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Economic and Ecological Costs and Benefits of Streamflow Augmentation Using Recycled Water in a California Coastal Stream

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ABSTRACT: Streamflow augmentation has the potential to become an important application of recycled water in water scarce areas. We assessed the economic and ecological merits of a recycled water project that opted for an inland release of tertiary-treated recycled water in a small stream and wetland compared to an ocean outfall discharge. Costs for the status-quo scenario of discharging secondary-treated effluent to the ocean were compared to those of the implemented scenario of inland streamflow augmentation using recycled water. The benefits of the inland-discharge scenario were greater than the increase in associated costs by US$1.8M, with recreational value and scenic amenity generating the greatest value. We also compared physical habitat quality, water quality, and benthic macroinvertebrate community upstream and downstream of the recycled water discharge to estimate the effect of streamflow augmentation on the ecosystem. The physical-habitat quality was higher downstream of the discharge, although streamflow came in unnatural diurnal pulses. Water quality remained relatively unchanged with respect to dissolved oxygen, pH, and ammonia-nitrogen, although temperatures were elevated. Benthic macroinvertebrates were present in higher abundances, although the diversity was relatively low. A federally listed species, the California red-legged frog (*Rana draytonii*), was present. Our results may support decision-making for wastewater treatment alternatives and recycled water applications in Mediterranean climates.

I. INTRODUCTION

Highly treated wastewater approaching drinking water quality, which we refer to as recycled water, is a valuable resource for addressing water scarcity. Recycled water is used in water-stressed regions around the world for a variety of applications including landscape and agricultural irrigation, industrial use, and groundwater recharge.[1] One application gaining increased attention is the direct and intentional use of recycled water to benefit aquatic ecosystems,[2−4] such as the creation or augmentation of wetlands and streams.

Wetlands and streams are well poised to benefit physically, chemically, and biologically from augmentation using recycled water that is superior in quality to the receiving streams. In the western U.S., for example, 55% of wadeable streams and small rivers are in poor or fair condition compared to their best available reference sites.[5] The United States Environmental Protection Agency (USEPA) reported 44% of the streams and rivers in the National Water Quality Inventory as impaired or unable to support their designated uses, such as swimming or fishing, as a result of water quality declines.[5,6] Urban stream habitats are particularly impaired. Compared to pristine streams, urban streams can be afflicted by a so-called "urban stream syndrome" that includes simplified habitat, flashier hydrographs, reduced baseflows, elevated concentrations of nutrients and pollutants, and decreased biotic richness.[7,8]

Purposeful addition of recycled water to wetlands or streams may rejuvenate these natural systems and provide a number of additional ecosystem services.[9] For example, urban wetlands and streams provide recreation, aesthetics, nutrient removal, and aquatic habitat,[10,11] and marginal increases in streamflow raise the value of a number of these benefits.[12−15] The value generated is especially high in urban areas where a relatively large number of people have access to the stream. Urban streams in Baltimore, depending on vegetation type, were valued at US$1,800−US$3,600 per linear meter of restored riparian habitat based on recreation and aesthetic benefits alone.[16]

A major benefit of streamflow augmentation is that excess recycled water can be put toward beneficial reuse. A survey of water utilities in the United States found that only 35% of the

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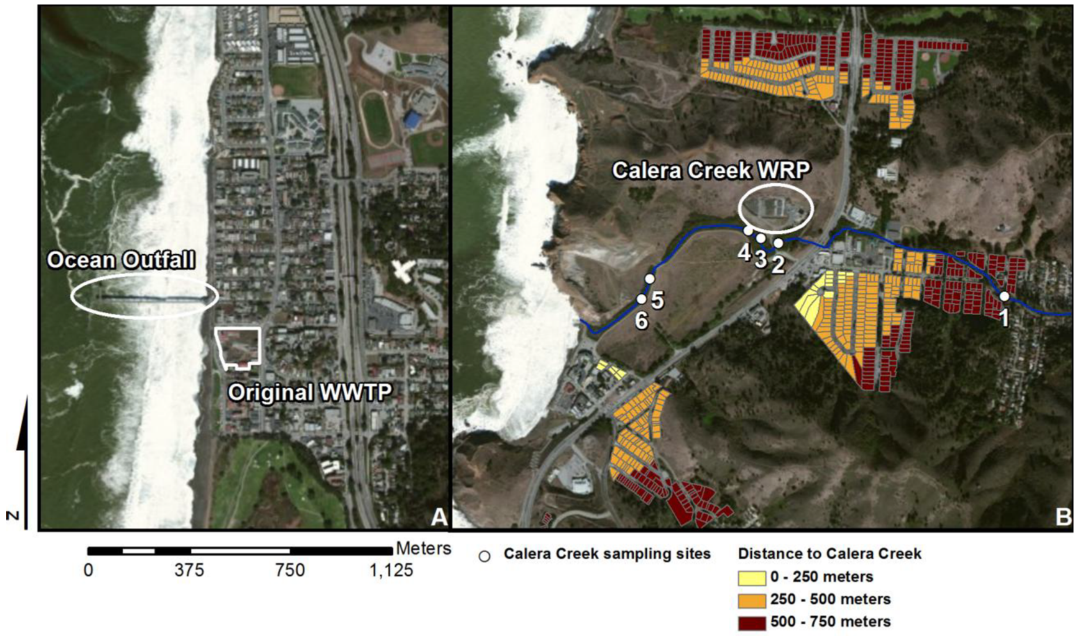

