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Can Smart Stormwater Systems Outsmart the Weather? Stormwater Capture with Real-Time Control in Southern California

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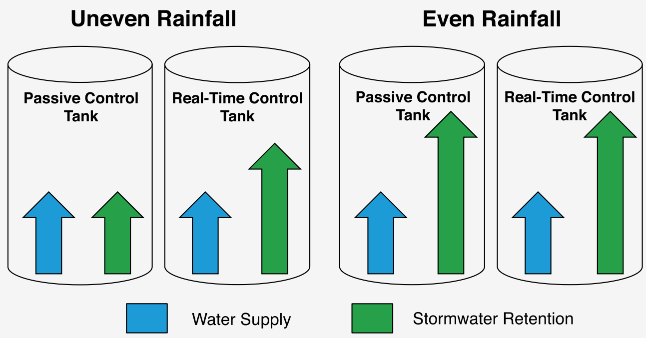
ABSTRACT: Stormwater capture systems have the potential to address many urban stormwater management challenges, particularly in water-scarce regions like Southern California. Here, we investigate the potential best-case limits of water supply and stormwater retention benefits delivered by a 10,000 m^3 stormwater capture system equipped with real-time control (RTC) on a university campus in Southern California. Using a copula-based conditional probability analysis, two performance metrics (percent of water demand satisfied and the percent of stormwater runoff captured) are benchmarked relative to (1) precipitation seasonality (historical rainfall and a counterfactual in which the same average annual rainfall is distributed evenly over the year); (2) annual precipitation (dry, median, and wet years); and (3) three RTC algorithms (no knowledge of future rainfall or perfect knowledge of future rainfall 1 or 2 days in advance). RTC improves stormwater retention, particularly for the highly seasonal rainfall patterns in Southern California, but not water supply. Improvements to the latter will likely require implementing stormwater capture RTC in conjunction with other stormwater infrastructure innovations, such as spreading basins for groundwater recharge and widespread adoption of green stormwater infrastructure.



KEYWORDS: *stormwater capture, stormwater harvesting, rain tank, stormwater reuse, real-time control, urban stream syndrome, ecosystem health, water scarcity, water supply, local water source*

1. INTRODUCTION

Southern California has historically relied on a combination of imported water and unsustainable use of local ground and surface waters to meet its water needs, consuming freshwater faster than it can be replenished.[1,2] Decision makers in the region are increasingly looking for more resilient and sustainable water supply solutions as they grapple with two primary stressors: continued population growth and increasing precipitation volatility associated with climate change.[3−7] The UCLA-led Sustainable Los Angeles Grand Challenge, for example, aims to transition Los Angeles County to 100 percent local water by 2050, and stormwater capture is poised to play an important role in meeting this goal.[8] At the state level, the California State Water Resources Control Board has set a goal of increasing California's stormwater use, relative to 2007 levels, by >1 million acre-feet per year by 2030.[9]

In addition to providing water supply benefits, stormwater capture systems can also reduce the environmental toll from municipal separate storm sewer systems (MS4s).[10] Typically, MS4s discharge high velocity stormwater runoff and associated pollutant loads to receiving waters, causing erosion and downcutting of urban streams (so-called hydromodification), surface water impairments, beach closures, and cascading ecological impacts.[10−15] Many of these problems can be addressed by implementing stormwater control measures that (1) reduce the volume of urban stormwater runoff discharged from MS4s, ideally to the point where the catchment's annual water balance matches the pre-development conditions[16−19] and (2) deliver post-storm flows that mimic the volume, timing, and water quality of pre-development baseflow.[20,21] The first can be accomplished by modifying conventional MS4 systems with gray and green infrastructure that captures, treats, and stores (e.g., in tanks) the runoff generated during storm events from roofs, parking lots, roads, and other impervious surfaces in the urban landscape[22,23] and then utilizes the captured runoff as a new water resource in the interval between storms for fit-for-purpose activities, including irrigation, freshwater aquatic habitats (so-called "environmental water"), and non-potable activities (e.g., toilet flushing), to name a few.[5] The second can be accomplished through a variety of green infrastructure approaches that remove pollutants and

