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Renewing Urban Streams with Recycled Water for Streamflow Augmentation: Hydrologic, Water Quality, and Ecosystem Services Management

Heather N. Bischel,[1,2] Justin E. Lawrence,[1,3] Brian J. Halaburka,[1,2] Megan H. Plumlee,[1,4] A. Salim Bawazir,[1,5]
J. Phillip King,[1,5] John E. McCray,[1,6] Vincent H. Resh,[1,3] and Richard G. Luthy[1,2,*]

[1]*Engineering Research Center for Re-Inventing the Nation's Urban Water Infrastructure (ReNUWIt), National Science Foundation, Stanford, California.*
[2]*Department of Civil & Environmental Engineering, Stanford University, Stanford, California.*
[3]*Department of Environmental Science, Policy, and Management, University of California, Berkeley, California.*
[4]*Kennedy/Jenks Consultants, San Francisco, California.*
[5]*Department of Civil Engineering, New Mexico State University, Las Cruces, New Mexico.*
[6]*Department of Civil & Environmental Engineering, Colorado School of Mines, Golden, Colorado.*

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Abstract

As demands for freshwater withdrawals continue to escalate in water-stressed regions, negative consequences of alterations to natural systems will become ever more severe. Habitat restoration projects may mitigate some of these challenges, but new strategies will be needed to maintain or enhance ecosystem health while simultaneously meeting human needs. Recycled water is a reliable water source that can be used both directly and indirectly to renew degraded urban stream ecosystems. In this review, aspects of hydrology, water quality, and ecosystem services in relation to water reuse for urban stream renewal are evaluated to identify research needs and design considerations for new systems. Use of recycled water for streamflow augmentation in urban areas remains largely unexplored scientifically, despite its potential widespread applications among water and wastewater utilities. To move this innovative concept toward implementation, experimental studies in stream microcosms are needed to examine ecological response to coupled modification of both hydrology and water quality. Appropriate methods for selecting potential sites for urban stream renewal should be identified, along with ecological and economic metrics for evaluating success. Examples of projects in California, Japan, Israel, and Spain are used to identify different management scenarios. However, design criteria from both successful and unsuccessful case studies require additional review and synthesis to develop robust guidelines for recycled water use in urban stream renewal. Motivations for past stream renewal projects include regulatory requirements for water quality improvement and endangered species protection, although these motivations alone may not be enough to facilitate widespread adoption of reusing wastewater for ecosystem enhancement. Consequently, future project designs should include more detailed ecosystem service valuations to describe broader societal benefits and attract the attention of government agencies and private organizations that ultimately make the choice between environmental perturbation or enhancement.

Key words: critical review; ecosystem renewal; natural system enhancement; recycled water; streamflow augmentation

Introduction

INCREASES IN WATER USE associated with urban growth and development have led to dramatic, negative impacts on aquatic ecosystems (Paul and Meyer, 2001; Groffman *et al.*, 2003; Walsh *et al.*, 2005). The consequences observed are especially severe in arid and semiarid regions (Patten, 1998; Brooks *et al.*, 2006). However, the recognized need to ensure long-term ecological integrity of riverine systems, which are highly degraded in many urban areas, has resulted in a significant increase in the undertaking of stream restoration (Bernhardt *et al.*, 2005; Bernhardt *et al.*, 2007; Palmer *et al.*, 2007).

With continuing improvements in wastewater treatment technologies and escalating water demands, recycled water is a resource that can be used to a greater extent to benefit ecosystems (Jackson *et al.*, 2001; Sala and Serra, 2004). Success stories of recycled water use in managed natural systems,

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**Corresponding author:* Department of Civil and Environmental Engineering, Stanford University, Yang & Yamazaki Environment & Energy Building, 473 Via Ortega, Rm. 191, Stanford, CA 94305-4020. *Phone:* (650) 721-2615; *Fax:* (650) 725-9720; *E-mail:* luthy@stanford.edu

predominately for constructed wetlands, demonstrate that effective planning of water reuse projects at local and regional scales can enhance aquatic habitat, improve water quality, and provide public value (Vymazal *et al.*, 2006; Vymazal, 2007; Rousseau *et al.*, 2008). However, the intentional use of recycled water for stream renewal is an often-overlooked opportunity. Reasons for this include an absence of regulatory guidance or prohibitory regulations in some cases, presence of competing demands for recycled water use, and lack of appropriate water quality standards and riparian habitat indicators to monitor and demonstrate benefits (Latino and Haggerty, 2007; Bischel *et al.*, 2012; Plumlee *et al.*, 2012). Nevertheless, with integrated water resource management, recycled water has the potential to serve as a viable resource for renewal of water-stressed streams (*i.e.*, rivers, creeks).

Ecosystem renewal in this context refers to replenishing and regenerating natural systems to guide them toward a future dynamic state in which the abiotic and biotic components are within the historic range of natural variability for that location or region. This definition is similar to that which is often used in the literature for ecosystem enhancement, restoration, or rehabilitation (Grenfell *et al.*, 2007). The term ecosystem renewal is adopted for the purpose of this review and is intended as a general phrase that includes any restoration, rehabilitation, or enhancement project that incorporates a return of water, including recycled water available from wastewater reclamation, back to a stressed ecosystem. Stream renewal assumes that flow augmentation occurs alongside other objectives, as flow augmentation by itself may not be adequate to meet the objectives of a recycled water project designed for ecosystem enhancement. The objective was not a restoration of a system to the exact conditions at a specific point in the past; we are not suggesting an approach to outperform nature or force an oppressively fixed structure onto a system that requires dynamism. Rather, a successful project will maintain or increase the resilience and resistance of the biological communities (Stanley *et al.*, 1994).

The motivations for stream enhancement and restoration are diverse, and include moral, regulatory, political, and economic concerns (Wu *et al.*, 2003; Clewell and Aronson, 2006; Corsair *et al.*, 2009). Moral arguments recognize that stream ecosystems are part of our natural heritage and that our duty as stewards of the environment is to protect them (Lee and Roth, 2003). Likewise, federal and state governments have regulations in place to protect the environment, such as the Endangered Species Act and the Clean Water Act, which water utilities must adhere to in their effluent-release procedures (Rosan, 2000; MacDonnell, 2009). However, regulations and moral arguments are often not enough to provide an adequate level of protection (Moyle and Yoshiyama, 1994; Costanza *et al.*, 1997). Analyses of the economic benefits that intact ecosystems provide, which are often described as ecosystem services, may increasingly provide the information necessary to motivate institutional change (Postel and Thompson, 2005; Goldman *et al.*, 2007).

The objective of this review is to assess the potential for water reuse to renew urban stream ecosystems, with a focus on both the opportunities and concerns for management in relation to hydrology and ecology, water quality and treatment, and ecosystem services. Because research specifically addressing the intentional application of recycled water for urban stream renewal is limited, we drew broadly from evaluations of ecosystem responses to altered flow regimes, water quality in effluent-dominated streams, and ecosystem service provisions identified from past natural system restoration projects. Experiences from a particularly relevant stream renewal project are subsequently highlighted in a detailed case study of Calera Creek in Pacifica, California. After the review and case study, we identify barriers to implementation, outline research needs, and envision how success may be achieved in the future. The analysis represents a part of a larger research effort coordinated through the U.S. National Science Foundation's Engineering Research Center for Reinventing the Nation's Urban Water Infrastructure (ReNUWIt) (Sedlak *et al.*, 2013).

Review

Water reuse for ecosystem enhancement in practice

Wastewater treatment plants (WWTPs) often discharge secondary-treated effluent directly into streams and freshwater wetlands (Tchobanoglous *et al.*, 2003; Carey and Migliaccio, 2009). This practice is especially common for inland facilities, whereas many coastal facilities discharge directly into the ocean. In some cases, effluent discharged under low-flow stream conditions may incidentally serve to protect the integrity of aquatic ecosystems downstream (Brooks *et al.*, 2006), especially when industrial pollution inputs to the wastewater and river systems are low. While wastewater effluent requires specified treatment for disposal requirements, recycled water is the end product of wastewater reclamation that meets additional and appropriate water quality requirements and is produced with the intent of being used for beneficial purposes (Levine and Asano, 2004; NRC, 2012). Because the quality of recycled water used for stream renewal would be no lower, and likely higher, than that of traditional wastewater effluent, wastewater effluent discharge to surface waters represents a worst-case scenario for identifying potential ecological effects of using recycled water for streamflow augmentation (NRC, 2012). Discharge of wastewater with low levels of treatment into streams has resulted in ecosystem degradation in many cases, and as a result, negative perception of the effects of wastewater on the environment is widespread (Carey and Migliaccio 2009; Grantham *et al.*, 2012).

Alternatively, when carefully managed for augmentation in natural systems, recycled water, a term here used synonymously with reclaimed water, can renew urban streams either directly or indirectly in a variety of planned scenarios (Table 1). Direct augmentation as practiced in Calera Creek (Pacifica, CA) and the San Antonio River (San Antonio, TX) entails identifying opportunities to supplement streamflow in ecologically critical stream reaches as well as securing existing or new sources of recycled water. As an alternative to existing centralized recycled water facilities, distributed treatment plants could be constructed to produce recycled water at the location of an intended augmentation. The water quality required for stream renewal can also be achieved in some locations by using the intrinsic filtration capabilities of natural systems, such as through unit-process wetland treatment, before streamflow augmentation (Sala and Tejada, 2008; Jasper *et al.*, 2012). In these systems, unit-process wetlands could serve as the tertiary treatment needed to produce recycled water from secondary-treated wastewater. A stream reach

Table 1. Management Scenarios for Recycled Water to Augment Streamflow and Case Studies