Figure 1. Site maps of (A) Pacifica's original wastewater treatment plant with ocean outfall, which was decommissioned in July 2000, and (B) the current Calera Creek Water Recycling Plant (CCWRP), which was put online in August 2000. The original treatment plant is located approximately one mile north of CCWRP. Locations of sampling sites for physical habitat and benthic macroinvertebrate surveys and distance to Calera Creek Park for houses within 750 m of Calera Creek Park are indicated.

recycled water produced is actually reused.[17] In the San Francisco Bay Area, recycled water supply was estimated at 600,000 acre-ft/yr (740×10^6 m^3/yr), whereas demand was only 150,000 acre-ft/yr (185×10^6 m^3/yr).[18] Using recycled water for environmental applications may allow utilities to obtain the full benefit of current and future recycled water supplies.

Despite the experience available from existing streamflow augmentation projects, a number of technical and regulatory challenges prevent streamflow augmentation from becoming more widespread. Few studies have investigated the merits of streamflow augmentation with recycled water, and those that have focus only on economic measures and do not evaluate the coupled economic and ecological impacts. One ecosystem service valuation study indicates that potential nonmarket environmental benefits of recycled water application for streamflow augmentation are larger than investment and operational costs of the necessary treatment facilities.[3] However, this study evaluates a postulated scenario, and thus relies on stated willingness to pay rather than observed behavior. Second, a major barrier to implementing streamflow augmentation projects is the lack of information on how recycled water will ultimately affect aquatic ecosystems. Streamflow augmentation projects have been canceled in California and Florida due to public concerns over effluent water quality,[19] likely because the ecological impacts and benefits of streamflow augmentation with high-quality recycled water are not well documented. Lastly, current regulations are designed to minimize the impact of effluent discharges, but fail to encourage discharges that benefit the environment. As a result, utilities implementing streamflow augmentation for environmental benefit may face additional permitting requirements and the involvement of multiple agencies.

The objective of this paper is to evaluate the economic and ecological costs and benefits of an existing streamflow augmentation project in a water-scarce coastal environment using simple and widely applicable metrics based on cost-benefit analysis, physical habitat assessments, water quality information, and benthic macroinvertebrate collections. The study seeks to provide utilities and regulators with an improved understanding of the benefits and risks of streamflow augmentation using recycled water, and to support decision-making for wastewater treatment alternatives and recycled water applications.

II. MATERIALS AND METHODS

Site Description. Pacifica is a coastal community in northern California located approximately 21 km south of San Francisco (Figure 1), with a population of approximately 39 000.[20] The city's original treatment facility, built in 1955, was an activated-sludge plant located in a residential area that discharged effluent to the ocean via an outfall pipe (Figure 1A). The original plant had numerous problems: residents near the plant complained about its odor; the plant was issued a cease-and-desist order for discharging wastewater that failed to meet regulatory standards; and the ocean outfall failed numerous times as a result of corrosive conditions and rough ocean currents.[21] In 1990, the city council agreed to secure funds to build a new wastewater treatment plant.[21] Two scenarios reached the final stages of consideration: (1) replace the offshore outfall and activated sludge treatment plant at the current location; or (2) build a new water-recycling plant at a different location with an inland discharge coupled with the creation of an urban park and the restoration of an urban wetland and stream habitat.

In light of the above issues, Pacifica chose to build the Calera Creek Water Recycling Plant (CCWRP) (Figure 1B).[6] The plant consists of sequencing batch reactors for primary and secondary treatment and nutrient removal, followed by tertiary-level sand filtration and ultraviolet disinfection.[20] The plant treats an average dry-weather flow of 15 000 m^3/day, and the effluent is discharged in irregular, diurnal pulses to a small

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Table 1. Recreation and Aesthetic Values Reported for Urban Greenspace, Restored Urban Streams, And Pedestrian Trails Similar to the Calera Creek Park