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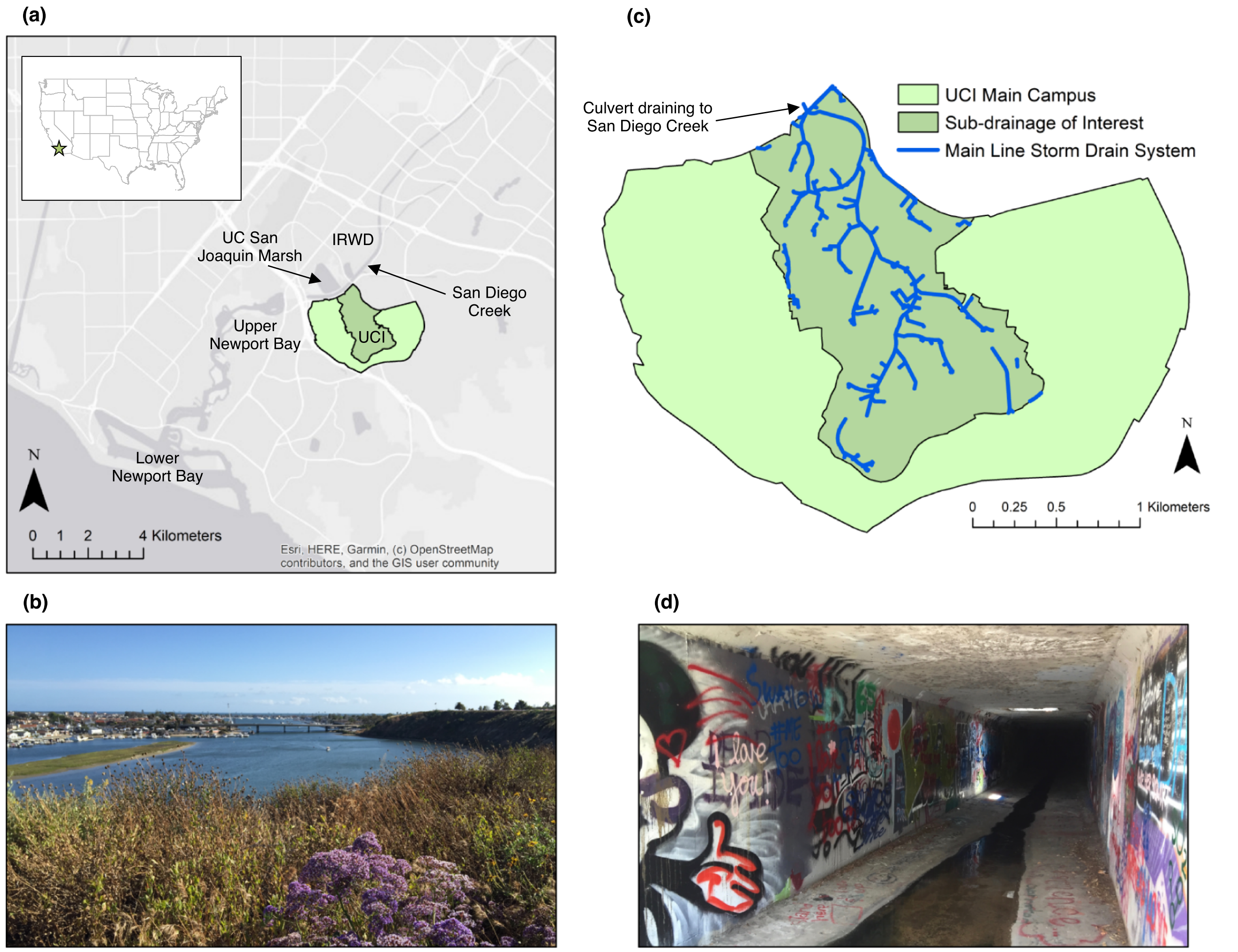

Figure 1. (a) The UC Irvine campus (green shaded area) is located close to the UC San Joaquin Marsh, the Irvine Ranch Water District (IRWD) natural treatment system and water recycling facility, and San Diego Creek. (b) San Diego Creek flows into Upper Newport Bay and then Lower Newport Bay, transitioning from natural wetland habitat to a popular recreational marina. (c) The largest campus stormwater sub-drainage (darker green shaded area) routes all stormwater runoff from the sub-drainage through a culvert (shown in (d)) to San Diego Creek.

allow for infiltration (e.g., rain gardens) or controlled release of stormwater between storm events (e.g., rain tanks outfitted with outlets that slowly release captured water after treatment).[20,24−31] In addition to addressing the stream morphology, water quality, and ecological problems noted above, as well as providing a new (renewable) water supply,[32−34] many stormwater control measures also have the potential to reduce urban flood risk[35−37] and provide a greener urban environment with many human co-benefits.[38−41]

Smart stormwater systems are gaining popularity as a tool to increase the efficiency of conventional stormwater capture. These systems rely on an integrated network of sensors and control structures for real-time control (RTC) of stormwater infrastructure at a system level.[42,43] For example, smart stormwater detention ponds respond to weather forecasts by releasing stored water in advance of precipitation events.[44−46] Smart systems have been developed to detect and reduce combined sewer overflows[47−50] and forecast and reduce urban flood risk.[51−53] Recent studies have explored the use of RTC technology to manage environmental flows,[54] shape streamflow,[55] and achieve multi-objective scenarios including, for example, stormwater retention and pollutant removal.[31,46,56−59] RTC technology also allows for the adaptation of stormwater systems to future land use changes, population growth, and climate change.[43,60,61] While the addition of RTC to a stormwater capture system cannot directly increase water supply, it can increase the volume of stormwater captured.[31,61−63] For example, Luthy et al.[64] suggested that "in drought-prone regions where stormwater capture can contribute to water supply, RTC can improve both the quality and quantity of water recharged" to aquifers. However, it is unclear to what extent RTC systems can address the challenge of stormwater capture at the sub-drainage scale in areas like Southern California with strongly seasonal precipitation, where most of the annual precipitation occurs in the winter season from December to February.[65]

In the search for innovative water supply solutions, universities can serve as living laboratories for new ideas that require evaluation and field-testing before they are implemented on a city- or state-wide scale.[66] In that spirit, the five University of California campuses in Southern California participated in a multi-year research project, "Fighting Drought with Stormwater," focused on identifying and overcoming perceptual, regulatory, and technical barriers associated with making stormwater a significant component of Southern California's water supply portfolio.[41,67−69] Focusing on the