Scenario	*Concept*	*Example projects*	*Example design or management challenges*
Wastewater effluent-dependent streams	Treated effluent is discharged routinely to streams with regulatory-driven ambient water quality protection and may provide habitat for aquatic species.	San Luis Obispo Creek, San Luis Obispo, CA (DiSimone, 2006; Asano *et al.*, 2007) Hadera River, Israel (Hophmayer-Tokich and Khot, 2008)	Status quo approach lacks active streamflow management and introduces hydrological and water quality challenges.
Direct streamflow augmentation	Recycled water may be designed to flow directly from the engineered treatment system into the designated stream reach.	Salado Creek and San Antonio River, San Antonio, TX (Dean and Shih, 1975; Crook, 2004; Eckhardt, 2004; USEPA, 2004) Nobidome and Tanagawa Streams, Tokyo, Japan (Ohgaki and Sato, 1991; Maeda *et al.*, 1996) Bell Creek, City of Sequim, WA (Latino and Haggerty, 2007) Calera Creek, City of Pacifica, CA (see case study)	Insufficient guidelines exist for project development and implementation. Permitting processes may be complex and lengthy or regulations may not allow stream augmentation. Potential recycled water quality issues include excess nutrients, chlorine residual, and elevated temperature.
Unit-process wetland treatment system	Recycled water passes through a constructed wetland before augmenting the targeted stream reach, creating habitat, and receiving additional treatment.	Tossa de Mar Creek, Tossa de Mar, Spain (Sala and Tejada, 2008) Danshui River, Taipei, Taiwan (Cheng *et al.*, 2011) River Dommel, Boxtel, The Netherlands (Kampf and Claassen, 2004) Petaluma River, City of Petaluma, CA (USEPA, 2004)	Requires land for wetland cells and treatment reliability. Efficacy of long-term treatment by wetlands and mechanisms are uncertain.
In-stream treatment zone	Recycled water passes through a designated in-stream treatment zone upstream of the targeted augmentation stream reach.	Natural attenuation of trace organics in Santa Ana River, CA (Lin *et al.*, 2006) and Trinity River, TX (Fono *et al.*, 2006)	Uncertain treatment capacity in hyporheic zone, riverbanks, or macrophytes. Potential degradation of upstream reach.
Indirect augmentation or discharge	Recycled water percolates into groundwater and indirectly augments streamflow. The subsurface may be used to cool water or attenuate contaminants when recycled water exceeds limits protective of in-stream biota.	Subsurface discharge through a 300-ft perforated pipe adjacent to the Columbia River in Dallesport, WA (Dallesport, 2007) Pilot-scale infiltration wetland at the Pudding River, City of Woodburn, OR (Stewart, 2010)	Requires land for infiltration; requires groundwater flow and temperature modeling to establish streamflow connection and expected water quality changes.
Agricultural return flow	Recycled water used to irrigate agricultural fields is collected and treated before runoff into adjacent streams. Recycled water could also be used to irrigate stream banks during native vegetation germination periods to simulate floods that no longer occur.	Landscaping at polishing wetlands irrigated with recycled water at Petaluma River, City of Petaluma, CA (USEPA, 2004) Agricultural return flow treated in constructed wetland before stream discharge in Kongju City, Korea (Maniquiz *et al.*, 2012)	Return flow water quality may be compromised from agricultural chemical inputs (*e.g.*, nutrients and pesticides).
Water savings/ indirect benefits	Water conservation or savings from water reuse can indirectly provide environmental benefit by allowing maintenance of flows.	Water conservation and recycling for more natural flows in the Russian River, Sonoma County Water Agency (Dickinson *et al.*, 2011)	Requires appropriation of in-stream flows or commitments to reduce requests for further diversions.

with unique substrate characteristics and location in relation to the groundwater table (*i.e.*, upwelling or down-welling areas), rather than a constructed wetland, could also be identified as a natural treatment zone upstream of the target stream reach.

Alternative streamflow management scenarios may also be achieved indirectly using recycled water. Infiltration basins and subsurface wetlands can offer a filtration function (Stewart, 2010; Jasper *et al.*, 2012; Lawrence *et al.*, 2012), providing soil aquifer treatment for wastewater discharged to a stream via a hydraulically connected groundwater aquifer. Another benefit of indirect discharge may be temperature mitigation—for example—by attenuation of wastewater temperature via the subsurface (made possible by the large heat capacity of aquifer materials) as modeled for the Pudding River in Oregon (Stewart, 2010) and demonstrated in Dallesport, WA adjacent to the Columbia River (Dallesport, 2007). Over 300 WWTPs indirectly discharge treated wastewater through rapid infiltration to nearby surface waters (Crites *et al.*, 2000). Recycled water can also renew stream ecosystems through its application toward uses that would otherwise draw water from streams. Water resource managers in the San Francisco Bay Area of California, for example, recognize that using recycled water for agriculture could reduce the need for imported water and diversions from the sensitive San Francisco Bay-Delta ecosystem (BARWRP, 1999). Likewise, recycled water applications to vineyards in Sonoma County, California, may indirectly augment streamflows through reduced groundwater abstractions (Lawrence *et al.*, 2011) and increased return flow. Lastly, reduction of degradation associated with excessive wastewater effluent discharge in one location via redistribution of the water for stream renewal where needed at an alternative location has the potential to improve the ecosystem health through strategic flow management.

Upgrades of existing WWTPs to meet stricter regulatory requirements for effluent discharge will in some cases blur the line between intentionally planned and unintentional cases of ecosystem renewal. For example, if wastewater is discharged through constructed wetlands for additional polishing before river discharge (Green *et al.*, 1996), river water quality is improved, even though the design may lack additional elements that would further promote stream renewal (*e.g.*, management of flows to mimic natural hydrographs). Ecosystem renewal should entail a holistic evaluation of stream needs related to factors, including managing flow, water quality, geomorphology, and habitat in concert, distinguishing optimally designed streamflow augmentation from traditional wastewater discharge.

Streamflow augmentation using recycled water will likely provide the greatest rejuvenating effect in urban streams that are most severely degraded in hydrology, ecology, and water quality (Ponce and Lindquist, 1990). Augmentation will not be universally applicable, however. For example, many urban streams actually have too much water as a result of importation from outside of the drainage basin, which can cause dry weather flows. Excess water can turn historically nonperennial streams into perennial streams, which can have adverse effects on indigenous flora and fauna that are adapted to the natural seasonal cycles of wetting and drying (Gasith and Resh, 1999). These problems are especially prevalent in the semiarid or Mediterranean climates, such as in California, where water is transported over great distances to urban centers. These experiences highlight the importance of proper site selection based on both historical data and modeling efforts to understand baseline hydrologic regimes and water quality characteristics. Nonetheless, some streams were perennial historically and are now nonperennial as a result of urbanization, and these streams certainly warrant further investigation as potential augmentation sites (BARWRP, 1999). Additionally, climate change will reduce flows in some streams, which could be mitigated through water reuse applications. Better understanding of the science, the motivations, and the institutional impediments of water reuse for ecosystem renewal is needed to determine to what extent this will be a viable approach in the future.

Hydrology and ecology

Flow modifications in urban environments. Freshwater biota are highly adapted to the local components of the natural flow regime, which include the magnitude, frequency, duration, timing, and rate of change of flows over time (Richter *et al.*, 1996; Poff *et al.*, 1997; Tharme, 2003). The natural flow regime in water-stressed regions often includes seasonally predictable wet and dry periods (Fig. 1). The adaptations of freshwater biota to the natural flow regime are especially pronounced in water-stressed areas, such as deserts and Mediterranean climate regions (Gasith and Resh, 1999). Migratory fish (Bunn and Arthington, 2002; Jager and Rose, 2003), benthic macroinverterbrates (Mendez and Resh, 2008), and riparian vegetation (Merritt *et al.*, 2010) all show key inter-relationships with flow. Moreover, the characteristics of the natural flow regime are essential to maintaining community structure and food-web dynamics in these complex ecosystems (Power *et al.*, 2008).

Flow has been called the "master variable" (Power *et al.*, 1995) and the "maestro that orchestrates pattern and process in rivers" (p. 85, Walker *et al.*, 1995). The 1960s mantra, "the solution to pollution is dilution," illustrates how water quality and flow are related; however, many studies have shown that even dilute concentrations of pollutants can have deleterious effects on biota. Flow also affects habitat quality (*e.g.*, temperature magnitude and fluctuations, shading provided by the riparian canopy, substrate characteristics, and diversity of pool and riffle habitats). Furthermore, the interconnectedness of flows and ecosystems among streams, hyporheic zones, groundwater, wetlands, and estuaries is of great importance [as exemplefied by Christensen *et al.* (1996), Slocombe (1998), and Granek *et al.* (2010)]. An understanding of the effects of human disturbance on these interconnected natural flow regimes, and mediating these effects through innovative solutions involving both natural systems and engineered systems, is a major goal of integrated water resource management and is essential for preserving biodiversity (Jewitt, 2002; Draper *et al.*, 2003).

Urban streams have dramatically altered hydrology as a result of human development. For example, groundwater withdrawals, water diversions, and WWTP discharges can modify all of the components of the natural flow regime (*e.g.*, decreasing flood magnitudes, altering the frequency of high flow events, and/or changing the timing of flows). Urban streams tend to be flashier than natural streams in the sense that the streamflow rises much more quickly and to a higher

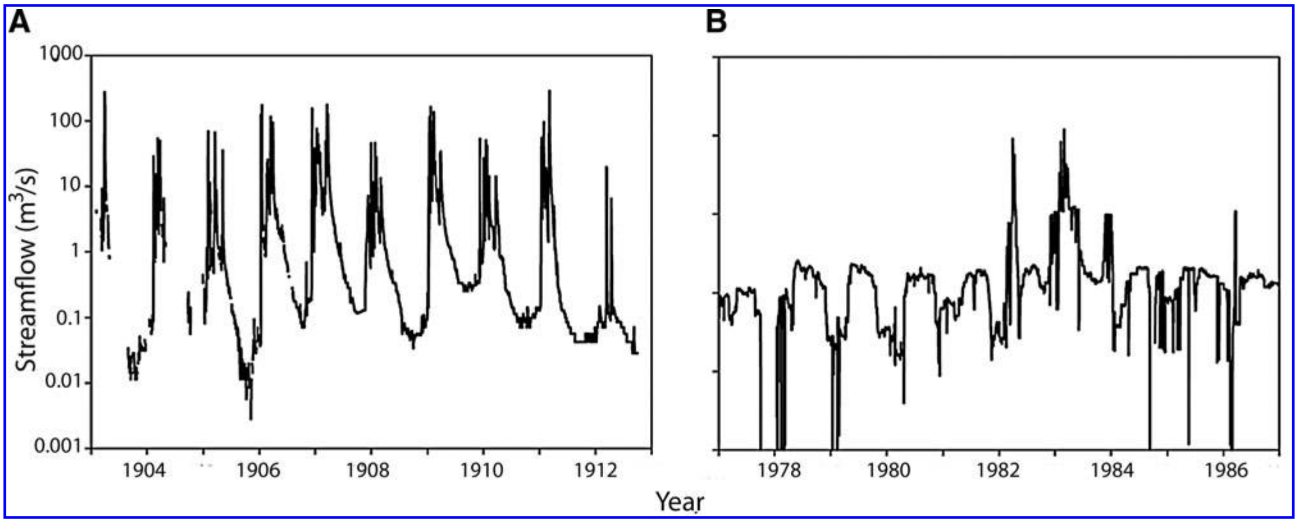

FIG. 1. Flow regimes for Coyote Creek from USGS gage #11170000 showing the **(A)** natural flow regime and **(B)** altered flow regime. Coyote Dam and LeRoy Anderson Dam were constructed upstream of this gage in 1936 and 1950, respectively. The natural flow regime of Coyote Creek **(A)** is representative of a typical perennial stream in a Mediterranean-climate region with predictable seasonality in wet-season and dry-season flows. In the altered flow regime **(B)**, wet-season floods are decreased dramatically in both magnitude and frequency, and summer low flows are severely reduced or eliminated.

magnitude during storm events (Konrad and Booth, 2005; Walsh *et al.*, 2005). This flashiness is primarily a result of the relatively high coverage of impervious surfaces in the urban environment, such as paved roads, parking lots, and roofs on buildings, which alter hydrologic flow paths (Arnold and Gibbons, 1996; Paul and Meyer, 2001). These higher-magnitude streamflows also increase flooded areas in downstream wetlands and estuaries, and can increase incision in stream channels, which can both scour the hyporheic zone and drain the local groundwater reservoir (Henshaw and Booth, 2000; Groffman *et al.*, 2003).