	value/visit (USD 2000	activity	site	location	year	reference
recreational value	\$6.08[a]	hiking	urban trail	Oakland, CA	1995	Siderelis et al. [51]
	\$19.08	hiking	suburban rail-trail	Northeast Georgia	1999	Betz et al. [52]
	\$4.70	general recreation	national forest	Virginia	1992	Teasley et al. [53]
	\$12.58	general recreation	reservoir	Central Valley, CA	1976	Knetsch et al. [54]
	\$8.49	walking/cycling	urban greenway	Indianapolis, IN	2004	Lindsey et al. [55]
	home value (% change)	**amenity**	**distance to houses**	**location**	**year**	**reference**
aesthetic value	0−12%	urban parks	500 m	Portland, OR	2001	Lutzenhiser & Netusil [56]
	1.3−3.4%	public parks	500 m	Portland, OR	2007	Bolitzer & Netusil [57]
	2−5%	trails and greenbelts	adjacent	San Antonio, TX	2009	Asabere & Huffman [58]
	0−11%	trails and greenbelts	750 m	Indianapolis, IN	2004	Lindsey et al. [55]
	2.6−13.2%	suburban open space	400 m	Central Maryland	2002	Irwin [59]
	11−13%	restored streams	330 m	Bay Area, CA	1995	Streiner & Loomis [33]
	5−12%	urban open space	400 m	Netherlands	2000	Luttik [60]
	5%	urban open space	adjacent	Lawrence, KS	2006	Earnhart [61]

[a]Value used to estimate base-case recreation value of Calera Creek Park.

wetland and Calera Creek where it flows one-half mile to the Pacific Ocean. Effluent from the plant meets California Title 22 standards for water reuse at the point of discharge, and a cascade outfall aerates the effluent before it enters the wetlands.[20] CCWRP was built in a former rock quarry that contained a highly degraded segment of Calera Creek, modified to flow through a dirt channel before discharging to the ocean. The city rehabilitated the last half mile of the creek by mimicking the hydrogeomorphology of several streams in the ecoregion, planting over 100 000 native trees and shrubs along its banks, and restoring approximately 8.1 ha of riparian buffer areas in the upper watershed.[9] Additionally, the city converted 6.5 ha of the former rock quarry into an urban park with a paved trail for runners, walkers, bikers, and dog walkers.[21] The restored section of Calera Creek provides habitat for both the endangered San Francisco Garter Snake (*Thamnophis tetrataenia*) and the threatened California red-legged frog (*Rana draytonii*), and the pedestrian path provides recreational opportunities to the community.[22] A more complete description of this site can be found in Bischel et al.[9]

Economic Costs and Benefits. *Capital and O&M Costs.* For the ocean outfall scenario, capital costs included the treatment plant and ocean outfall pipe and were determined from feasibility-level engineering design estimates prepared for the city.[23] Maintenance costs for the ocean outfall were also determined from these feasibility-level engineering design estimates. Operations and maintenance (O&M) costs of the proposed activated sludge plant included employee salaries, gas and electricity, operation supplies, chemicals, laboratory service, and sludge removal, and were estimated from the annual budget records of the city's original activated sludge plant during the fiscal periods from August 1991 to July 2000. To account for the uncertainty in the capital and O&M cost estimates, a range of −20% and +30% of the base case was used to estimate lower and upper limits, following established cost-estimate classification-guidelines.[24]

For the CCWRP scenario, capital costs included the construction of the treatment plant, the purchase of 13 ha of land for the new treatment plant and creek, the creation of the urban park, and the rehabilitation of the stream habitat. These costs were determined from actual construction costs of the CCWRP as detailed in the annual budgets. Annual O&M costs for CCWRP were obtained from the average annual O&M costs of the new plant during the fiscal periods from August 2000 to July 2007. Because these values represent the actual cost incurred to build and operate this plant, no lower and upper limits were estimated.

All values were normalized to year 2000 U.S. dollars using the consumer price index (CPI), and used to calculate the difference in the net present value (NPV) of the two scenarios without including the ecosystem service benefits of the CCWRP.

Ecosystem Services. Ecosystem service benefits can be measured by how much a user would be willing to pay in excess of current costs to continue to have access to a natural area or to improve a natural area. Prior to CCWRP, Calera Creek Park was a privately owned abandoned rock quarry with little recreational, aesthetic, and habitat value. The land suffered from "severe soil compaction" resulting from historic land uses, and the stream itself was "highly degraded" and "did not provide high faunal support/habitat functions".[25] The rehabilitation of the stream and land was motivated by the desire to discharge recycled water into the stream, therefore it is assumed that all of the ecosystem service benefits of the rehabilitated stream and land can be attributed to the streamflow augmentation. To quantify the value of ecosystem enhancements at Calera Creek, we used a benefit transfer approach, which is the application of ecosystem service value information obtained from existing study sites to an unstudied site.[26] The goal was to estimate the sum of the benefits present, and a benefit transfer approach was used because it allows for multiple benefits to be quantified without having to perform several independent valuations. We used an average or median value benefits transfer to obtain recreational, aesthetic, and habitat values for the CCWRP scenario. Benefits were converted to per unit values (e.g., value per recreation day, value per household, or value per hectare), and normalized to year 2000 U.S. dollars using the CPI.