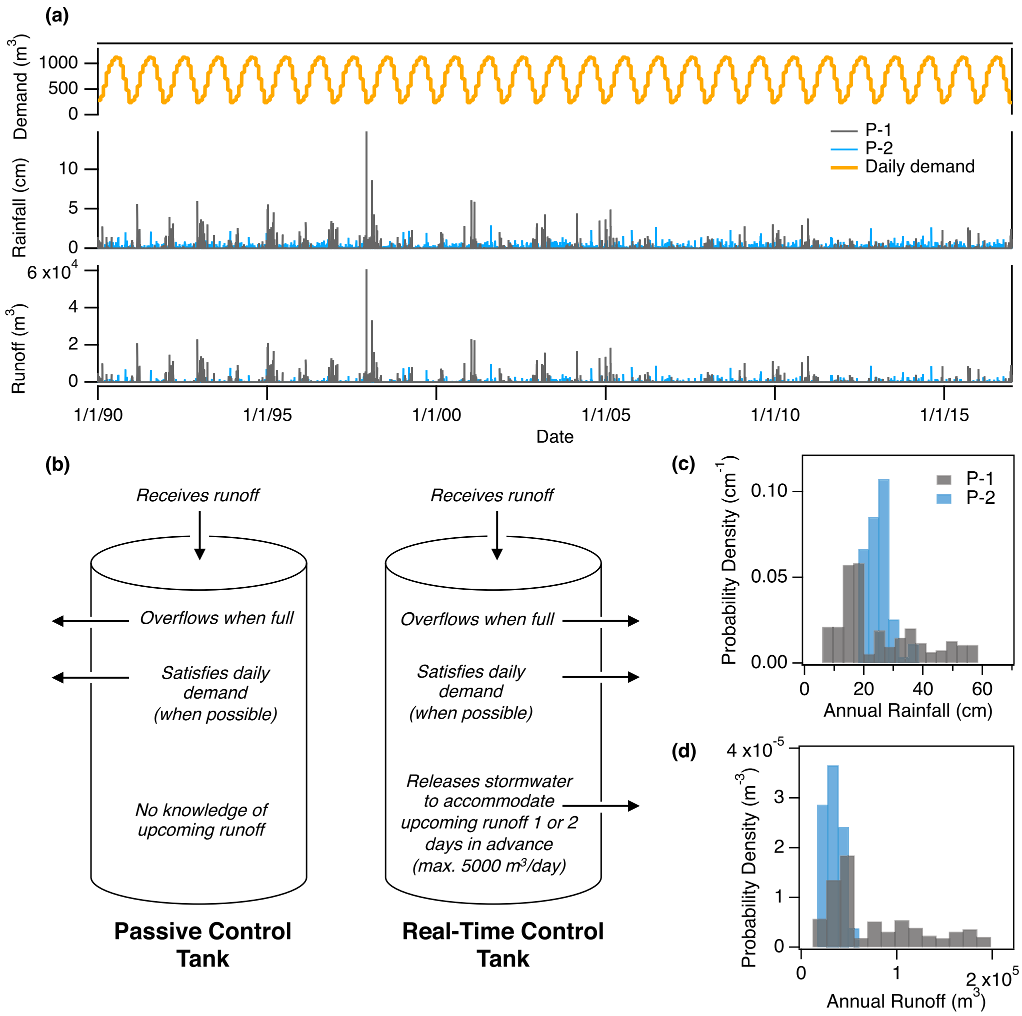

Figure 2. (a) Time series of daily water demand, rainfall, and simulated runoff generated by the largest UCI stormwater sub-drainage over 27 years for two precipitation scenarios (P-1, seasonally uneven rainfall characteristic of Southern California, and P-2, counterfactual scenario with more evenly distributed rainfall). (b) Schematic showing the key features of passive and RTC stormwater storage tanks described in this study. (c) Distribution of annual rainfall and (d) annual runoff from the sub-drainage for P-1 and P-2 precipitation scenarios.

University of California, Irvine (UCI) campus in Irvine, California, as a test bed, this paper answers the following question: what are the best-case limits of an RTC stormwater capture system on the UCI campus relative to delivering water supply and stormwater retention benefits, and how do these benefits depend on the total rainfall each year and the region's seasonal patterns of precipitation? We hypothesize that the water supply and stormwater retention benefits of a stormwater capture system at this scale, as well as the level of improvement in stormwater retention benefits achieved by RTC, will be strongly dependent on rainfall seasonality (unevenness) and total annual rainfall (dry, median, or wet year).

Our study is noteworthy in several respects. First, it fills an important knowledge gap by evaluating the stormwater retention and water supply benefits of a smart stormwater capture system (storage volume: 10,000 m^3) intermediate in size between the more frequently studied household-to-neighborhood scale systems that capture and store roof and parking lot runoff in small tanks (storage volume: ca., 1−50 m^3)[32,33,70,71] and large-scale managed aquifer recharge systems (MARs) with annual storage capacities exceeding 5 × 10^7 m^3.[72−76] Second, to test our hypothesis, we employ copula-based conditional probability distributions to evaluate the water supply and stormwater retention benefits achieved by a stormwater capture system under various scenarios of annual cumulative rainfall (dry, median, or wet years), rainfall evenness, and choice of RTC algorithm. The resulting probability distributions provide a novel, intuitive, and generalizable approach for evaluating the performance of smart stormwater systems over a wide range of operating conditions.

2. METHODS

2.1. Campus Runoff Model. UCI is located adjacent to San Diego Creek, an urban waterway that drains to an ecologically sensitive tidal saltwater wetland (Upper Newport Bay) and from there to the coastal ocean through a popular marina (Lower Newport Bay) (Figure 1a,b). All stormwater from the largest of UCI's sub-drainages (area of ∼2 km^2) is routed, without treatment, through a single stormwater culvert to San Diego Creek (Figure 1c,d). The daily volume of runoff generated by this sub-drainage was estimated with a field-calibrated stochastic hydrologic framework implemented in MATLAB (MathWorks, Natick, MA) and Hydrus 1D[77] (details of the model and its calibration with storm flow

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measurements at the culvert outlet are described in Texts S1 and S2, respectively, Supporting Information). Stochastic realizations of daily runoff were generated for the UCI sub-drainage, taking as input historical daily measurements (from 1990 to 2016) of local precipitation[78] (precipitation scenario P-1; Figure 2a), irrigation (determined from UCI's recycled water consumption, as UCI relies almost exclusively on recycled water for irrigation[79]), and evapotranspiration.[80] Runoff was estimated from both the sub-drainage's pervious area (47% of the total area) using Hydrus 1D and impervious area (53% of the total area) using the rational method with a unit runoff coefficient.[81] Hydrologic variability was captured by randomly sampling, for each Hydrus 1D runoff simulation, probability distributions of soil texture and depth to shallow groundwater, and perturbing the magnitude of each rain event by a multiplier randomly drawn from a uniform distribution (ranging from 0.8 to 1.2) (Text S1, Supporting Information). By repeating this 27-year modeling exercise ten times, we obtained nearly 100,000 stochastic realizations of daily runoff volume from the UCI sub-drainage.