Natural flow regimes in semiarid regions are often characterized by a low-flow period that occurs in the dry season (Fig. 1). During this part of the year, the effects of urbanization on freshwater biota are magnified, because any changes in flow have a larger effect on the total volume [see Smakhtin (2001) for a review of low-flow hydrology]. Urban streams can have reduced base flows relative to the natural flow regime from water diversions, or if the groundwater reservoir is depressed as a result of withdrawals from wells, reduced infiltration during rainfall events, or stream-channel incision (Paul and Meyer, 2001; Konrad and Booth, 2005). In contrast, urban streams can have higher base flows during this water-stressed period of the year caused by augmentations, altered microclimates, irrigation return flow, hydropower releases, recreational flow releases for boaters or anglers, WWTP discharges, and landscaping applications, as well as from increased groundwater recharge from septic tank discharge and/or leaks in underground potable or nonpotable water lines [examples have been reported by Lerner (2002) and Garcia-Fresca and Sharp (2005)].

Many urban streams are highly degraded, signifying great potential for creative engineering solutions to renew these ecosystems through new approaches to the design and operation of urban water infrastructure. For these ecosystem benefits to be realized, it must be determined how the flows in these urban streams are altered from the natural flow regime and what components of that regime are most important ecologically (Stoddard *et al.*, 2006; Poff *et al.*, 2010). Management of the magnitude, timing, and variability of flows should take higher priority than just providing a minimum flow, which has been the standard management practice in many regions of the United States (Postel and Richter, 2003). Fortunately, this minimal-flow approach is being reconsidered as a result of new environmental flow policies in many U.S. states (MacDonnell, 2009).

In many cases, it will not be possible or desirable in cases where it increases flooding risks, to return a streamflow regime to a historic condition, but significant benefits could still be realized by providing a new flow regime that captures some ecologically important aspects of the natural hydrograph (Naiman *et al.*, 2002). This was accomplished at Putah Creek in California, where targeted changes to the flow regime below a dam re-established native fishes and reduced abundances of alien fishes (Kiernan *et al.*, 2012). Such hydrologic modifications may also prove beneficial to establishing native riparian flora. For example, along the Rio Grande River in the southwestern United States, non-native riparian plants such as salt cedar (*Tamarix* spp.) outcompete native plants such as cottonwoods (*Populus* spp.) and willows (*Salix* spp.), because the annual floods have been largely eliminated by upstream dams and water withdrawals (Stromberg *et al.*, 2007). Although recycled water volumes are insufficient to restore the natural floods along this river to their full magnitude, the banks of the active channel and the floodplain could be irrigated seasonally with recycled water to simulate aspects of the natural flood cycle while preventing damaging floods on private property. This process could allow native plants to regain a competitive stronghold against invasive species.

Managed streamflow augmentation using recycled water offers important opportunities to renew streams in urban and periurban environments where other sources of water have been allocated for competing uses (*e.g.*, residential, agricultural, or industrial), and either flows are reduced relative to the natural flow regime, or there is an opportunity to mitigate aquatic habitat loss elsewhere in the urbanized watershed. For example, a historically nonperennial stream could be made perennial if many of the perennial stream habitats in the region have been eliminated by human development. Table 2 provides examples of hydrologic metrics for evaluating streamflow relative to historic conditions and effects of augmentation. Selected metrics should include low-flow conditions when possible, because augmentation with recycled water will likely have the most impact under these conditions. In addition to such hydrologic indices, multiple biological, physical, and chemical parameters should be utilized to assess how alternative water management scenarios for recycled water might impact ecosystem integrity (Richter *et al.*, 1996).

Although many studies have documented declines in freshwater biota in response to altered flow regimes [see Poff and Zimmerman (2010) for a review], very few have examined the ecological response to intentionally augmented flow [see Ponce and Lindquest (1990) for the most recent review]. Based on observations of natural systems and either unintentional or indirect flow augmentations, managed streamflow augmentations clearly have demonstrated a potential to benefit ecosystems not only in the water column and benthos of streams, but also in the hyporheic zones [as reported by Kasahara and Hill (2007)]. Moreover, groundwater reservoirs, wetlands, estuaries, and riparian zones to which these streams are inextricably connected may also benefit (Wolff *et al.*, 1989; Debano and Schmidt, 1990; Henszey *et al.*, 1991; Troendle *et al.*, 2001; Robinson *et al.*, 2003; Huertas *et al.*, 2006; Zou *et al.*, 2010).

Evaluating benefits. The type of fauna used to evaluate ecosystem integrity will dramatically affect the duration of flow augmentation required to evaluate changes (Resh and Jackson, 1993; Carlisle and Clements, 1999) where recycled water is used for stream renewal. For example, diatoms can show changes on the order of hours (Winter and Duthie, 2000; Smucker and Vis, 2011), but benthic macroinvertebrates show responses over the course of several months (Resh and Jackson, 1993; Resh, 1994). In contrast, fishes may require multiple years (Karr, 1981; Aparicio *et al.*, 2011), and riparian forests can take decades to respond (Hierl *et al.*, 2008; McClain *et al.*, 2011). Microbial diversity is also a fundamental indicator of stream ecological health and is influenced by changes in geomorphology and exposure to certain water quality constituents [such as those reported by Davy-Bowker (2006) and Feris *et al.* (2003)], but is rarely used for quantifying ecosystem benefits or degradation. In terms of comparative advantages, benthic macroinvertebrates respond in a timeframe that is most amenable to scientific evaluation, and they are very sensitive to a variety of disturbances (Resh, 2008).

The evaluation of whether a change in benthic fauna with recycled water flow augmentation is a net benefit that can be performed using a multitude of structural and functional metrics, including those that describe abundance, composition, diversity, and biological traits. Multivariate statistical metrics that predict the proportion of taxa observed relative to those that would be expected under reference conditions, often determined using a RIVPACS-type predictive model [for examples, see Hawkins *et al.* (2000) and Ostermiller and Hawkins (2004)], may also be useful in some cases. The selection of evaluation metrics should be tailored to the site under examination in that the choice should make the best possible use of the historical biological information available and should be sensitive to the unique taxa that are present.

Species composition, diversity, and trait metrics are widely applied for aquatic ecosystem assessments and may be applied to quantify benefits of flow augmentation. For example, as a composition metric, the proportion of the individuals or species present in the three insect orders—Ephemeroptera, Plecoptera, and Trichoptera—relative to the total benthic macroinvertebrate community is widely considered to be indicative of water quality, and thus an increase in the value of this metric can be considered a benefit (Carter *et al.*, 2009; Purcell *et al.*, 2009). Other composition metrics, such as

TABLE 2. EXAMPLES OF HYDROLOGIC METRICS FOR MONITORING THE EFFECTS OF STREAMFLOW AUGMENTATION

Component of the natural flow regime	*Metric code*[a]	*Description of metric*	*How to calculate*
Magnitude	ML22	Specific mean annual minimum flow	Calculate the mean of annual minimum flows and divide by the drainage area.
Frequency	FL1	Low flood pulse count	Calculate the average number of flow events with flows below a threshold equal to the 25th percentile value for the entire flow record and determine the average number of events.
Duration	DL18	Number of zero flow days.	Calculate the number of zero-flow days for the entire flow record and determine the mean number per year.
Timing	TL3	Seasonal predictability of low flow	Divide years into 2-month periods, count the number of events with flows $\leq$5-year flood threshold in each period over the entire flow record, and calculate the maximum number of these events in any one period divided by the total number of such events.
Rate of Change	RA3	Fall rate (m^3/day)	Calculate the change in flow for days in which the change is negative for the entire flow record and determine the mean of these values.

Metric values at a site should fall within the regional range of natural variability for the five components of the natural flow regime (Richter *et al.*, 1996), which can be determined using historical USGS streamflow gauge data.

[a] Kennen *et al.* 2007.

Sources: Olden and Poff (2003); Kennen *et al.* (2007).

regional indices of biotic integrity (Ode *et al.*, 2005; Rehn *et al.*, 2007; Lunde and Resh, 2012), are also useful. Likewise, as a biodiversity metric, taxa richness is widely accepted as an indicative of ecosystem health, and an increase in the value of this metric would also be considered a benefit (Bonada *et al.*, 2006; Resh, 2008). Two other diversity metrics, Shannon-Wiener diversity and Simpson's diversity, are also widely used, and increases in their values could be considered a benefit (Resh, 1994; Pires *et al.*, 2000).

Traits metrics describe the functional adaptations of organisms to their environment and as such can be useful to track biotic responses to specific physical changes in the environment, such as in temperature, streamflow, and nutrient availability (Bêche and Resh, 2007; Lawrence *et al.*, 2010). As a relatively newer biological monitoring tool, trait databases are still in development, and the methods for their application are being tested (Usseglio-Polatera *et al.*, 2000; Vieira *et al.*, 2006). Several of these are potentially useful in evaluating benefits of augmented stream flow (Table 3).

In the inevitable tradeoff among selective advantages conferred by different traits, managed streamflow augmentation will certainly benefit some taxa and hinder others, and these changes can be hypothesized and examined using our knowledge of each taxon's set of traits (Table 3). For example, benthic macroinvertebrates that are filter feeders should increase proportionally over time under higher flows as a result of the increased suspension of organic matter in the water column (James *et al.*, 2008; Fuller *et al.*, 2010). Likewise, diatoms, a higher-quality food source for many macroinvertebrates and fish, should replace the lower-food-quality filamentous algae (Robson *et al.*, 2008). In terms of restoration of fauna and flora, if the streamflow augmentation mimics the natural flow regime, the benefits should accrue mostly to the native taxa as opposed to the non-native taxa. Evolutionarily, the native taxa have acquired their unique set of traits through natural selection under historical flow conditions, whereas invasive species tend to be opportunistic and are favored in modified and disturbed environments.