The annual recreational value of the CCWRP scenario was approximated by multiplying the estimated annual number of visitors by the value per visit associated with urban trails. Visitors to the CCWRP urban park were counted at 6 h intervals on 10 different occasions from June to August 2012. One enumerator was stationed at each end of the Calera Creek Park recreational pathway, located next to parking lots on either end of the restored creek segment. We assumed that the park would receive more visitors during summer than winter because

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of weather. Therefore, for sensitivity analysis our base-case assumes the park receives $^{1}/_{2}$ the number of visitors during winter relative to summer, the lower limit assumes $^{1}/_{4}$ the number of visitors during the winter, and upper limit assumes $^{3}/_{4}$ the number of visitors during winter. The lower-limit, base-case, and upper-limit estimates for value per visit were obtained from a review of valuation studies from the past 30 years.[27] These studies used the travel cost method to obtain estimates of recreational values for activities such as walking, running, bird watching, and dog walking. The upper and lower limits represent the highest and lowest values found in the literature review, and the base-case was taken to be the value reported by the study with site characteristics most similar to Calera Creek, listed first in Table 1.

Total aesthetic value of the CCWRP urban park was estimated by multiplying the average single-family home value in Pacifica by the percentage increase in value attributed to the urban park and the number of homes impacted by the presence of the park. A review of hedonic studies, including urban open space, natural parks, urban wetlands, restored streams, and trails and greenbelts, was performed to obtain estimates for (1) the percent increase in property as a result of the natural feature, and (2) the distance from the natural feature at which a statistically significant effect was observed (Table 1). The average price used for a single family home in Pacifica in 2000 was \$368,000.[28] The number of houses located within the lower-limit, base-case, and upper-limit distance from the CCWRP were determined using ArcGIS 10 (ESRI) (Figure 1B). Lastly, the upper and lower limits of the property value increase were the greatest and least observed change determined from the literature review, and the base case was the most commonly reported percent increase.

Total habitat value for the CCWRP urban park and aquatic habitat was estimated using the results from a meta-analysis of 39 wetland valuation studies, broken down by ecosystem service, which reported wetland habitat values of \$996 per hectare per year, with a 90% confidence interval of \$309/hectare-yr to \$3192/hectare-yr.[29] We multiplied the lower-limit, base-case, and upper-limit values by 6.5 ha, the area of the rehabilitated CCWRP aquatic habitat.

Economic Sensitivity Analysis. To account for uncertainty, a Monte Carlo simulation was performed using triangular distributions for each variable, conditioned with the lower-limit, base-case, and upper-limit values, to determine the probability that the NPV of the CCWRP scenario is greater than the NPV of the ocean-outfall scenario. To understand the impact of each variable individually on the outcome of the project, the upper and lower limits were converted to a percentage of the base-case value, and the change in the NPV between the two scenarios as a result of a percent change in each variable was calculated.

Two additional variables were included in the sensitivity analysis: (1) discount rate, and (2) expected project life. A discount rate of 5%, based on the rate at which the city is able to issue bonds, was chosen as the base case. The range of 3–7% was determined based on USEPA's guidelines for discounting future costs and benefits of public projects.[30] The typical estimated life of a wastewater treatment plants is 25 years, with 20 years being the lower estimate.[31] However, the NPV of stream restoration projects are typically assessed using a project life of 50 years.[16] Therefore 20, 25, and 50 years were used as the lower-limit, base-case, and upper-limit scenarios, respectively.

Ecological Costs and Benefits. *Physical Habitat.* Physical habitat assessments were conducted at two sites upstream of the recycled water discharge (sites 1 and 2), one site at the outlet (site 3), and at three sites downstream (sites 4–6) (Figure 1B). These assessments visually characterize the habitat value of a riparian ecosystem by assigning scores for a variety of habitat parameters, such as bottom substrate, embeddedness, streamflow, canopy cover, and channel alteration.[32] The resulting scores indicate whether the physical habitat at a location falls into an optimal, suboptimal, marginal, or poor category.[32]

Water Quality. Water quality data for dissolved oxygen, pH, ammonia-nitrogen, and temperature were collected by CCWRP staff quarterly from April 2007 to September 2009, and on 18 April 2012 at the time of the benthic macroinvertebrate survey. Samples were collected from sites 2, 3, 5, and 6 (Figure 1B) using hand-held probes and according to the manufacturer's protocol. Dissolved oxygen, pH, and temperature measurements were collected using a HACH HQ 40d meter with a HACH PH 301C electrode for pH, and a HACH LDO electrode for dissolved oxygen and temperature. Ammonia concentrations were measured using an Orion 920A pH/ISE meter and an Orion ammonia gas sensing electrode.

Benthic Macroinvertebrates. Benthic macroinvertebrates were surveyed in Calera Creek at two sites upstream (sites 1 and 2) of the recycled water discharge and at three sites downstream (sites 4–6) on 18 April 2012 (Figure 1B). Samples upstream reflected conditions without streamflow augmentation, whereas those downstream reflected conditions with augmentation. Benthic macroinvertebrate samples were also collected at five sites at similar elevations along San Pedro Creek, a nearby stream (about 3.5 km away) with similar geomorphic characteristics but without a recycled water influence. This stream served as a reference site to evaluate the influence of the augmentation. Three replicate, 1 min timed-samples were collected using a 500 μm, D-frame kicknet at each site. Specimens were preserved in 70% alcohol, transported to the laboratory, and identified to the taxonomic level of family. Differences in the benthic macroinvertebrate community among sites were evaluated using metrics of total abundance (the total number of organisms), taxa richness (the number of distinct families), evenness (the closeness in numbers of each taxon), and percent EPT individuals (the pollution-sensitive orders Ephemeroptera [mayflies], Plecoptera [stoneflies], and Trichoptera [caddisflies]).