The stochastic runoff simulations described above were repeated using a counterfactual precipitation scenario (P-2; Figure 2a) in which the same average annual rainfall was distributed more evenly throughout the year. The P-2 scenario was constructed from a 27-year daily time series (1990−2016, excluding snowfall) of precipitation[78] for the Washington DC area, rescaled so that the average annual rainfall matched the average annual rainfall for P-1. By investigating the best-case limits of stormwater retention and water demand satisfaction under both P-1 and P-2 precipitation scenarios, our goal is to isolate the influence of Southern California's semi-arid Mediterranean climate (i.e., its relative seasonal unevenness) on the water supply and stormwater retention benefits of a smart stormwater collection system, and thereby directly test the hypothesis raised earlier. The Gini index was adopted as a measure of rainfall evenness

$$G = \frac{1}{n}\left(n + 1 - 2\left(\frac{\sum_{i=1}^{n}(n+1-i)y_i}{\sum_{i=1}^{n} y_i}\right)\right) \quad (1)$$

where y_i is the daily precipitation [L] sorted in increasing order and n is the number of days per year (365 or 366).[82] The Gini index, G [unitless], ranges between 0 and 1, corresponding to the extreme limits where annual rainfall, respectively, is evenly distributed across 365 days ($G = 0$) and falls on a single day ($G = 1$).[82]

2.2. Tank Simulations. Our proposed stormwater runoff capture and storage system, or "tank," intercepts stormwater runoff from the UCI stormwater culvert before it reaches San Diego Creek. Based on preliminary simulations with tank sizes ranging from 1000 to 60,000 m^3, and consistent with previous results,[83] we found that the stormwater retention benefits (as described below) saturated for tanks larger than 10,000 m^3 (Figure S2, Supporting Information). We therefore set the tank size to 10,000 m^3, consistent with our goal of assessing the theoretical upper limit of what is achievable at this site with RTC technology. The capital costs for a tank this size ($10−20 million[84]) are at the outer limits of what is financially feasible for many communities, including university campuses. To assess the water supply benefits of such a system, we adopted a seasonally varying demand profile (for the irrigation of a nearby wetland marsh system, described in Section 2.3) with low demand in the winter and high demand in the summer (Figure 2a).

The tank water balance was carried out using the "yield before spillage" algorithm[85,86] implemented on a daily time step (Figure 2b). Our tank's demand fraction d and storage fraction s are in the range ($d \in [0.5, 1]$ and $s \in [8, 16]$) where a daily time step should not introduce errors in the estimation of stormwater capture benefits.[83] Here, the demand and storage fraction are defined as follows, $d = D_d/(AR_d)$ and $s = S/(AR_d)$, where D_d is the average daily water demand for the year [L^3], R_d is the average daily rainfall for the year [L], S is the tank storage capacity [L^3], and A is the effective impervious area draining to the tank [L^2].[83] The volume of water in the tank was updated each day by adding the current day's incoming runoff (generated by the stochastic runoff model, see previous section) to the tank's stored runoff volume from the previous day and then subtracting the amount of stormwater needed to satisfy daily demand. On days when the volume of runoff from the sub-drainage exceeded tank capacity, excess runoff was diverted to San Diego Creek, thereby reducing the retention benefit conferred. Conversely, on days when the tank was empty, demand was not met, thereby reducing the water supply benefit conferred. This water balance was performed separately for the two precipitation scenarios (P-1 and P-2) and three RTC scenarios as follows: (1) a passive control tank that has no knowledge of future weather conditions (passive); (2) an RTC-enhanced tank that has perfect knowledge of the daily runoff volume that will occur 1 day in advance (RTC-1); and (3) an RTC-enhanced tank that has perfect knowledge of the daily runoff volume that will occur 2 days in advance (RTC-2) (Figure 2b). Based on its perfect knowledge of future runoff conditions, the RTC algorithm released additional volume to San Diego Creek [but no more than 5000 m^3 per day to prevent hydromodification and ecological impacts of stormwater runoff on San Diego Creek (discussed further in Section 3.6)] as needed to accommodate the runoff volume slated to occur in the next 1 or 2 days. For all combinations of these precipitation and RTC scenarios, tank performance was quantified based on the fraction of annual stormwater runoff volume captured (stormwater retention benefit, also called the volumetric retention efficiency) and the fraction of annual demand satisfied (water supply benefit, also called water saving efficiency).[83]

2.3. Seasonal Demand Profile. Several different potential end uses of the water captured by the tank were explored in consultation with local university, environmental, and utility stakeholders. Outdoor irrigation of campus green space was ruled out because UCI relies almost exclusively on recycled water for irrigation[79] and thus the substitution of captured stormwater for non-potable recycled water would not reduce potable water demand. We also ruled out baseflow restoration of the nearby San Diego Creek because Southern California's reliance on imported water has resulted in increased summer river discharge in urban areas.[87] Promising alternative end-uses included (1) pumping the captured water to the nearby UC San Joaquin Marsh, for which the environmental water demand regularly exceeds supply; (2) discharging the captured water to UCI's sanitary sewer system to supplement sewage flows to the Irvine Ranch Water District's (IRWD) Michelson Water Recycling Plant, where the water would undergo tertiary treatment and be subsequently distributed to consumers, including UCI, through IRWD's recycled water system; or (3) pumping the captured water to IRWD's nearby treatment