Obvious changes, such as general increases in abundance with augmented recycled water, may have to be examined more closely. For example, abundance metrics can be indicative of improved conditions when a stream that is depauperate shows an increase in the total number of organisms. Nonetheless, if this increase in abundance is dominated by non-native, invasive, or pollution-tolerant organisms, then the increase should not be considered a benefit. An increase in the abundance of a species that is listed as endangered is certainly a benefit, and such benefits once achieved are protected under the Endangered Species Act in the United States [see Good *et al.* (2007) for example]. Ideally, multiple metrics should be used so that the benefits (or harms) can be quantified and evaluated using multiple lines of evidence, and if the time and resources are available, metrics based on other fauna such as fish, amphibians, reptiles, algae, zooplankton, and riparian vegetation could be included in the analysis to provide a more comprehensive benefit assessment (as demonstrated in Table 4).

Water quality and treatment technologies

Effluent-dominated streams have often raised water quality and ecotoxicological concerns (Brooks *et al.*, 2006; Nilsson and Renofalt, 2008; Canobbio *et al.*, 2009), especially when wastewater comprises a majority of streamflow. Yet, treated effluent has also long been recognized for its ecological value in supporting riparian and aquatic habitats in effluent-dependent ecosystems in the arid West (USEPA, 1992). For example, improved water quality and endangered species presence were recorded after the discharge of tertiary-treated wastewater to San Luis Obispo Creek, an effluent-dependent creek in California (Arnold, 2000; DiSimone, 2006). For streamflow augmentation using recycled water, water quality variables that significantly influence ecosystem processes should be identified for the planned flow conditions (Poole *et al.*, 2004; Palmer *et al.*, 2005; Grantham *et al.*, 2012).

The recycled water quality will be an improvement compared to baseline stream conditions for some water quality parameters, but treatment technologies must be selected and designed to lower concentrations of other constituents before the recycled water is added. In Coyote Creek (San Jose, California), where flow augmentation using recycled water was under consideration for a demonstration project, metals and pathogen contamination in the creek were expected to improve from dilution with the better-quality recycled water. However, increased temperatures from the warmer recycled water were a concern, as were perfluorochemical concentrations that were higher in the recycled water than the receiving stream waters and associated groundwater (Plumlee *et al.*, 2011). Although this demonstration project was not implemented, management of the recycled water release volume and timing was planned to mitigate temperature issues.

Riverine environmental flow management often lacks explicit consideration of natural water quality variability in space and time, prioritizing water quantity over water quality parameters (Nilsson and Renofalt, 2008; Olden and Naiman, 2010). However, when water quality variables (*e.g.*, temperature, dissolved oxygen, ammonia, biological oxygen demand, and trace metals) fluctuate beyond acceptable ranges, ecological status may decline even when specified flow conditions are met. For example, in a stream mesocosm study, increased secondary-treated wastewater discharge volumes and corresponding altered concentrations of ammonium, dissolved oxygen, chloride, soluble phosphate, and sulfate negatively impacted the composition and diversity of the resident aquatic invertebrate community (Grantham *et al.*, 2012). Given the interrelated nature of biogeochemical and aquatic chemistry processes (Nimick *et al.*, 2011), it can be difficult to predict how stream ecosystems will react to changes in contaminant loading from the addition of reused water. Water quality design parameters for streamflow augmentation programs and appropriate treatment technologies for enhancing in-stream biological integrity are necessarily site specific such that water quality guidelines will be difficult to apply broadly. To better assess stream renewal using recycled water, additional comparative mesocosm experiments are needed to evaluate changes in biotic integrity with recycled water that undergoes tertiary processes such as biological nutrient removal and alternative disinfection strategies.

From an operations perspective, project managers must avoid exceeding predetermined concentration limits, or maintain water quality above minimum thresholds for key parameters (such as those shown in Table 4). In some cases, the discharge volumes may be reduced to achieve levels within an acceptable range based on known natural

Table 3. Examples of Aquatic and Semiaquatic Taxa That Could Benefit from Managed Streamflow Augmentation Based on Their Biological Traits

Biological trait category	*Favored trait*	*Reason*	*References*
Benthic macroinvertebrates			
Body size	Large body size	Large taxa will benefit from increased aquatic habitat	Bêche *et al.*, 2006; Townsend and Thompson, 2007; Feio and Dolédec, 2012
Functional feeding group	Filter-feeders	Filter feeders will benefit from greater suspension of organic matter	Spooner and Vaughn, 2008; Paillex and Dolédec, 2009; Feio and Dolédec, 2012
Body shape	Streamlined body shape	Thin-bodied taxa are morphologically adapted to faster-moving water	Bêche and Resh, 2007; Statzner and Bêche, 2010; Feio and Dolédec, 2012
Locomotion	Greater swimming abilities	Strong swimmers would benefit from increased water availability	Poff *et al.*, 2006; Tullos *et al.*, 2009; Rice *et al.*, 2010
Fish			
Body size	Large body size	Large taxa will benefit from increased aquatic habitat	Poff and Allan, 1995; Mims *et al.*, 2010; Olden and Kennard, 2010
Body shape	Streamlined body shape	Thin-bodied taxa are morphologically adapted to faster-moving water	Craven *et al.*, 2010; Haas *et al.*, 2010; Schaefer *et al.*, 2011
Locomotion	Greater swimming abilities	Strong swimmers would benefit from increased water availability	Craven *et al.*, 2010; Olden and Kennard, 2010; Rice *et al.*, 2010
Amphibians and reptiles			
Body size	Large body size	Large taxa will benefit from increased aquatic habitat	Indermauer *et al.*, 2010; Johansson *et al.*, 2010; Winne *et al.*, 2010
Locomotion	Greater swimming abilities	Strong swimmers would benefit from increased water availability	Johansson *et al.*, 2010; Kupferberg *et al.*, 2011
Adult longevity	Short-lived adult life spans	Less stress on juvenile recruitment because of continuous water availability	Gibbons *et al.*, 2006; Bateman *et al.*, 2008
Algae			
Light requirements	Lower light requirements	Deeper water will have less sunlight penetration	Schiller *et al.*, 2007; Poulíčková *et al.*, 2008; Centis *et al.*, 2010; Tornés and Sabater, 2010
Substrate preference	Suspended in the water column	Increased availability of habitat in the water column	Murdock *et al.*, 2004; Suren and Riis, 2010
Development rate	Fast development	Algal taxa develop faster in moving water as a result of constant disturbance	Reynolds, 1994; Culp *et al.*, 2010
Zooplankton			
Body size	Large body size	Large taxa will benefit from increased aquatic habitat	Barnett *et al.*, 2007; Hart and Bychek, 2010
Functional feeding group	Filter-feeders	Filter feeders will benefit from greater suspension of organic matter	Barnett *et al.*, 2007
Riparian vegetation			
Tissue flexibility	Flexible tissues	Taxa with flexible tissues could better withstand stress from high flows	Bornette *et al.*, 2008; Merritt *et al.*, 2010; Bornette and Puijalon, 2011
Vascular system	Arenchymous tissue	Taxa with arenchymous tissue can better transport oxygen when submerged	Blom and Voesenek, 1996; Merritt *et al.*, 2010
Water demand	High water demands	Taxa with high water demands will increase with increased water availability	Merritt *et al.*, 2010; Stromberg *et al.*, 2010

conditions and biota requirements. Water quality requirements for existing augmentation projects, such as those specified in national pollutant discharge elimination system (NPDES) permits, provide the context for the current level of regulatory guidance aimed at minimizing harm associated with wastewater discharge (*e.g.*, see Calera Creek case study below), but are insufficient for the design of projects aimed at stream renewal. For example, current regulations for contaminants are limited to addressing known priority contaminants with high ecotoxicological and human health risks.

Table 4. Important Water Quality Parameters and Typical Limitations for Recycled Water Used in Streamflow Augmentation

Parameter	*Remarks*[a]	*Typical recommended range*[a]	*Calera Creek treatment plant limitations*[b] *for recycled water*	*Example tertiary treatment options for recycled water use in streamflow augmentation*[a,c]
Chlorine residual	Disinfectant for water treatment, but exhibits toxicity in many fish species.	Total $Cl_2 < 0.1$ mg/L (dechlorinated)	UV disinfection applied[d]	Dechlorination (residual remains); UV disinfection as an alternative
TDS	Measure of salinity. May be toxic to aquatic species. Compliance may be difficult due to high TDS in source water.	Subject to NPDES compliance	Regulated as an inland freshwater stream by the Basin Plan	Electrodialysis; distillation; ion exchange; nanofiltration; reverse osmosis
TSS	Conventional water quality indicator.	< 20 mg/L avg. annual	< 10 mg/L (10 NTU turbidity instantaneous max.)	Chemical coagulation/filtration; membrane bioreactor; advanced oxidation processes
DO	Requirements should be based on the most sensitive species.	DO ≥ 5 mg/L	DO ≥ 7.0 mg/L in receiving waters	Discharge methods that introduce turbulence as well as modification of flow and stream morphology can enhance aeration.
Organic matter	Degradation of organic matter, as measured by BOD, can deplete DO.	BOD < 20 mg/L	$BOD_5 < 10$ mg/L (5-day BOD at 20°C)	Carbon adsorption; unit-process wetlands; soil aquifer treatment
Nutrients	May cause eutrophication leading to nuisance algal growth and oxygen depletion. Unionized ammonia is toxic to aquatic life.	Total nitrogen < 3 mg/L Ammonia < 2 mg NH_3-N/L Total phosphorous < 1 mg/L	Ammonia-nitrogen: < 2 mg NH_3-N/L, dry season; < 5 mg NH_3-N/L, wet season Basin Plan requires unionized ammonia: < 0.025 mg NH_3-N/L in receiving waters	Selective ion exchange; overland flow; biological nutrient removal; chemical precipitation; unit-process wetlands
Temperature	Important for sensitive fish species.	± 2.8°C (± 5°F) of ambient stream water temperature	Regulated in CA Thermal Plan[e]	Riparian vegetation can shade stream to lower the water temperature; subsurface cooling in pipeline or via infiltration (indirect discharge) to stream.
Inorganic and organic trace constituents	Metals and other priority pollutants are regulated by Clean Water Act provisions (*e.g.*, NPDES permits).[f] The ecotoxicity of many unregulated trace organic chemicals remains uncertain.	Varies	0.017 μg/L Hg 6.0 μg/L Bis(2-ethylhexyl)phthalate 3.2 μg/L Pb 4.5 μg/L CN 10 μg/L Cu	Advanced oxidation processes; ozonation; carbon adsorption; chemical precipitation; nanofiltration and reverse osmosis; unit-process wetlands
Pathogens	Bacterial indicators (total and fecal coliform) typically regulated for recreational waters. May be present in the surface waters due to wildlife.	23 coliform MPN/100 mL (avg.) 240 coliform MPN/100 mL (max.)	< 200 MPN/100 mL 5-sample geometric mean	Chlorine; UV disinfection; membrane filtration

[a] Adapted from Asano *et al.* (2007).