III. RESULTS

Economic Costs and Benefits. *Capital and O&M Costs.* Under the lower-limit and base-case, capital and O&M costs of the ocean-outfall scenario were less than for the CCWRP scenario (Table 2). The cost of the CCWRP scenario was calculated to be greater than the cost of the ocean outfall scenario by \$32.7 M for the lower-limit, and \$16.4 M for the base-case. However, in the upper-limit scenario, the CCWRP scenario costs were calculated to be less than the ocean outfall scenario by \$10.4M.

Ecosystem Services. Ecosystem service benefits were evaluated for the implemented, CCWRP scenario (assuming no such benefits for the ocean discharge alternative). The average number of weekday visitors to the CCWRP urban park was estimated to be 420 per day and weekend visitors to be 635 per day. The upper-limit of the number of visitors per year was estimated at 175 000, with a base-case total recreational value of

Table 2. Estimated Range of Costs and Benefits for Secondary Treatment with Ocean Discharge (Ocean Outfall Scenario) versus Tertiary Treatment with Park and Streamflow Augmentation (Calera Creek Water Recycling Plant scenario)

element	lower limit (% of base case)	base case	upper limit (% of base case)
ocean outfall scenario construction costs[a]	$31 M (80%)	$44 M	$57 M (130%)
ocean outfall scenario O&M costs[a]	$2.2 M/yr (80%)	$2.8 M/yr	$3.6 M/yr (130%)
CCWRP scenario construction costs[b]	NA	$50.5 M	NA
CCWRP scenario O&M costs[b]	NA	$3.4 M/yr	NA
discount rate[c]	3% (60%)	5%	7% (140%)
treatment plant design life[c]	20 years (80%)	25 years	50 years (200%)
no. of visitors to Calera Creek Park[d]	88 000 (67%)	131 000	175 000 (133%)
estimated willingness to pay per visit[d]	$4.70 (20%)	$6.00	$19.00 (400%)
no. of homes that experience aesthetic benefit[e]	20 (6%)	345	690 (200%)
home value increase from aesthetic benefit[e]	0% (0%)	5%	13% (260%)
habitat value of restored stream/wetlands[f]	$2,000 (31%)	$6,450	$20,670 (320%)

[a]Values used to calculate costs of ocean outfall scenario. [b]Values represent actual costs incurred. [c]Values used to calculate net present value of both scenarios. [d]Values used to calculate recreational value of Calera Creek Water Recycling Plant (CCWRP) scenario. [e]Values used to calculate aesthetic value of CCWRP scenario. [f]Values used to calculate habitat value of CCWRP scenario.

the CCWRP scenario estimated at $11.1 M using the recreational values described in Table 1.

Percent increases in property value from Table 1 ranged from 0% to 13%. The radius of influence for a measurable property value increase ranged from 0 to 750 m. The most commonly reported property value increase was 5%, and the most commonly reported radius of influence was 500 m. These base-case values gave a total aesthetic value of $6.3M.

When these ecosystem services are accounted for (i.e., the above visitor recreation and property values), the NPV of the CCWRP scenario exceeded the NPV of the ocean outfall scenario for both the base-case and upper-limit (Figure 2A). In the lower-limit, the ocean outfall scenario still has the greater NPV. With respect to ecosystem services for the CCWRP scenario, recreational benefits had the largest NPV, ranging $4.4 M to $85.5 M (Figure 2A). The second largest estimated benefit was aesthetics, ranging $0–$33 M. Habitat value was comparatively insignificant, with a NPV ranging $21–$500 K.

Economic Sensitivity Analysis. From the Monte Carlo simulation, we found the likelihood that the NPV of the CCWRP, when including ecosystem services, is greater than the ocean-outfall scenario is 87%. The spider plot shows how a percent change in each variable affects the outcome of the project (Figure 2B). Construction and operation costs have a low degree of uncertainty relative to the other variables, but have a large impact on project NPV. Changes in recreational and aesthetic benefits have a smaller impact, but larger uncertainty. Most scenarios show positive NPV for the streamflow option and in some cases a very large NPV due to the potentially great recreational and aesthetic benefits.

