Management Ministerial Council; Environment Protection and Heritage Council; National Health and Medical Research Council. *Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 2) Stormwater Harvesting and Reuse*, 2009.
(32) Page, D.; Gonzalez, D.; Dillon, P.; Vanderzalm, J.; Vadakattu, G.; Toze, S.; Sidhu, J.; Miotlinski, K.; Torkzaban, S.; Barry, K. *Managed Aquifer Recharge and Urban Stormwater Use Options: Public Health and Environmental Risk Assessment. Final Report*; Goyder Institute for Water Research: Adelaide, South Australia, 2013.
(33) Page, D.; Gonzalez, D.; Naumann, B.; Dillon, P.; Vanderzalm, J.; Barry, K. *Stormwater Managed Aquifer Recharge Risk Based Management Plan, Parafield Stormwater Harvesting System, Stormwater Supply to the Mawson Lakes Recycled Water Scheme, Industrial Uses and Public Open Space Irrigation*; Goyder Institute for Water Research: Adelaide, South Australia, 2013.
(34) Sharvelle, S.; Ashbolt, N.; Clerico, E.; Holquist, R.; Leverenz, H.; Olivieri, A. *Risk Based Framework for the Development of Public Health Guidance for Decentralized Non-potable Water Systems, Final Report of WE&RF Project No. SIWM10C15*; the National Water Research Institute for the Water Environment & Reuse Foundation.: Alexandria, VA, 2017.
(35) Guchi, E. Review on Slow Sand Filtration in Removing Microbial Contamination and Particles from Drinking Water. *American Journal of Food and Nutrition* **2015**, 3 (2), 47−55.
(36) Dallman, S.; Spongberg, M. Expanding Local Water Supplies: Assessing the Impacts of Stormwater Infiltration on Groundwater Quality. *Professional Geographer* **2012**, *64* (2), 232−249.
(37) Makepeace, D. K.; Smith, D. W.; Stanley, S. J. Urban Stormwater Quality - Summary of Contaminant Data. *Crit. Rev. Environ. Sci. Technol.* **1995**, *25* (2), 93−139.
(38) Jurgens, B. C.; Burow, K. R.; Dalgish, B. A.; Shelton, J. L. *Hydrogeology, Water Chemistry, and Factors Affecting the Transport of Contaminants in the Zone of Contribution of a Public-Supply Well in Modesto, Eastern San Joaquin Valley, California*; U.S. Geological Survey, 2008.
(39) Edwards, E. C.; Harter, T.; Fogg, G. E.; Washburn, B.; Hamad, H. Assessing the effectiveness of drywells as tools for stormwater management and aquifer recharge and their groundwater contamination potential. *J. Hydrol.* **2016**, *539*, 539−553.
(40) Gan, J.; Bondarenko, S.; Oki, L.; Haver, D.; Li, J. X. Occurrence of Fipronil and Its Biologically Active Derivatives in Urban Residential Runoff. *Environ. Sci. Technol.* **2012**, *46* (3), 1489−1495.
(41) Grebel, J. E.; Mohanty, S. K.; Torkelson, A. A.; Boehm, A. B.; Higgins, C. P.; Maxwell, R. M.; Nelson, K. L.; Sedlak, D. L. Engineered Infiltration Systems for Urban Stormwater Reclamation. *Environ. Eng. Sci.* **2013**, *30* (8), 437−454.
(42) Wolfand, J. M.; Seller, C.; Bell, C. D.; Cho, Y.-M.; Oetjen, K.; Hogue, T. S.; Luthy, R. G. Occurrence of Urban-use Pesticides and Management with Enhanced Stormwater Control Measures at the Watershed Scale. *Environ. Sci. Technol.* **2019**.
(43) Nelson, C.; Washburn, B.; Lock, B. *Assessing the Risks of Using Dry Wells for Stormwater Management and Groundwater Recharge: The Results of the Elk Grove Dry Well Project (Fact Sheet)*; CA Office of Environmental Health Hazard Assessment, Submitted to City of Elk Grove, CA, 2017.
(44) Kazner, C.; Wintgens, T.; Dillons, P. Water reclamation technologies for safe managed aquifer recharge. *Water reclamation technologies for safe managed aquifer recharge* **2012**, *460*, 460.
(45) Dillon, P.; Toze, S.; Pavelic, P.; Skjemstad, J.; Davis, G.; Miller, R.; Correll, R.; Kookana, R.; Ying, G.; Herczeg, A.; Fildebrandt, S.; Banning, N.; Gordon, C.; Wall, K.; Nicholson, B.; Vanderzalm, J.; Le Gal La Salle, C.; Gilbert, M.; Ingrand, V.; Guinamant, J.-L.; Stuyfzand, P.; Prommer, H.; Greskowiak, J.; Swift, R.; Hayes, M.; O'Hara, G.; Mee, B.; Johnson, I. *Water Quality Improvements during Aquifer Storage and Recovery*; Goyder Institute for Water Research: Adelaide, South Australia, 2003.
(46) Higgins, K.; Roth, C., Sun Valley Park Storm Water Infiltration Basin Demonstration Project. In *Impacts of Global Climate Change*, **2005**; p 1.