[b] Average monthly value, unless specified. Effluent or receiving water limitations from the California Regional Water Quality Control Board, San Francisco, Bay Region, Order No. R2-2006-0067, NPDES permit No. CA0038776.

[c] Adapted from USEPA (2004).

[d] Chlorine residual prohibited by the U.S. Fish & Wildlife for restored Calera Creek Wetlands.

[e] Water Quality Control Plan for Control of Temperature in the Coastal and Interstate Water and Enclosed Bays and Estuaries of California (SWRCB, 1975).

[f] Example compounds shown for Calera Creek: water quality criteria and water quality objectives for priority pollutants in the receiving waters are based on the Water Quality Control Plan for the San Francisco Bay Basin (Basin Plan), the California Toxics Rule, and the National Toxics Rule.

BOD, biological oxygen demand; DO, dissolved oxygen; NPDES, National Pollutant Discharge Elimination System; TDS, total dissolved solids; TSS, total suspended solids; UV, ultraviolet.

Further research is required to assess the unknown risks of other potentially toxic wastewater-derived pollutants (Daughton and Ternes, 1999) to develop guidelines for recycled water use in stream renewal (Anderson *et al.*, 2012). Development of enhanced stream augmentation project design criteria that are based on coupled stream system flow–quality interactions would be valuable.

Technology options for tertiary or advanced treatment in a wastewater reclamation treatment process depend on the form of reuse and the locally identified priority contaminants (USEPA, 2004). For streamflow augmentation, some processes such as nitrification for ammonia removal will be especially important, whereas others may be avoided, as was chlorine disinfection in the case of Calera Creek. If the recycled water quality is anticipated to be inadequate based on initial water quality analysis, additional treatment may be considered either at the main treatment facility (*i.e.*, centralized treatment) or near the stream release site (*i.e.*, decentralized treatment), although advanced treatment technologies are not necessarily required for streamflow augmentation projects. Additionally, facilities developing recycled water programs for other purposes can incorporate ecological enhancement into facility master planning such that treatment processes adopted for planned uses also allow ecosystem renewal as an additional option (*e.g.*, leading to selection of ultraviolet [UV] disinfection instead of chlorination).

Three common issues and their treatment options are discussed in more detail below: temperature, nutrients, and trace metals and organic contaminants. With respect to water chemistry, these factors are consistently associated with urban stream degradation (Walsh *et al.*, 2005; Brooks *et al.*, 2006) and are key potential hindrances to the reuse of water for streamflow augmentation.

Temperature.

The ecological significance of water temperature is widely recognized (Magnuson *et al.*, 1979; Poole and Berman, 2001; Caissie, 2006). The daily cycle of stream water temperature is modulated by natural processes, including incident solar radiation, atmospheric heat exchange, and hyporheic zone processes (Nilsson and Renofalt, 2008). Temperature cycles influence streambed hydraulic conductivity and stream–groundwater exchange, chemical mass-transfer and transformation rates, metabolic processes, productivity of stream biota, and suitability of habitat for aquatic life (Nimick *et al.*, 2011).

Due to domestic warm water additions, wastewater effluent is usually higher in temperature than that of the water supply or receiving stream (Kinouchi *et al.*, 2007). Most aquatic organisms exhibit tolerance to a specific temperature range (Coutant, 1977), and the thermal tolerance of fish is typically used to develop criteria and set water quality standards (Welch and Lindell, 1992). High water temperatures in receiving streams decreases dissolved oxygen solubility, creating adverse habitat conditions for cold-water fisheries, and can lead to an increase in the presence of warm-water predators (Caissie, 2006; Spellman, 2011). Similar to environmental flows that attempt to mimic natural flow regimes (Acreman and Dunbar, 2004; Arthington *et al.*, 2006), recycled water temperature should be managed to maintain the riverine thermal regime (which naturally vary within a range) based on species present in the system or that are anticipated to return.

Advanced or tertiary-treated recycled water can have as much as a 20°C temperature variation between winter and summer (Abdel-Jawad *et al.*, 1999), so temperature may require engineered controls to achieve final stream temperatures within an established range, depending on the ecosystem requirements and designated uses. The cost associated with controlling temperature for restoration could be significant, influencing decisions about whether to restore native species or consider habitat creation for species tolerant to a greater thermal range. Recycled water or in-stream temperatures may be actively modulated by the use of heat exchangers (Shah *et al.*, 2000) and flow volume control (Plumlee *et al.*, 2012) or passively through heat loss in constructed wetlands (Steinmann *et al.*, 2003), shading in forested riparian zones (Osborne and Kovacic, 1993; Sinokrot and Stefan, 1993), and indirect discharge into the stream via the subsurface (Crites *et al.*, 2000; Lancaster *et al.*, 2005; Dallesport, 2007; Stewart, 2010). For example, a coupled wetland–indirect discharge system under consideration for temperature mitigation of treated wastewater discharged to the Willamette River (Oregon, USA) is predicted to reduce the discharge temperature by up to 5°C in the constructed wetland, followed by up to 2°C in the subsurface, allowing the discharger to meet regulatory temperature limits (Corvallis, 2011).

Nutrients.

Pollution of surface waters by nitrogen (as NH_3, NH_4^+, NO_3^-, and NO_2^-), phosphorous in its soluble and particulate forms (Vitousek *et al.*, 1997; Carpenter *et al.*, 1998; Correll, 1998), and other nutrients in wastewater has had widespread ecological impacts. Excess nutrients in effluent-dominated ecosystems alter ecosystem dynamics (*e.g.*, lowered primary-to-bacterial production ratios) and are a common cause of eutrophication (Vitousek *et al.*, 1997; Carey and Migliaccio, 2009; Waiser *et al.*, 2011b). Nitrogen as ammonia (NH_3) is particularly toxic to aquatic life (Passell *et al.*, 2007). Temperature- and pH-dependent regulation of ammonia is established by the National Ambient Water Quality Criteria, which accounts for greater sensitivity of freshwater mussels and fish early-life stages (USEPA, 2009), and state or regional authorities may establish stricter criteria. For example, the San Francisco Regional Water Quality Control Plan (Basin Plan) requires nonionized ammonia (NH_3) in receiving surface waters to remain < 0.025 mg NH_3-N/L (RWQCB, 2010).

Conventional secondary biological treatment processes do not remove total nitrogen (TN) or total phosphorus (TP) to a significant degree. However, more than 40 alternative biological and chemical technologies for nitrogen and phosphorus removal in municipal wastewater treatment are available, with annual average concentrations of ≤ 0.1 mg/L for TP and ≤ 3 mg/L for TN reliably achievable. Due to technological, regulatory, and cost considerations, biological nitrification–denitrification processes are generally preferred over physical–chemical nitrogen removal such as air stripping or ion exchange (USEPA, 2008). Nitrification for ammonia removal can improve the water quality of the effluent before in-stream application and lower nitrogenous oxygen demand (Asano *et al.*, 2007). Installation of nitrification/denitrification systems is increasingly common because of the adverse impacts of nitrogen (Schmidt *et al.*, 2003; Pehlivanoglu and Sedlak, 2004; USEPA, 2008).

Vegetated buffer strips employed in riparian zones and wetlands can lower nitrate concentrations from nitrified effluent as well as nonpoint sources as a secondary method to source control (Barling and Moore, 1994; Vought *et al.*, 1994; Vymazal, 2007). Use of constructed wetlands for ammonia removal has increased, for example, with reliable treatment demonstrated for an array of wastewater sources and volumes in diverse climates (Vymazal, 2007). Reconstructed stream features (*e.g.*, gravel bars and re-meandered stream channels) have also been shown to significantly lower nitrate concentrations in the hyporheic zone (Kasahara and Hill, 2007), although hyporheic zone flow is often negligible compared to total stream flow. Additional research on methods to increase flow through the hyporheic zone may prove to be fruitful. Attenuation of nutrients may also be achieved via soil aquifer treatment in indirect augmentation (Debroux *et al.*, 2012).

Trace metals and organic contaminants.

Risk assessments of trace metals are complicated in that some metals are essential nutrients for organisms at low levels while toxic at higher concentrations (Reiley, 2007). Further, metal speciation and complexation with other organic or inorganic ligands have long been recognized to affect compound bioavailability (Tessier and Turner, 1995). Monitoring and control of trace metals in streams augmented with recycled water will likely be dictated by regulatory authorities, and are particularly influenced by site-specific stream conditions (Brooks *et al.*, 2006). Recently, the Biotic Ligand Model (BLM) has been used to incorporate receiving water body characteristics, such as the presence of competing cations and expected metal speciation, in developing site-specific water quality criteria, and predicting metal bioavailability (Reiley, 2007). The BLM was used, for example, in updating nonregulatory aquatic life-ambient freshwater quality criterion recommendations for copper (USEPA, 2007). Further research is required to expand the BLM to other metals and to evaluate chronic exposure toxicity (Reiley, 2007; USEPA, 2007).

While regulatory measures limit the allowable concentrations of trace metals and some priority organic contaminants in wastewater (including recycled water) that is discharged to surface waters, other unregulated compounds (*e.g.*, trace organic chemicals [TrOCs]) may also pose risks to aquatic life (Kolpin *et al.*, 2002; Barber *et al.*, 2006; Brooks *et al.*, 2006; Wang *et al.*, 2007; Waiser *et al.*, 2011a). Dickenson *et al.* (2011) provides several examples of urban streams that contain concerning levels of TrOCs. Notably, estrogenic effects detected in fish exposed to WWTP effluent were linked to natural and synthetic hormones, including 17β-estradiol, 17α-ethynylestradiol, and estrone in effluent-dominated waters (Purdom *et al.*, 1994; Desbrow *et al.*, 1998). Gonadal intersex, impaired ovarian and testicular histopathology, and other deleterious effects on fish downstream of a WWTP in Boulder Creek, CO, were attributed to estrogenic wastewater compounds (Vajda *et al.*, 2008). Many TrOCs remain untested for their potential ecotoxicological effects, although modeling techniques will be useful to predict wildlife exposure at a river catchment scale without time-intensive field approaches (Sumpter *et al.*, 2006).