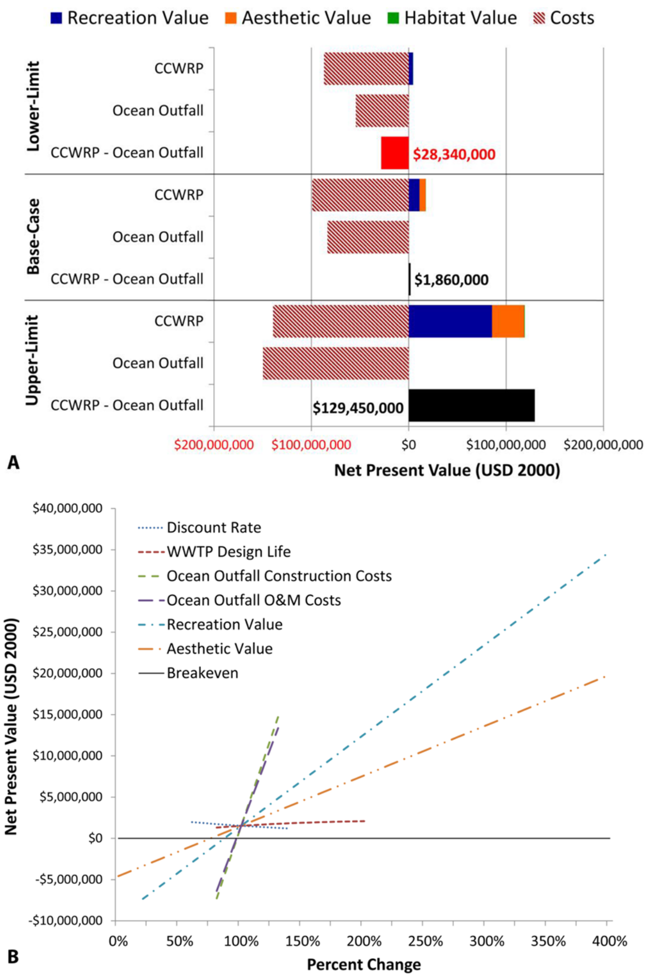

Figure 2. (A) Costs and benefits of the Calera Creek Water Recycling Plant (CCWRP) scenario versus the ocean outfall scenario. The difference between the net present value (NPV) of the two scenarios is shown in the third row for each case. The NPV of the CCWRP scenario exceeds the NPV of the ocean outfall scenario for the base-case and upper-limit. (B) Spider plot of the sensitivity of each variable used in the cost-benefit analysis. Lines above the breakeven point show the CCWRP scenario is more favorable, and lines below the breakeven point show the ocean outfall scenario is more favorable.

Ecological Costs and Benefits. *Physical Habitat.* The highest physical habitat score was observed at the two sites farthest downstream (sites 5 and 6; Figure 1), which were in optimal condition for almost all the habitat parameters examined. The assessment was conducted during the dry season, and the upstream sites (sites 1 and 2) had low to no streamflow. Flow was enhanced at the outlet (site 3) and downstream sites (sites 4–6), at least when the effluent was being discharged. Substrate cover and embeddedness (parameters 1 and 2) scored poorly at the effluent outlet and at site 4 immediately below the outlet because of increased siltation and scouring from the periodically high discharges (Table 3). Likewise, at site 4, the riffle-pool sequence was lost. Overall, however, the habitat quality improved below the effluent outlet and especially as distance from the outlet increased.

Water Quality. The water quality conditions were mixed (Table 3). Average historical temperatures were 5–7 °C higher downstream of the discharge, whereas dissolved oxygen and pH were relatively unchanged and ammonia-nitrogen increased slightly downstream. The water quality conditions at the time

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Table 3. Physical Habitat, Water Quality, And Biological Data from Calera Creek Collected in Summer 2012[e]

Survey	Metric	Upstream 1	Upstream 2	Outlet 3	Downstream 4	Downstream 5	Downstream 6
A.) Physical habitat	1. Bottom substrate /instream cover	14	15	5	5	18	17
	2. Embeddedness	14	18	5	5	19	18
	3. Stream flow/velocity[a]	1	3	2-20	2-20	15-20	15-20
	4. Canopy cover	14	17	17	17	18	18
	5. Channel alteration	16	19	3	18	18	18
	6. Pool/riffle ratio	14	18	2	5	18	15
	7. Bank stability[b]	10/10	9/10	7/7	10/10	10/10	10/9
	8. Bank vegetative protection[b]	10/7	9/9	9/5	9/9	10/10	10/10
	9. Streamside cover	15	20	15	15	18	19
	10. Riparian vegetation zone width[b]	5/5	8/10	10/10	10/10	10/10	10/10
	Total score	135	165	95-113	125-143	184-189	179-184
B.) Water quality	Dissolved oxygen (mg/L)	N/A	10.2 (8.4)	8.8 (6.0)	N/A	9.5 (8.7)	9.5 (6.7)
	pH	N/A	7.6 (7.3)	7.2 (7.2)	N/A	7.8 (7.6)	7.9 (7.3)
	Ammonia nitrogen (mg/L)	N/A	0.17 (0.1)	0.08 (1.49)	N/A	0.07 (0.80)	0.06 (0.39)
	Temperature (°C)	N/A	12.3 (13.8)	18.2 (21.5)	N/A	16.8 (19.5)	17 (19.1)
C.) Benthic macroinvertebrates	Total abundance	37 (29)	113 (48)	N/A	361 (207)	260 (24)	155 (25)
	Taxa richness	9 (3)	14(2)	N/A	5 (1)	5 (2)	8 (2)
	Evenness	0.86 (0.06)	0.67 (0.23)	N/A	0.30 (0.15)	0.34 (0.17)	0.37 (0.15)
	% EPT individuals[d]	58 (4)	16 (17)	N/A	0 (0)	0 (0)	0 (0)