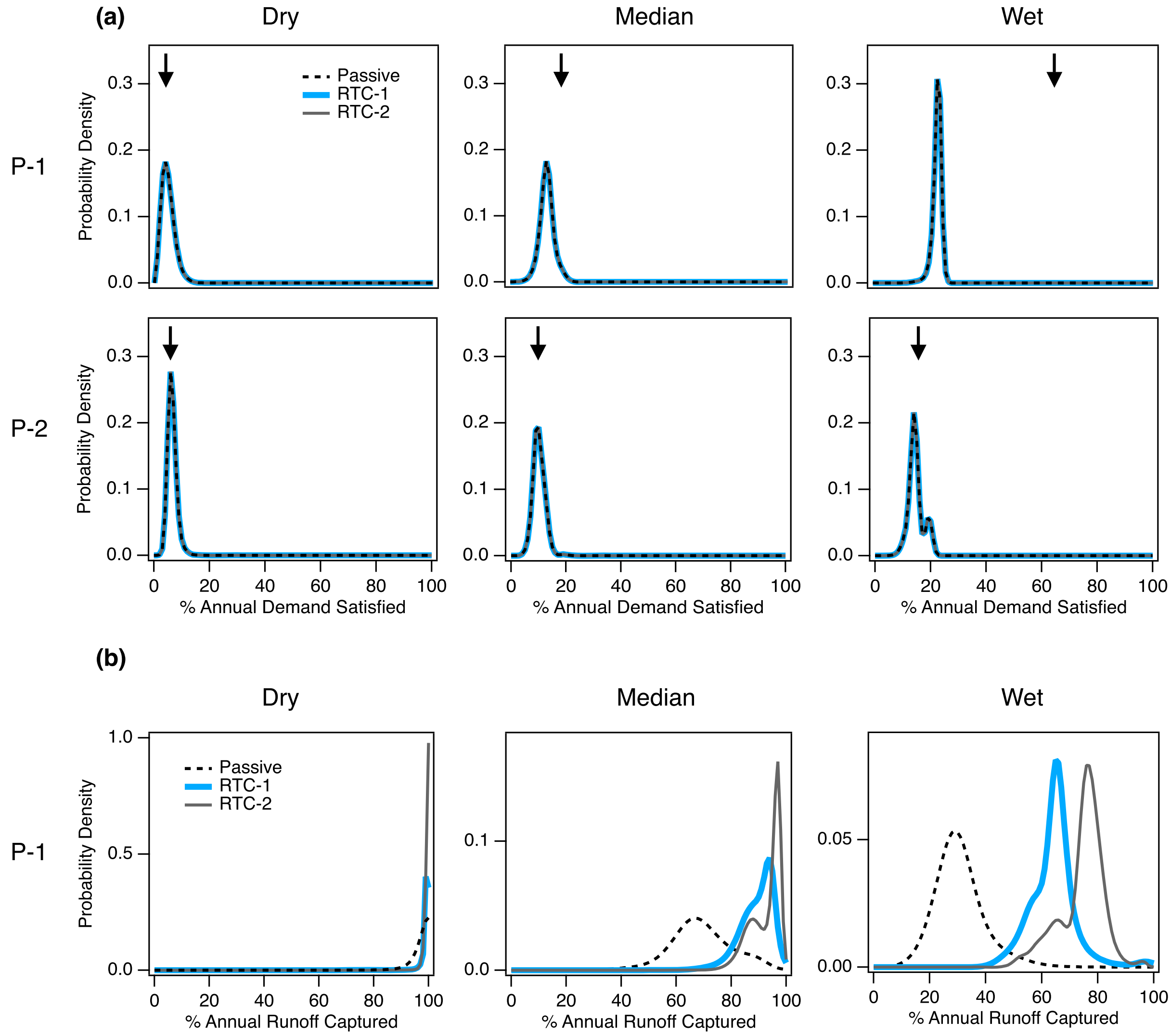

Figure 3. PDFs for (a) the percent of water demand satisfied under precipitation scenarios P-1 and P-2 and (b) the percent of runoff captured under scenario P-1, conditioned on dry (5th percentile), median (50th percentile), or wet (95th percentile) years. Colored curves represent the performance of a passive tank (dashed black curves), an RTC tank with 1 day of weather foreknowledge (blue), and an RTC tank with 2 days of weather foreknowledge (gray). Vertical arrows in panel (a) indicate the theoretical maximum water supply benefit.

marsh to provide environmental water for the UC San Joaquin Marsh and San Diego Creek (Figure 1a). The first option (sending the captured water directly to the UC San Joaquin Marsh) was ultimately selected based on the marsh's ecological significance (as part of the UC Natural Reserve System[88]), the lack of a sustainable source of water to support the marsh's freshwater habitat, particularly in the light of the ongoing drought in Southern California,[89] and the proximity of the marsh to the proposed tank location (directly across San Diego Creek from the stormwater culvert, see Figure 1a). Daily water demand for the marsh was estimated as follows: (1) a monthly time series of marsh evapotranspiration (ET) from 1990 to 2016 was generated using the Integrated Urban Water Model web tool[90] with a plant factor appropriate for marsh vegetation (see Text S3 in the Supporting Information for details) and (2) average ET for each month of the year was computed from (1) and divided by the number of days in a month to arrive at the final daily water demand profile (Figure 2a). The resulting daily marsh water demand ranged from 240 m^3/day (December) to 1120 m^3/day (July), with an annual total of approximately 2.6×10^5 m^3.