Attempts to narrow the suite of compounds that should be monitored, and possibly treated, in recycled water down to a range of representative, or indicator, compounds or treatment performance surrogates [such as those reported by Drewes *et al.* (2008)] would be valuable for the management of water reuse for streamflow augmentation. The presence or absence of a narrow, but diverse, suite of indicators may be used to infer the occurrence of other unknown TrOCs. Additionally, environmental risk assessments that characterize TrOC hazards, exposure, and effects can be used to identify specific compounds for potential monitoring and management (Knacker *et al.*, 2004). In adopting an approach for TrOC management in recycled water stream augmentation, project managers must identify water quality criteria that will drive decisions regarding an appropriate level of treatment for targeted wastewater-derived organic compounds. However, early adopters of stream renewal will likely encounter unanticipated challenges regarding water quality, and further research is needed to identify which unregulated contaminants merit additional monitoring and potential mitigatory action. Responding to such uncertainties regarding the risk of unregulated TrOCs, in this case perfluoro-octane sulfonate detected in the source-recycled water, a California utility cancelled its research demonstration streamflow augmentation project in Coyote Creek (Plumlee *et al.*, 2008, 2012). A planned recycled water streamflow augmentation project for the Hillsborough River in Tampa, FL, was similarly cancelled in part due to uncertainty regarding TrOCs (Latino and Haggerty, 2007).

Detection of many TrOCs in effluent-dominated rivers is dependent on the degree of treatment employed (Ramirez *et al.*, 2009). Some conventional technologies may have cobenefits for removal of TrOCs, including pharmaceuticals and personal care products (POSEIDON, 2004), though the effectiveness of many municipal wastewater treatment technologies for the removal of wastewater-derived TrOCs remains largely unknown. Tertiary or advanced treatment process schemes may be selected for removal of TrOCs depending on the chemical of interest. For example, endocrine-disrupting compounds such as steroid-derivative estrogens are of concern with respect to the ecotoxicological risk. Some endocrine-disrupting compounds may be removed in part via biological degradation (in membrane bioreactors or sequencing batch reactors [SBR]), advanced oxidation processes, membranes, sorption to activated carbon, or electrochemical methods (Basile *et al.*, 2011).

TrOCs may also undergo natural attenuation in effluent-dominated wetlands and rivers due to a combination of photolysis, microbial degradation, and sorption (Gross *et al.*, 2004; Gurr and Reinhard, 2006; Fono *et al.*, 2006; Conkle *et al.*, 2008; Pal *et al.*, 2010), although these processes are generally slower and less effective than natural or engineered subsurface systems (*e.g.*, soil aquifer treatment) (Drewes *et al.*, 2008). When considering TrOC removal, processes that lead to destruction of the target compounds are preferable to technologies that transform the constituent (*e.g.*, chlorination), which may produce more toxic compounds, or that transfer them, which leads to disposal challenges (*e.g.*, reverse osmosis).

Ecosystem services

While potential ecological benefits are a major driver for enhancement of freshwater ecosystems, consideration of economic benefits is highly important in a watershed management context. Economic benefits provide justification for public agencies to allocate limited financial resources toward environmental stewardship. Quantification of how much the public is willing to pay for ecosystem enhancement, which has not been typically expressed in monetary terms in the past, can help water resource managers identify both the magnitude and distribution of benefits of these projects to the public.

Ecosystems provide society with services that have value. Although ecosystem services can be defined in different ways [compare those reported by Boyd and Banzhaf (2007), Costanza *et al.* (1997), Daily (1997), and Fisher *et al.* (2009), for example], the widely utilized Millennium Ecosystem Assessment definition is adopted for use in this review, referring to ecosystem services as the benefits humans obtain from ecosystems, including the categories of provisioning, regulation, cultural, and supporting services (Millennium Ecosystem Assessment, 2005). These services include all processes that are necessary to sustain human life on a large scale (*e.g.*, nutrient cycling, soil stabilization, and climate regulation) and those that affect humans more directly (*e.g.*, water purification by forested watersheds and flood damage mitigation by coastal wetlands) (Brauman *et al.*, 2007). In particular, humans derive a number of benefits from water-related ecosystem services (Fisher *et al.*, 2009). Increasing stream flow in a river or improving water quality in a lake can result in improved recreational opportunities—including hiking, fishing, bird watching, and whitewater rafting—as well as improved natural aesthetics and habitat for threatened or endangered species (Table 5).

While the benefits derived from increasing stream flow or improving lake water quality may be easy to observe (*e.g.*, as an increase in the number of visitors to a lake or stream or in the diversity and abundance of wildlife observed at a lake or stream), it is more difficult to assign these benefits a dollar value for a benefit–cost analysis. However, economists have developed nonmarket valuation techniques to assign dollar values to goods and services that cannot be traded in a typical market (Wilson and Carpenter, 1999). The most popular techniques used for water-related ecosystem services include the contingent valuation method (Loomis, 1987; Loomis, 1998), the hedonic price index method (Bark-Hodgins and Colby, 2006), and the travel cost method (Duffield *et al.*, 1992; Loomis and Creel, 1992; Weber and Berrens, 2006). The contingent valuation method involves conducting a survey to assess how much individuals are willing to pay for a hypothetical environmental improvement. The hedonic price method relies on using a market commodity, such as real-estate prices, as a surrogate for environmental quality. Lastly, the travel cost method uses the cost of travel as an approximation for the value of an environmental amenity.

Potential benefits of water reuse for ecosystems. Environmental flows require allocation of water to streams with an appropriate magnitude, frequency, duration, timing, and rate of change. These flow regimes can include managed flood releases to reproduce benefits of floodplains such as nutrient cycling and off-channel habitat. Historically, in-stream flow provisions based on minimum-flow requirements (*e.g.*, 10% of the mean annual flow) were often used instead of more ecologically based environmental-flow provisions. However, the use of minimum-flow regimes is not typically economically efficient. In many cases, the marginal value of environmental flows in excess of the minimum-flow requirement (or the opportunity cost of reduced flows) far exceeds marginal economic benefits of competing uses of the water, such as for agriculture (Katz, 2006). Economic valuations of environmental flows have led to major policy changes, such as the provision of increased flows to Mono Lake in California and the re-regulation of Glen Canyon Dam in Arizona (Loomis, 1998). However, this type of analysis for the use of recycled water for environmental flows has not been thoroughly explored.

Recycled water is a market good, although with typically lower market value than pristine river water, which is commonly used for a variety of applications, including landscape irrigation, agriculture, groundwater recharge, other nonpotable uses, and indirect potable reuse. The use of recycled water for streamflow augmentation may generate value for society that far exceeds value from either competing uses (*e.g.*, agricultural irrigation) or, in some cases, complete lack of use (*e.g.*, via discharge directly to the ocean). However, the benefits of environmental flows are often distributed broadly (*e.g.*, to the public), whereas benefits of consumptive uses are more concentrated (*e.g.*, by private interests or local water agencies). Distributed financing mechanisms may be feasible to address this challenge. For example, the local population in the Segura River Basin in southeastern Spain was willing to almost double the wastewater treatment charge of their water utility bill to maintain sufficient stream flow in the Segura River, a component of achieving good ecological status under the European Water Framework Directive (Alcon *et al.*, 2012). While the Segura River Basin study provides a good example of the economic value of using recycled water for ecosystem renewal, there is a need for additional studies demonstrating the value of water reuse for ecosystems in other management contexts and environmental conditions.

Services provided by streamflow augmentation. Ecosystem valuation case studies of different projects illustrate the potential for increased streamflow to provide value under a variety of circumstances (Table 5). A number of valuable freshwater ecosystem end services can be created or renewed by augmenting streamflow, including creation of habitat, provision of recreational opportunities, increased water infiltration to aquifers, improved water quality, and enhanced biodiversity. Quantification of such values suggests potential mechanisms for financing water supply contracts or recycled water infrastructure to access new water sources. For example, based on hedonic-pricing indices, reduction of groundwater withdrawals and investment in riparian habitat restoration would significantly increase property values near riparian corridors in the Sonoran Desert of Arizona, and thus increase property tax revenue (Bark-Hodgins and Colby, 2006). The economic benefits of increased streamflow for recreational opportunities are especially pronounced (Table 5). Angling and whitewater-rafting activity were found to escalate as a result of increased dam releases (Duffield *et al.*, 1992; Loomis and Creel, 1992), and unimpaired flows in a pristine environment were valued at a premium because of aesthetic enhancement (Weber and Berrens, 2006). Aesthetics and recreational value, quantified using contingent valuation, comprised a significant fraction of benefits ($560–$1100 per foot) conferred by urban stream restoration in Baltimore, MD (Kenney *et al.*, 2012). The preservation of Mono Lake in California's Sierra Nevada Mountains was considered valuable enough for the city of Los Angeles to seek an alternate source of water (Loomis, 1987).