[a]Scores separated by a '–' indicate when effluent is not released versus when it is released, respectively. The releases come in diurnal pulses as a result of a sequencing batch reactor. [b]Scores separated by a '/' indicate left bank and right bank scores, respectively. [c]Data collected on April 18 2012. Values in brackets indicate historical quarterly average from April 2007 to September 2009. ND values for ammonia not included. [d]EPT represent the pollution-sensitive orders of benthic macroinvertebrates: Ephemeroptera (mayflies), Plecoptera (stoneflies), and Tricoptera (caddisflies)n. [e](A) Physical habitat parameters measured at sites 1-6. Dark green = optimal, light green = sub-optimal, orange = marginal, and red = poor; (B) Water quality data collected by CCWRP at sites 2,3,5,6; and, (C) Benthic macroinvertebrate metrics calculated from community samples collected at sites 1,2,4,5,6. Values represent average of three replicates with standard deviation in parentheses.

of the benthic macroinvertebrate survey were consistent with historical averages.

Benthic Macroinvertebrates. The total abundance of benthic macroinvertebrates was much higher downstream of the outlet (a 219% increase from upstream site 2 to downstream site 4), which is likely attributable to the fact that there was little or no flow upstream (Table 3). However, this increase in abundance was coupled with a reduction in both taxa richness and evenness, the latter reflecting the dominance of a single species in the community (a 64% decrease and a 55% decrease, respectively). The pollution-sensitive EPT orders of benthic macroinvertebrates completely disappeared below the discharge outlet. Likely, the loss of these organisms was associated with the periodic and highly variable increases in flow below the outfall. In contrast to Calera Creek, the total abundance, richness, evenness, and % EPT individuals measured along the entire length of the reference site were much more consistent.

A potentially important pattern was casually observed in terms of human health. Biting mosquitoes (*Culex tarsalis* and *Culex pipiens* complex) were quite abundant above the outlet at sites with low-flowing water and stagnant pools, but they were absent below it.

IV. DISCUSSION

Numerous benefits were generated at Pacifica by inland discharge of recycled water, including recreation, aesthetics, and habitat for native or endangered species. For example, the pedestrian path following the rehabilitated section of Calera Creek provides recreational benefit to people who use it for walking, biking, bird watching, and dog walking. The restoration also improved the aesthetics of the neighborhood, which can have a significant positive effect on housing prices.[33−35] Additionally, the creek provides habitat for a number of native plant and animal species, which may provide people with the satisfaction of knowing that a certain species or ecosystem exists for future generations.[36] In the case of CCWRP, the economic benefits were greater than the additional costs of streamflow augmentation compared to a traditional ocean discharge with no beneficial water reuse. A novel aspect of this study was the quantification of multiple nonmonetized benefits, which has not been applied to water reuse for streamflow augmentation.

As a result of the inherent uncertainties in the benefit transfer model, we erred on the side of conservatism when applying values from other studies to Calera Creek. First, recreational value, which was the highest valued ecosystem service in our study, was estimated at \$10.20 (SD = \$5.80) per visitor per recreation day for the base-case. In comparison, average values reported in other studies for a recreation day of bird watching and hiking were \$29.60 and \$30.84, respectively.[27] Informal interviews conducted during visitor counts revealed that some visitors drove over 60 km to visit the park, reflecting the park's high recreational value. Second, the range of habitat values used in this study did not account for the value people attribute to endangered species. The CCWRP wetland and stream restoration created or improved habitat for the California Red-legged Frog, whose population has increased by an order of magnitude since the restoration.[37] The value of protecting habitat for endangered species can be substantial,[33,36] and in some cases is the most valuable ecosystem service of a stream restoration.[35]

Reports on streamflow augmentation projects in other locations have identified similar benefits, but few identify the magnitude of their values. Nobidome Stream in Tokyo, which dried up after its headwaters were diverted, was augmented with 15 000 m^3/d of tertiary-treated effluent and now provides an attractive riverine environment in an inner suburb of Tokyo.[38] In a similar case, the San Antonio River, which flows through downtown San Antonio, TX, dried up due to excessive groundwater pumping.[39,40] After its tributaries were augmented with 118 000 m^3/d of recycled water, this formerly impaired river now provides scenic value in the city's downtown Riverwalk District and habitat to pollution-sensitive aquatic species.[40,41] Similar benefits from streamflow augmentation with recycled water have been observed in San Luis Obispo Creek in San Luis Obispo, CA, the Las Vegas Wash in Las Vegas, NV, and the Segura River in Costa Brava, Spain.[3,18,42−44]