2.4. Copula-Based Bivariate Distributions and Conditional Probabilities. From the approximately 100,000 daily runoff, ET, and tank water balance simulations described in Sections 2.1 through 2.3, we prepared marginal probability distributions of annual rainfall [L], percent of annual runoff volume captured (stormwater retention benefit), and percent of annual demand satisfied (water supply benefit). Because the benefits of the tank are measured as percentages, their marginal distributions are on the support 0 to 100%. Marginal distributions for annual rainfall and benefits conferred by the tank were joined by a copula to yield bivariate cumulative distribution functions (CDFs) of the form $F_{BR}(b,r) = C[F_B(b),F_R(r)]$. Here, B and R are random variables for the annual benefits achieved (percent of either runoff captured or demand satisfied) and annual rainfall, respectively, b and r are specific realizations of these random variables, and C is the CDF of the copula. We used the Multivariate Copula Analysis Toolbox (MvCAT[91]) to select an optimal copula function from the Archimedean, Plackett, and BB1 families (based on Bayesian Information Criterion ranking) and infer distribution parameters from the annual rainfall and benefits time series.

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The probability density function (PDF) form of the benefits, conditioned on a specific annual rainfall, was then calculated as follows.[92]

$$f_{B|R}(b|r) = c[F_B(b), F_R(r)]f_B(b) \quad (2)$$

Here, c is the PDF form of the copula and the function $f_b(b)$ is the PDF of the marginal distribution for annual benefits conferred by the tank. Specific conditioning events considered included dry (5th percentile), median (50th percentile), or wet (95th percentile) years (annual rainfall of 6, 17, and 52 cm, respectively for P-1; 18, 23, and 30 cm, respectively for P-2). The copula analysis was numerically implemented in the computational software package Wolfram Mathematica (Wolfram, Champaign, IL, version 10.1).

3. RESULTS AND DISCUSSION

3.1. Rainfall and Runoff. Precipitation scenario P-1 represents the strongly seasonal rainfall pattern characteristic of Southern California (annual average Gini index of 0.96) while P-2 is a counterfactual scenario in which the same annual average rainfall is more evenly distributed over the year (annual average Gini index of 0.87) (Figure 2a). The distribution of cumulative annual rainfall for the counterfactual scenario P-2 is relatively narrow, ranging from roughly 20 to 40 cm (blue probability distribution in Figure 2c). Rainfall in Southern California, on the other hand, varies considerably from year-to-year, resulting in a broad distribution of cumulative annual rainfall for scenario P-1, from less than 10 cm to nearly 60 cm during dry and wet years, respectively (gray probability distribution, Figure 2c). The runoff generated from these two rainfall scenarios exhibit similar patterns, with relatively broad and narrow ranges of annual runoff, respectively, under scenarios P-1 (0.1 to 2×10^5 m^3) and P-2 (0.1 to 0.6×10^5 m^3) (Figure 2d). While P-1 and P-2 have the same average annual rainfall, the average annual runoff generated from P-1 ($0.7 \pm 0.5 \times 10^5$ m^3) exceeds that for P-2 ($0.3 \pm 0.09 \times 10^5$ m^3) because, under the P-1 scenario, most rain falls in a small number of large storm events in the winter (Figure 2d). These large storms rapidly saturate the soil in pervious areas of the UCI sub-catchment, resulting in large runoff events. Under the counterfactual P-2 scenario, storms are generally smaller and distributed throughout the year and, as a result, the soil in the permeable portion of the drainage area is less frequently saturated and runoff events are less frequent and smaller in size.

3.2. Copula-Based Conditional Probability Analysis: Water Supply Benefits. The average annual water demand for the marsh (2.6×10^5 m^3) exceeds the annual average runoff generated from the UCI sub-catchment under both the P-1 (0.7×10^5 m^3) and P-2 (0.3×10^5 m^3) scenarios. Thus, on an average annual basis and in the theoretical limit where our proposed tank captures all runoff discharged from the UCI campus sub-catchment, no more than 27 and 12% of the annual marsh demand can be satisfied under precipitation scenarios P-1 and P-2, respectively. In any given year, the theoretical maximum water supply benefit will fall above or below these annual averages, depending on the cumulative rainfall that fell that year. Under precipitation scenario P-1, the theoretical maximum water supply benefit is 4, 18, and 65% in dry (5th percentile), median (50th percentile), and wet (95th percentile) years, respectively (vertical arrows in top panels of Figure 3a). For scenario P-2, the theoretical maximum water supply benefit is 6, 10, and 15% in dry, median, and wet years, respectively (vertical arrows in the bottom panels of Figure 3a). These theoretical limits serve to benchmark the tank's actual water supply benefits under various RTC and precipitation scenarios.