Despite their value proposition, ecosystem services provided by augmenting streamflow with recycled water are often left unquantified. The San Antonio River, whose flow

Table 5. Examples of Ecosystem Valuation Studies Conducted for Streamflow Augmentation Projects or Scenarios

Study	*Ecosystem benefit (valuation method)*	*Description*	*Valuation*	*Policy change*
Montana's Big Hole and Bitterroot Rivers (Duffield *et al.*, 1992)	Provision of fish for angling (Travel Cost Method)	Estimated the economic value of stream flows for the Big Hole and Bitterroot rivers.	Net increase of $10–20 per acre-foot for stream flows during low flow compared to irrigation.	Results indicate that gains may be achieved at many flow levels by reallocating water from consumptive use to stream uses.
San Joaquin and Stanislaus Rivers (Loomis and Creel, 1992)	Provision of fish for angling (Travel Cost Method)	Survey of California households to determine trip frequency changes due to increased flows in San Joaquin and Stanislaus Rivers.	Net increase of $70 per acre-foot for stream flow versus consumptive use.	Study supports potential to renew contract for minimum flows from the Friant Dam of the Federal Central Valley Project.
Sonoran Desert Conservation Plan, AZ (Bark-Hodgins and Colby, 2006)	Aesthetic Value (Hedonic Price Indices)	Estimated increase in property values and property tax associated with healthy riparian corridors compared to the cost of providing flow for water-dependent habitat.	Property premiums estimated at $126.54–$253.08 million; $1.23–2.46 million per annum in incremental property tax revenue. Cost of supply water is $0.54 million annually.	Results demonstrate that urban riparian habitat restoration can be self-supporting and indicate potential benefits to modifying well-spacing rules in Arizona.
Arizona's Aravaipa Wilderness (Weber and Berrens, 2006)	Recreation and camping (Travel Cost Method)	Estimated the recreational value of maintaining stream flows to the Aravaipa Wilderness from cost of travel to visit site.	Consumer surplus per visitor day values estimated at $25.06 and $17.31 (in 2003 dollars), for two separate access sites. Total net present value of wilderness estimated at $3.6–4.7 million.	Study indicates that surface water ecosystems have significant nonuse value. The public will pay a premium for the remoteness of a site.
Mono Lake in Southern California (Loomis, 1987; Loomis, 1998)	Bird habitat and biodiversity (Contingent Valuation Method)	Survey of California households estimated the value of increase flows into Mono Lake.	Value of bird habitat estimated at $1.3 billion, over 50 times the cost of developing an alternative water source.	Los Angeles's water rights decreased by half to allow for increased flows into Mono Lake.
Reregulation of Glen Canyon Dam, AZ (Loomis, 1998)	White-water rafting (Contingent Valuation Method)	Survey of white-water rafting companies estimated value of increased flow through Glen Canyon Dam.	Increased base flows represented a potential increase of $2 million annually in rafting activities.	Study-opened discussion for the eventual re-regulation of Glen Canyon Dam to mimic natural flow regimes
Segura River, Segura River Basin, Spain (Alcon *et al.*, 2012)	Water Framework Directive good ecological status (Contingent Valuation Method)	Survey of individuals estimated increased willingness to pay for using recycled water to augment stream flow in the Segura River.	Respondents were willing to increase their household water bill by an average of €63.72 annually, amounting to €24.1 million of annual benefits.	Study demonstrates that willingness to pay for increased river flow using recycled water is larger than the costs of recycled water in the Segura River Basin.

augmentation using recycled water began in 2000 after a severe water quality decline in regional streams and litigation to maintain flows for endangered species protection, provides a picturesque setting for a vibrant commercial area in downtown San Antonio known as the Riverwalk (Eckhardt, 2004). Yet, no studies have comprehensively evaluated ecosystem services provided by this effluent-dominated system. Similarly, the Las Vegas Wash in Nevada, comprising a 12-mile-long effluent-dominated stream and associated wetlands flowing from Las Vegas to Lake Mead, sustains numerous ecosystem services. Despite major historical changes in ecosystem dynamics, the system provides a riparian habitat for migratory birds and other wildlife, wastewater treatment capacity through natural processes, and recreational opportunities for residents (Stave, 2001; Adhikari *et al.*, 2011). Quantification of such positive externalities can be an important tool for incentivizing the maintenance and enhancement of ecosystems threatened by human development and for examining the economic, social, and environmental tradeoffs of recycled water application for stream renewal.

Case Study

Urban stream renewal in Calera Creek (City of Pacifica, CA)

Project setting. The City of Pacifica's Calera Creek Water Recycling Plant is located just south of San Francisco, CA, and serves a population of 39,000 people. The tertiary treatment plant handles an average daily dry weather flow of 4.0 MGD and releases all of this effluent through a constructed wetland into Calera Creek, which then runs a length of about one-half mile (~900 m) before reaching the Pacific Ocean (Fig. 2). The City of Pacifica selected the current location for its treatment plant in 1995, responding to increased capacity needs for wastewater treatment that could not be met by the former treatment facility (Pacifica, 1997). Replacement of the treatment plant was accompanied by restoration of ~9 acres (4 ha) of wetlands (below the mean high water level) in a former rock quarry and ~20 acres (8 ha) of additional stream bank and upland buffer areas (RWQCB, 2006; S. Holmes, personal communication, January 4, 2012). Recycled water releases for ecosystem benefits began in 2002 under an allowance for a shallow-water discharge from the local regulatory authority that eliminated the use of an offshore outfall. The project resulted in a return of the lower stream channel of Calera Creek, which was formerly channelized and diverted from its historical course, to its natural path. This relatively small-scale water reuse project exemplifies a multiuse stream improvement project that provides various forms of both environmental and social benefits.

Project planning and design. In initial project planning, navigating the regulatory framework for stream enhancement using recycled water presented a challenge, because the creation of an inland outfall was a new concept for a coastal treatment facility (S. Holmes, personal communication,

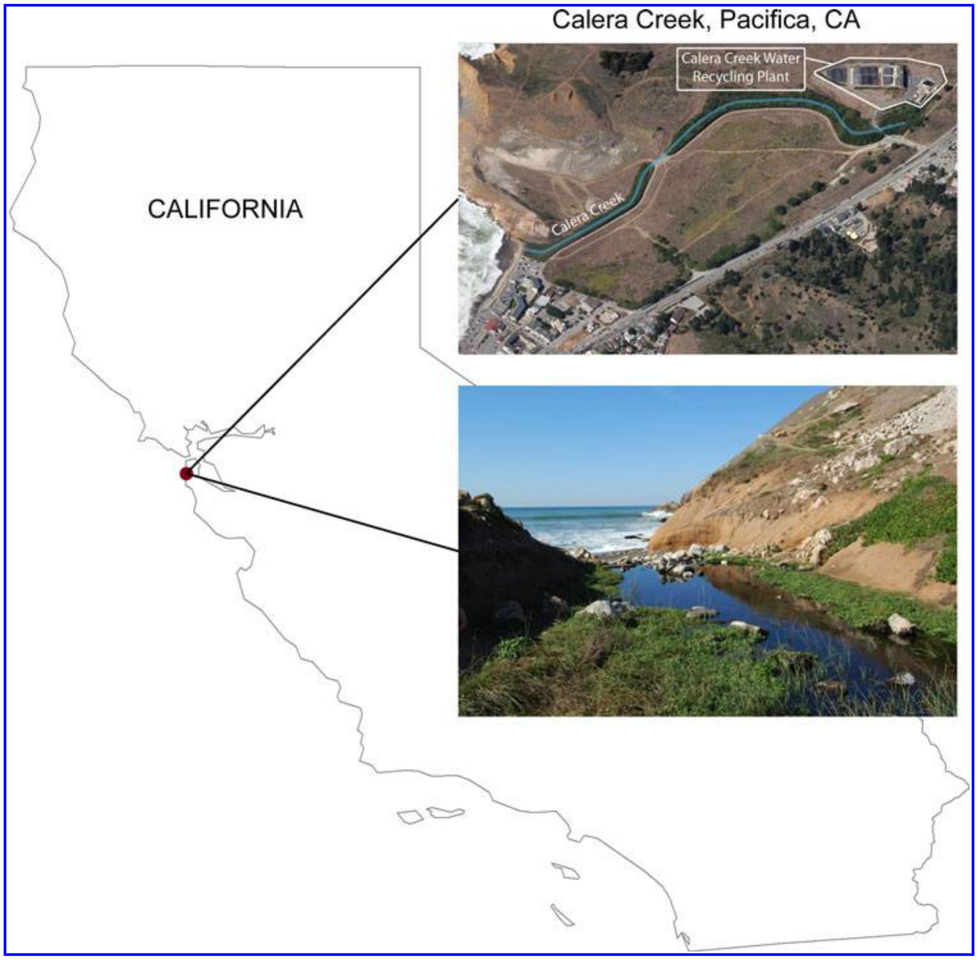

FIG. 2. The restored Calera Creek meets the Pacific Ocean (bottom) after streamflow mixes with tertiary-treated effluent from the Calera Creek Water Recycling Plant (top).

January 4, 2012). The tertiary effluent was required to meet Title 22 standards (CDPH, 2010) for an unrestricted use at the point of discharge into Calera Creek, such that polishing treatment from the wetland and creek could not be used to meet the treatment requirement. Nevertheless, improving water quality by increasing the residence time of water within the wetland ecosystem was an initial project objective (Pacifica, 2007), and local geology dictated placement of the constructed wetland (S. Holmes, personal communication, January 4, 2012). Project planning also involved navigating permitting requirements from four agencies that have jurisdiction over the waters and wetlands impacted by the project: the San Francisco Bay Region California Regional Water Quality Control Board (Regional Board), the U.S. Army Corps of Engineers, the California Department of Fish and Game, and the California Coastal Commission (Pacifica, 2010).

Using a hydrogeomorphic method, comparable streams and their riverine wetlands along the California coast were sampled to provide a reference framework for developing design criteria for the functions of the restored Calera Creek wetland in terms of hydrology, biogeochemistry, plant community, and habitat (Pacifica, 1997). The planners of the restoration sought to create a relatively natural flow regime that would accommodate additional discharge from the water recycling facility while establishing a compositionally and structurally complex ecosystem (Pacifica, 2007). Unfortunately, historical hydrographs were unavailable for this stream, and thus the natural flow regime can only be approximated through inference. A detailed monitoring plan included yearly characterization of stream biological and physical habitat, vegetation density, and water quality over a 5-year period after implementation (Pacifica, 1996).

Water quality and treatment. The treatment facility comprises screens at two pump stations, grit removal, SBR for primary and secondary treatment and nutrient removal, sand filters, and UV disinfection (RWQCB, 2006). A cascade outfall aerates the effluent as it enters the wetland. Several numeric water quality NPDES permit limits are summarized in Table 4. SBR was the preferred treatment technology to produce high-quality effluent and accomplish nutrient removal with a mechanically simple process in a minimum number of steps (Pacifica, 1997). Forested wetlands were also selected for shading to minimize growth of filamentous algae in the stream from high nutrient loads. Despite large energy use, production of tertiary-treated recycled water with UV disinfection eliminates risks associated with chlorine residual and the formation of halogenated disinfection byproducts (RWQCB, 2006; S. Holmes, personal communication, January 4, 2012). Incomplete dechlorination as well as refractory inorganic and organic chloramine byproducts formed during chlorination can pose threats to aquatic life (Jameel and Helz, 1999; Bedner *et al.*, 2004). Further, concern regarding safety in transportation and storage of chlorine gas as well as sulfur dioxide, which is commonly used for dechlorination, was expressed during project planning (Pacifica, 1990). UV disinfection can be comparable to chlorination/dechlorination in new facilities both in terms of costs and effectiveness (Blatchley *et al.*, 1996; Wojtenko *et al.*, 2001).