Quantitative analysis of ecosystem services would allow utilities to factor in these benefits upfront as part of decision-making and project design, in contrast to current practice where typically the benefits of streamflow augmentation projects are only realized after completion. Two unplanned streamflow augmentation projects serve as related examples. The City of San Luis Obispo, CA upgraded its wastewater treatment plant with the intention to limit discharges to San Luis Obispo Creek by using recycled water for landscape irrigation.[43] However, after the plant was built it was found that the discharges incidentally improved habitat for two federally listed species, the southern steelhead trout (*Oncorhynchus mykiss*) and tidewater gobi (*Eucyclogobius newberryi*), and the Department of Fish and Game required the utility to continue discharging to the creek to maintain the habitat.[43] Similarly, the Las Vegas Wash, NV, which receives all of Las Vegas' treated wastewater and surface water runoff, was originally used as a drainage channel.[42] However, as flows increased and the city upgraded its wastewater treatment to recycled water standards, the wash became an attractive location with lush vegetation, providing valuable recreation and aesthetic amenities such as a camping, hiking, and bird watching, to the residents of Las Vegas.[42] Additional research is needed to quantify the benefits of streamflow augmentation so utilities can include these values when deciding between wastewater treatment alternatives.

The physical, chemical, and biological outcome of streamflow augmentation at Calera Creek was more nuanced, reflecting some potential benefits, but also leaving room for improvement. Some favorable effects were observed downstream of the discharge, including an increase in physical habitat scores, unchanged pH and dissolved oxygen levels, decreased ammonia-nitrogen levels, and increased benthic macroinvertebrate total abundance (Table 3). However, some arguably negative effects included a drop in physical habitat scores from sediment accumulation directly at the outlet, a temperature increase of 5−7 °C downstream of the outlet, and a decrease in benthic macroinvertebrate taxa richness, evenness, and % EPT levels downstream (which was not observed in the reference stream). Benthic macroinvertebrates are widely used as indicators of ecological integrity because of their ubiquity, relative ease of collection and identification, and their broad range of tolerance to different forms of water pollution and habitat disturbance.[45] Because benthic macroinvertebrates are known to be responsive to streamflow and temperature,[46,47] the unnatural diurnal flow regimes and elevated water temperatures are suspected to be responsible for these negative observations.

Nonetheless, the ecological effects of streamflow augmentation at Calera Creek may be more promising than our baseline data indicate. One limitation of our study is that we used conditions upstream as representative of conditions downstream of the outlet prior to restoration. Ideally, physical habitat, water quality, and biological indices would be measured before and after the restoration and streamflow augmentation. However, most of this information was not available prior to the restoration, as is nearly always the case for restoration projects on small streams.[48] Downstream conditions prior to the project were likely much worse than current upstream conditions because the downstream portion of the creek flowed through a straightened and unvegetated channel, in contrast to the relatively healthy upstream habitat. Although the downstream benthic macroinvertebrate richness, evenness, and % EPT that we measured were relatively low, these parameters were likely as low or lower prior to the restoration. Additionally, the reduction in mosquito abundance below the outfall is a potentially significant advantage of the addition of recycled water, in that abundance was high above the outflow but absent below it. Besides their nuisance potential, mosquitoes are major vectors of a variety of human diseases.[49] The two mosquitoes (*C. tarsalis* and *C. pipiens* complex) present above the outflow are of public health concern and potential vectors of West Nile Virus.[50]

Our results demonstrate the value (and difficulty) of considering both the economic and ecological costs and benefits when evaluating streamflow augmentation projects. Using Pacifica as a test site, we found that streamflow augmentation with recycled water can be economically favorable to the alternative of discharging secondary-treated effluent directly to the ocean with no beneficial reuse. One of the most challenging issues for wastewater utilities is the construction cost of new or upgraded treatment facilities. The cost of a tertiary treatment plant may appear to be prohibitive, but as we have shown may actually be the most cost-effective option when all benefits have been taken into account. However, as demonstrated for the CCWRP project, economic and ecological benefits do not always go hand-in-hand. Additional research is needed to evaluate how the design and operation of recycled water plants can lead to the most beneficial ecological improvements. Specifically, questions remain regarding the most suitable treatment technologies, water quality requirements, and flow commitment and timing with respect to competing recycled water uses.

A barrier to implementing streamflow augmentation projects is that a lack of regulatory guidelines makes permitting difficult. For example, the City of Pacifica was required to obtain five permits from four different agencies in order to construct the CCWRP,[25] and seven different agencies were involved in permitting the streamflow augmentation project in San Luis Obispo, CA.[43] As we learn more about how recycled water can benefit aquatic habitats, it may be appropriate to develop a more streamlined regulatory and permitting process for streamflow augmentation.

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Notes

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ABBREVIATIONS

CCWRP	Calera Creek Water Recycling Plant
CPI	consumer price index
EPT	Ephemeroptera, Plecoptera, and Trichoptera
NPV	net present value
O&M	operations and maintenance
USEPA	United States Environmental Protection Agency

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