The copula-based conditional probability analysis reveals how climate, vadose zone hydrology, demand seasonality, and RTC technology collectively determine the water supply benefits achieved by the proposed tank. Under precipitation scenario P-2, individual rain events are generally smaller, permeable sediments in the sub-catchment are less frequently saturated, infiltration rates are generally faster (due to the influence of capillary forces on infiltration under unsaturated conditions[93]), and consequently runoff events are smaller, less frequent, and distributed more evenly throughout the year. This combination of factors reduces the theoretical maximum water supply benefit below 20% for all rainfall conditions evaluated (vertical arrows in bottom panels, Figure 3a) but also ensures that virtually all runoff from the sub-catchment is captured by the tank and available to satisfy demand (i.e., the probability distributions for demand satisfaction align with the theoretical upper limits, bottom panels in Figure 3a). The theoretical maximum water supply benefit is higher under scenario P-1 during median and wet years (vertical arrows, top panels, Figure 3a), because rainfall is concentrated in large winter storms that saturate permeable sediments in the sub-catchment and more efficiently convert rainfall to runoff. However, much of this excess runoff cannot be used to satisfy demand due to more frequent tank overflows and the seasonal mismatch between when most of the rain falls (winter) and when ET demand in the marsh is the highest (summer) (Figure 2a). These two patterns—lower achievement of higher theoretical maximum water supply benefits (under scenario P-1) and higher achievement of lower theoretical maximum water supply benefits (under scenario P-2)—balance out so that the absolute water supply benefits provided under both precipitation scenarios are quite similar, ranging from 0 to 15% (during dry years), 5 to 20% (median years) and 10 to 30% (wet years) (Figure 3a).

Another striking result from the copula analysis is the degree to which RTC appears to have no effect on water supply benefits (i.e., the probability distributions generated for the passive, RTC-1 and RTC-2 scenarios overlap, Figure 3a). This result has been reported previously in the literature[31] and can be rationalized by noting that a full tank (whether a passive tank that filled up and overflowed, or a smart tank that released water in advance then filled up) will always have the same volume of water available to satisfy demand between rain events. Thus, under the yield before spillage water balance approach utilized here, a smart and passive tank will satisfy demand equally, although the passive tank may provide less stormwater capture benefit (see next section). In practice, it may not be possible to satisfy demand prior to discharging water in advance of a storm, and in this event, the introduction of RTC can reduce demand satisfaction, all else being equal.[94]

3.3. Copula-Based Conditional Probability Analysis: Stormwater Retention Benefits. Because runoff events are generally small under the counterfactual P-2 scenario (see last section), nearly 100% of the annual runoff volume is captured across all three conditioning events (dry, median, and wet years) and across all three tank configurations (passive, RTC-1, and RTC-2) (results not shown). On the other hand, the percent of annual runoff volume captured under the P-1

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precipitation scenario depends both on the conditioning event (dry, median, and wet years) and tank configuration (passive, RTC-1, and RTC-2) (Figure 3b). RTC confers little or no benefit for runoff capture during a dry year (left panel, Figure 3b) because the tank can accommodate all runoff from the sub-catchment with or without RTC. During median and wet years, probability distributions of the stormwater capture benefit shift progressively rightward as the tank is transitioned from passive to RTC-1 to RTC-2 (middle and right panels, Figure 3b).

3.4. Copula-Based Conditional Probability Analysis: Summary. In addition to providing a straightforward and generalizable approach for summarizing and interpreting the outcome of hundreds of thousands of runoff and water balance simulations, the copula-based probability distributions presented above reveal the likely benefits of stormwater RTC, compared to a passive system, under various climate and precipitation scenarios—precisely the type of information required to evaluate likely outcomes associated with investing in stormwater RTC, for example, as part of a hydro-financial Environmental Impact Bond (EIB) framework.[95,96]

Relative to stormwater capture on the UCI campus, we find that (1) RTC does not improve water supply benefits under any of the scenarios evaluated; (2) the theoretical upper limit in water supply benefits (equal to the percent of annual water demand that can be satisfied if all annual runoff from the sub-catchment is captured) is generally higher under the seasonally uneven precipitation scenario (P-1) characteristic of Southern California, compared to the counterfactual precipitation scenario (P-2) in which the same annual rainfall is distributed more evenly over the year; (3) under the P-1 scenario, probability distributions of the water supply benefit fall substantially below theoretical upper limits, particularly during median and wet years, due to frequent tank overflows and the strong seasonal mismatch between demand and supply; (4) under the P-2 scenario, probability distributions of the water supply benefit achieved by the tank approach, or equal, theoretical upper limits, because in this case, most stormwater runoff from the sub-catchment can be captured and stored for later use; (5) the net result of (3) and (4) is that probability distributions of the water supply benefit are very similar for scenarios P-1 and P-2 in dry, median, and wet years; and (6) RTC substantially improves the delivery of stormwater retention benefits under the P-1 scenario, particularly during median and wet years but not under the P-2 scenario. In the latter, a passive tank can capture most stormwater runoff generated by the sub-catchment.

3.5. Defining "Smart". In this study, we defined a smart stormwater system as a storage tank that discharged water in advance of upcoming rainfall, based on perfect knowledge of the weather forecast either 1 or 2 days in advance. This approach is consistent with the literature, which has generally focused on stormwater RTC with the primary goal of optimizing environmental benefits.[43,46,56] However, stormwater systems have the potential to be "smart" in different ways. For example, discharging water directly to San Diego Creek is a straightforward strategy for pre-storm release, but this water could also be sent to any of the possible demand options identified in Section 2.3, thereby increasing the tank's water supply benefits. This approach could also have environmental benefits for San Diego Creek, by reducing hydromodification and the negative impacts of flow alteration on benthic invertebrate communities.[55,97,98]

Embedding campus-scale (or smaller) smart stormwater systems into larger smart stormwater networks is another strategy for increasing both water supply and stormwater retention benefits. For example, a regionally integrated smart network could utilize distributed tanks and green infrastructure systems for runoff capture and infiltration and then divert excess captured runoff to central spreading basins for groundwater recharge.[1,75,76] Implementing "real-time distributed control" of stormwater expands both the capacity of the system (thus reducing overflows) and the delivery of water supply, thus increasing overall reliability and performance.[61,99,100] However, real-time distributed control of stormwater systems also comes with the risk of exacerbating inequities that already exist in urban environments, for example, by shifting the negative impacts of urban runoff to at-risk communities.[101−103] Community engagement is therefore critical to ensure that efforts to improve stormwater infrastructure performance do not erode trust in critical civil infrastructure.[104,105] Cities implementing smart stormwater systems will also need to address the many issues facing future "smart cities," such as data privacy and cybersecurity.[51,106]