Ecological performance. Although Calera Creek was converted from a nonperennial to a perennial stream and is now effluent dominated in the summer months, the highly degraded stream conditions that existed before the restoration presented an opportunity to recreate a lost habitat for both the endangered San Francisco Garter Snake (*Thamnophis sirtalis tetrataenia*) and the threatened California red-legged frog (*Rana arora draytonii*). The red-legged frog population has increased dramatically from several adult and juvenile individuals recorded in the year 2000 at baseline conditions (Pacifica, 2000) to high population levels documented in the year 2009 (*e.g.*, >40 individuals recorded in a single survey of the ponds onsite) (Pacifica, 2010). Plants have also benefited from the use of recycled water. Dense growth of native riparian trees and shrubs, such as willows (*Salix* sp.) and horsetails (*Equisetum arvense*), is occurring along the stream. The rapid growth of native plants helps control invasion of non-native plants adjacent to the stream to some extent, although weed control has been a challenge (Pacifica, 2007), particularly because of regulatory requirements that must be met to ensure that no harm is done to the now-resident red-legged frogs that are protected under the Endangered Species Act. The San Francisco Garter Snake has not yet been observed in this stream ecosystem (Pacifica, 2010), and no native fish were documented in the stream. However, if a fish population does become established, particularly of an endangered species, additional regulatory requirements could be imposed at a much higher burden for plant operations and maintenance. Additionally, benthic macroinvertebrate community analyses were not conducted to document and evaluate changes in Calera Creek after augmentation.

Ecosystem services. An inland outfall coupled with a restored creek system avoided costly maintenance (ca. >$100 k/yr) and uncertain performance experienced with an ocean outfall at the former facility. In fact, approval with the local City Council was largely an economic decision based on the tradeoffs between a new inland outfall and treatment facility with nutrient removal and UV disinfection versus a replacement offshore pipeline with expanded secondary treatment capacity at the former facility (S. Holmes, personal communication, January 4, 2012). Selection of the appropriate level of treatment for stream enhancement may increase treatment facility costs relative to ocean disposal. However, in this case, avoided maintenance costs with an outfall were recognized as important savings. Invasive plant species (*e.g.*, pampas grass) control remains an ongoing cost for wetland maintenance. In addition to serving as an outfall alternative, the newly created wetlands provide a habitat for locally endangered and threatened species. An actively used, paved walking/biking path now runs alongside the creek and provides a significant additional recreational value to the local community. Specific beneficial uses of the inland stream, including preservation of rare and endangered species, creation of freshwater and wildlife habitat, and contact and noncontact water recreation (RWQCB, 2006), were not explicitly considered in economic terms for the project.

Discussion

Barriers to water reuse for ecosystems, research needs, and envisioning success

The comprehensive review of literature and case studies conducted suggests that recycled water use for ecosystem renewal through streamflow augmentation remains a largely unexplored research topic, which could have widespread applications in engineering, restoration, and aquatic ecology practice. Barriers identified for the development of water reuse for ecosystems programs give rise to several core short-term and long-term research needs (Table 6), which span across diverse disciplines, including aquatic ecology, hydrology, environmental engineering, environmental management and planning, social science, law, and water resource economics.

The motivations for individual stream renewal projects, whether moral, regulatory, or financial, will directly inform the site-specific design criteria. Both the natural flow regime and water quality should be used to guide decisions on whether streamflow augmentation is appropriate for a particular site. In many cases, augmentation may not be appropriate or may be appropriate only during particular seasons. Flexible designs that allow recycled water releases to be tailored to natural variability will likely result in the greatest ecosystem benefits. Distributed or satellite treatment plants that process water in lower volumes may allow tailoring both the water quantity and quality to the site (Latino and Haggerty, 2007), and installation of such plants closer to the headwaters where many streams are most water-stressed (in contrast to traditional downstream wastewater discharge) could provide greater benefits (Gengenbach *et al.*, 2010). The added energy and construction costs must be considered in planning such systems, but much progress is being made toward producing energy-positive treatment plants at relatively low cost (Verstraete *et al.*, 2009). Upstream unit-process wetlands, or soil aquifer treatment during indirect (subsurface) augmentation of streamflow, can also provide decentralized tertiary treatment capacity with lower energy investments [see Hoppe-Jones *et al.* (2010) for example].

Although water reuse projects may be driven by regulatory requirements for wastewater discharge [such as those reported by Bischel *et al.* (2012)], regulatory constraints and lack of incentives for wastewater treatment facilities to play a role in stream restoration activities may also limit implementation of streamflow augmentation using recycled water. For example, it is easier to reach agreement on effluent quality for discharge, and to measure chemicals in a pipe for an NPDES permit, than to achieve consensus on how to plan, monitor, and evaluate ecosystem status and restoration success. As experienced at Calera Creek, the permitting process currently used in California did not particularly lend itself to ecological restoration with recycled water. Current discharge regulations focus on preventing the harm associated with water quality impacts rather than creating a positive ecological impact, and there is currently no regulatory framework

Table 6. Barriers to Water Reuse for Ecosystem Renewal and Research Needs

Barrier	*Short-term research or logistical need*	*Long-term research or logistical need*
Few successful water-reuse stream augmentation cases implemented worldwide; little regulatory guidance	Select potential metrics for both identifying project opportunities and evaluating project success. Identify new opportunities at regional scales based on historical stream hydrology, water quality and ecosystem needs, and recycled water availability.	Develop engineering practice guidelines for urban stream renewal using recycled water. Address habitat management issues that may result from return of endangered species. Assess stream renewal using recycled water as a mitigation alternative for changing population and climactic conditions.
Available structural and functional biological metrics not widely applied to relevant scenarios	Develop and select biological indices that are responsive to manipulations in water flow and quality over varied time scales.	Apply metrics to evaluate success of streamflow augmentation under a range of environmental conditions.
Uncertainty regarding the impacts of wastewater-derived TrOCs	Develop and utilize environmental risk assessments to characterize TrOC hazards, exposure, and effects to identify indicator compounds for potential monitoring and management.	Develop water quality guidelines specifically for implementing and permitting recycled water-based stream enhancement projects.
Lack of streamflow augmentation-controlled environmental flow experiments	Conduct proof-of concept demonstration studies to establish quantitative relationships between benthic invertebrate indices and modified flow regimes.	Conduct large-scale coupled flow-water quality experiments to provide insight into the treatment needs for stream renewal projects and anticipated biological responses.
Motivations to implement new projects lack economic component; ecosystem services valuation not applied widely at the scales of individual projects	Evaluate and apply appropriate ecosystem valuation methods to case studies of recycled water for stream renewal.	Compare the public value of stream renewal as a recycled water portfolio option with competing uses and incorporate analyses into recycled water master planning.
Institutional impediments and uncertainties regarding financial sustainability	Explore cost recovery mechanisms and water rights ownership and transfer for streamflow augmentation.	Establish key institutional partnerships and update regulatory processes to couple water-recycling production with ecosystem renewal goals.

TrOCs, trace organic chemicals.

or guideline for implementing and permitting recycled water-based stream enhancement projects.

In addition to improving aquatic life habitat, stream restoration in urban environments may be implemented to meet storm water total maximum daily load requirements under the Clean Water Act and NPDES permits (Kenney *et al.*, 2012), insofar as restored streams are better able to assimilate contaminants loads such as nutrients. Such an approach could be performed in conjunction with flow augmentation using recycled water. This type of watershed-scale approach for storm water pollutant reduction, which encourages enhancement of waterways throughout the watershed over end-of-pipe strategies, requires integrated regional management, greater institutional capacity, consistent regulatory oversight, and effective funding and market incentives (Roy *et al.*, 2008).

Low-quality wastewater historically released into streams either untreated or after only primary or secondary treatment has had dramatic negative effects on many aquatic ecosystems and has also been the cause of numerous public health concerns (Cooper, 1991; Carey and Migliaccio, 2009; Grantham *et al.*, 2012). As a result, a negative public perception has developed toward wastewater in many cases that are often linked to concerns regarding the quality of the drinking water supply (Robinson *et al.*, 2005; Dolnicar and Schäfer, 2009; Dolnicar *et al.*, 2011). Although every case will be unique, typically recycled water use for stream renewal should be at least tertiary treated (*e.g.*, filtration and nutrient removal) to gain public support as well as to reduce risks associated with exposure to pathogens, nitrogen, phosphorous, suspended solids, organics, and metals. Water temperature should also be managed to maintain levels at which the native fauna are adapted, which will require some knowledge of historical conditions, or to support known species of concern in the system. Ecosystem valuation studies could provide incentive for water utilities to initiate water reuse for ecosystem projects, because they would allow water and wastewater managers to assess the value of the public benefits.

Recycled water that is used to renew streams will eventually re-enter the drinking water supply as it passes through the water cycle, though the distance it travels through the water cycle as well as the amount of natural filtration and dilution that will occur are highly variable depending on the particular system (Weiss and Reemtsa, 2008; Vizintin *et al.*, 2009; Musolff *et al.*, 2010). Some freshwater systems will inevitably have higher natural filtration abilities than others, and some streams will have higher potential to influence (or contaminate) regional potable water sources than others, including both groundwater aquifers and surface reservoirs (Reinoso *et al.*, 2008). Recycled water additions may actually improve the quality of some potable water sources. An understanding of these complexities and risks is a high priority for water professionals and requires significant investment in region-specific hydrogeological studies. The precautionary principle should continue to be applied with water infrastructure projects when risks are very high or uncertain.

Water needs in the future will certainly evolve in ways that are somewhat though not entirely foreseeable as a result of changing population demographics, cultural attitudes and behaviors, urban water infrastructure, and climate change (Oki and Kanae 2006; Mackie *et al.*, 2009). As populations grow or contract and people become more conscious of their environmental impacts, water conservation programs should be used in conjunction with water reuse programs to renew and regenerate ecosystems (Curry and Carson, 2008; Tom *et al.*, 2011). However, neither of these programs used alone can rise to the challenge of addressing the increasing level of water scarcity in urban areas. Such programs will require incremental changes in human behavior and views, which will take time and effort to achieve. Success will likely require that water utilities, academic institutions, government agencies, environmental nonprofit organizations, and other advocacy groups engage with one another to create institutional partnerships to garner public support and to fund, design, and implement water reuse for ecosystem benefit.

Advanced technologies, including higher levels of treatment, energy capture from wastewater, desalination, and sensors that continuously monitor effluent volume and quality could be utilized as components of ecosystem renewal projects and should be designed for applications in water reuse for ecosystem enhancement. Water reuse could also be used to mitigate the anticipated effects of climate change by augmenting altered flow regimes and thereby reducing seawater intrusion. Although ecosystem renewal will require management of hydrology and water quality, potential benefits to the environment and society as a whole could be significant.

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