(47) Hatt, E.; Fletcher, D.; Deletic, A. Hydraulic and pollutant removal performance of stormwater filters under variable wetting and drying regimes. *Water Sci. Technol.* **2007**, *56* (12), 11−19.

(48) U.S. Environmental Protection Agency *The Class V Underground Injection Control Study. Vol. 3 Storm Water Drainage Well*; Washington, DC, 1999.

(49) Dillon, P. Future management of aquifer recharge. *Hydrogeol. J.* **2005**, *13* (1), 313−316.

(50) Los Angeles Department of Water and Power. *2010 Urban Water Management Plan*; Los Angeles, CA, 2010.

(51) Mitchell, V. G.; Deletic, A.; Fletcher, T. D.; Hatt, B. E.; McCarthy, D. T. Achieving multiple benefits from stormwater harvesting. *Water Sci. Technol.* **2007**, *55* (4), 135−144.

(52) Rauch, W.; Seggelke, K.; Brown, R.; Krebs, P. Integrated approaches in urban storm drainage: Where do we stand? *Environ. Manage.* **2005**, *35* (4), 396−409.

(53) Page, D.; Miotlinski, K.; Gonzalez, D.; Barry, K.; Dillon, P.; Gallen, C. Environmental monitoring of selected pesticides and organic chemicals in urban stormwater recycling systems using passive sampling techniques. *J. Contam. Hydrol.* **2014**, *158*, 65−77.

(54) Ulrich, B. A.; Im, E. A.; Werner, D.; Higgins, C. P. Biochar and Activated Carbon for Enhanced Trace Organic Contaminant Retention in Stormwater Infiltration Systems. *Environ. Sci. Technol.* **2015**, *49* (10), 6222−6230.

(55) Ashoori, N.; Teixido, M.; Spahr, S.; LeFevre, G. H.; Sedlak, D. L.; Luthy, R. G. Evaluation of pilot-scale biochar-amended woodchip bioreactors to remove nitrate, metals, and trace organic contaminants from urban stormwater runoff. *Water Res.* **2019**, *154*, 1−11.

(56) Roy, A. H.; Wenger, S. J.; Fletcher, T. D.; Walsh, C. J.; Ladson, A. R.; Shuster, W. D.; Thurston, H. W.; Brown, R. R. Impediments and solutions to sustainable, watershed-scale urban stormwater management: lessons from Australia and the United States. *Environ. Manage.* **2008**, *42* (2), 344−359.

(57) Kerkez, B.; Gruden, C.; Lewis, M.; Montestruque, L.; Quigley, M.; Wong, B.; Bedig, A.; Kertesz, R.; Braun, T.; Cadwalader, O.; Poresky, A.; Pak, C. Smarter Stormwater Systems. *Environ. Sci. Technol.* **2016**, *50* (14), 7267−7273.

(58) Quigley, M.; Rangarajan, S.; Pankani, D.; Henning, D. New directions in real-time and dynamic control for stormwater management and low impact development. In *Proceedings of the World Environmental and Water Resources Congress, Honolulu, Hawai'i, USA, 12−16 May, 2008* 2008; 030−030.

(59) Gilpin, A.; Barrett, M., Interim Report on the Retrofit of an Existing Flood Control Facility to Improve Pollutant Removal in an Urban Watershed. *World Environmental and Water Resources Congress 2014: Water Without Borders. 2014 World Environmental and Water Resources Congress. Proceedings*, 2014; pp 65−74.

(60) Zhang, K.; Randelovic, A.; Page, D.; McCarthy, D. T.; Deletic, A. The validation of stormwater biofilters for micropollutant removal using in situ challenge tests. *Ecological Engineering* **2014**, *67*, 1−10.

(61) Bradshaw, J. L.; Ashoori, N.; Osorio, M.; Luthy, R. G. *Modeling Cost, Energy, And Total Organic Carbon Trade-Offs for Stormwater Spreading Basin Systems Receiving Recycled Water Produced Using Membrane-Based, Ozoone-Based, And Hybrid Advanced Treatment Trains*; Environmental Science & Technology, 2019; DOI: 10.1021/acs.est.9b00184, web release Jan. 31, 2019.

(62) *Los Angeles County Flood Control District Measure W, Safe, Clean Water Parcel Tax*. (September 12).

DOI: 10.1021/acs.est.8b05913
Environ. Sci. Technol. XXXX, XXX, XXX−XXX