Finally, it is important to note that the water supply and environmental benefits achieved by the tank considered in this study are dwarfed by the corresponding benefits provided by the permeable portion of the UCI sub-drainage. The annual average volume of water retained by the permeable portion of the sub-drainage by infiltration and evapotranspiration (3.9×10^5 and 4.3×10^5 under the P-1 and P-2 precipitation scenarios, respectively) exceeds the total annual ET demand of the San Joaquin Marsh (2.6×10^5 m^3) and the annual average maximum (theoretical) volume of runoff that could be captured by our tank under the P-1 (0.7×10^5 m^3) and P-2 (0.3×10^5 m^3) scenarios. This retained water provides tangible water supply and environmental benefits, by reducing the irrigation demand of green space on the UCI campus and recharging shallow groundwater aquifers that support baseflow in nearby streams, including San Diego Creek. This point underscores the fact that stormwater capture systems, smart or not, should be considered an option of last resort. The far smarter approach is to minimize urban imperviousness and the runoff it generates.

3.6. Study Limitations. Our study design entailed several simplifying assumptions that could limit its generalizability. First, we chose a relatively large tank size to maximize the amount of water that could be stored and available to satisfy demand during long antecedent dry periods. Stormwater capture systems of this scale (and larger) have been proposed and constructed in many urban areas to address combined sewer overflows.[84,107−109] Absent the regulatory pressure of the Clean Water Act, however, cities have less incentive to invest in expensive, large-scale stormwater storage systems. The \$10M capital cost required to construct a tank of this size is difficult to justify based on water supply arguments alone, when the same volume of water can be purchased for around \$12,000 (assuming present unit costs for imported water in Los Angeles of \$1500 per acre-foot).[110] However, if the primary goal is to capture runoff for flood control and environmental benefits, the capital costs may be less of a constraint, particularly as the RTC technology improves. For example, Xu et al.[94] found that increasing an RTC system's forecast lead time from 1 day to 7 days provided better flood protection than increasing tank capacity.

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Second, we assumed that RTC-1 and RTC-2 had perfect knowledge of rain events 1 and 2 days into the future, respectively. The assumption of perfect forecasts is commonly used in RTC modeling studies,[53,111] and a better understanding of the role of forecast accuracy has been cited as a key knowledge gap for RTC implementation.[43] RTC systems with imperfect weather knowledge can outperform passive systems in terms of runoff capture, but the opposite may be true for water supply—if a forecasted storm does not ultimately occur, water may be released unnecessarily, thereby reducing the volume of water available to satisfy the future demand.[94]

Third, we arbitrarily set a 5000 m^3 cap on the volume of pre-storm water that could be discharged to San Diego Creek over any 24 h period which, at this site, equates to an increase in the streamflow of approximately 0.06 $m^3\ s^{-1}$ or about 10% of the dry weather baseflow.[112] As noted by Xu et al.,[94] the hydrologic and ecological benefits of stormwater RTC will not be realized to the extent that the technology merely shifts the timing of high streamflow events from after a storm (without RTC) to before a storm (with RTC). Emerging decision support tools [such as the Ecological Limits of Hydrologic Alteration (ELOHA) framework[98]] could be used to prescribe the magnitude and timing of flow release from RTC stormwater capture systems, with the goal of minimizing the negative impacts of pre-storm releases on hydromodification and the biological integrity of streams.

4. CONCLUSIONS

Our study suggests that even perfectly smart stormwater systems (as represented here by RTC systems with perfect knowledge of rain events 1 or 2 days in the future) have their limits. Although engineers can incorporate safety factors into a tank's design (e.g., by increasing the tank size or adjusting the RTC pre-storm release algorithm), they cannot control the weather, and it is important to delineate how regional rainfall patterns affect smart stormwater infrastructure outcomes. By comparing the PDFs of water supply and retention benefits under various RTC algorithms (no knowledge of future rainfall or perfect knowledge of future rainfall 1 or 2 days in advance) and conditioned on wet versus dry years, we effectively bracket the range of operating conditions likely to be achieved in practice by a proposed stormwater capture system on the UCI campus—important information for risk assessment and cost-benefit analysis of RTC implementation, for example, to support EIB financing of stormwater capture. While our proposed tank generally performed well for stormwater retention, particularly when outfitted with RTC, it could not reliably satisfy more than 30% of the annual ET demand for a nearby marsh. The tank satisfied about the same amount of demand under both the Southern California (P-1) precipitation scenario and a counterfactual (P-2) precipitation scenario in which the same rainfall is distributed more evenly throughout the year, even though the P-1 scenario generates more runoff. The uneven rainfall in Southern California also results in a smaller fraction of runoff captured during median and wet years, relative to a counterfactual P-2 scenario. Such caps on the water supply and stormwater retention benefits of stormwater capture systems are likely to worsen under climate change, which for Southern California may translate to more precipitation during California's winter months and less precipitation in fall and spring.[7] The water supply, environmental, and flood reduction benefits of stormwater RTC are all likely to improve to the extent that stormwater capture systems are implemented as part of a distributed regional network of stormwater solutions including spreading basins, green stormwater infrastructure, and storage tanks.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsestwater.1c00173.

Details of the campus runoff model, flow data calibration, seasonal demand profile estimation, results of preliminary modeling, and cross-plots of benefits and annual rainfall (PDF).

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Notes

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