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Cover Page Footnote

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Temporal and Volumetric Characteristics of Lagoons in the Santa Monica Bay and the Passage Implications for Southern Steelhead Trout

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Abstract.—Record drought from 2012 to 2016 followed by rainfall in the winter of 2017 provided an opportunity to examine how changing climate conditions may affect migration opportunities for the endangered southern steelhead trout (*Oncorhynchus mykiss*). This study examined how intermittently open estuary-ocean interfaces in the Santa Monica Bay that have historically supported steelhead evolved temporally and volumetrically. All seven lagoons in the study area breached by January 2017 after five years of drought and nearly exclusively closed conditions. Duration of breach was affected by the size of the lagoon, with smaller lagoons remaining breached longer than larger lagoons. Conversely, volume capacity persisted longer in larger lagoons. Lagoon condition was quantified by presence/absence of breach and passibility, coupled with daily rainfall. This study provides important lagoon planning, restoration and management information needed to support recovery of southern steelhead trout populations in the face of climate change.

Southern steelhead trout, *Oncorhynchus mykiss*, are a Distinct Population Segment (DPS) of west coast steelhead listed under the Federal Endangered Species Act (ESA) in August 1997. Historic stock numbers have drastically declined due to factors such as loss of estuarine habitat, land use practices that impact watershed function, and connectivity. More recently, the effect of extreme drought[1] that has affected rainfall and freshwater ecosystems across California from 2012 to 2016 has caused even more stress on these populations (NMFS 2016). Fewer than ten anadromous adults have been observed annually in the Southern California Distinct Population Segment region extending from San Luis Obispo to the Mexican border from 2014-2018.[2]

Restoration projects across the range of historic steelhead habitat in southern California, and in the Santa Monica Bay in particular, have helped remove documented passage barriers for migrating steelhead in recent years. It should be noted that passability as defined in this study refers specifically to the lagoon – ocean connection, whereas the ability of fish to move upstream from the lagoon through the mainstems of creeks is usually of much shorter duration and more difficult to document. Three passage barriers, including a check dam and two Arizona crossings, were removed over the course of three years in Arroyo Sequit Creek in Leo Carrillo State Park. This restoration was completed just before

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[1] USGS. 2017. US Drought Monitor: California Drought. Accessed 8/9/2017 droughtmonitor.unl.edu/CurrentMap/StateDroughtMonitor.aspx?CA.

[2] Nature Conservancy. 2018. California Salmon Snapshots, http://www.casalmon.org/salmon-snapshots.

the rains of the 2016/2017 water year and resulted in the immigration of two anadromous steelhead trout (350 mm and 360 mm FL), the first anadromous individuals documented to return to the upper reaches of the creek since surveying began in 2004 (RCDSMM unpublished data). Similarly, the restoration of Lower Topanga Creek in 2009 and Malibu Lagoon in 2012-2013 have resulted in increased critical fish passage opportunities allowing three anadromous fish to migrate upstream from the ocean with the 2017 rains (RCDSMM unpublished data).

Despite the success of restoration and anthropogenic passage barrier removal projects, natural passage barriers still exist for *O. mykiss* due to the nature of intermittently open bar-built coastal lagoons that are characteristic of Mediterranean climate regions, such as those in the Santa Monica Bay (McLaughlin et al. 2014). These "small creek" archetypal systems are identified as intermittently open bar-built estuaries.[3] According to the lagoon classification system by Jacobs et al. (2011)[4], the small, steep coastal creeks draining into the Santa Monica Bay respond similarly to the complex interactions of wave exposure, longshore transport, sediment delivery, watershed size, and formation processes. While historic data on creek mouths provided in the US Coast and Geodetic Topographic Survey (T-sheets) provides interesting information on past conditions, we found that due to extensive modifications over time, bar-built estuaries along the Santa Monica Bay needed to be further examined to better understand present constraints.

Lagoons not only provide important fish passage opportunities, but also can provide important foraging habitat for smolts - young trout migrating outward to the ocean (Bond et al. 2008). In central and northern California systems, the opportunity to spend time in brackish water adjusting to higher salinity levels also lowers stress levels for smolts during the freshwater to ocean transition (MacDonald et al. 1988). In order to support the recovery of southern steelhead trout, adequate connectivity is needed for immigration of anadromous adults to spawn and for juvenile smolts to migrate out to the ocean. If this exchange of habitat is unable to occur, gene flow and fecundity will continue to be reduced in the populations within the Santa Monica Bay, making them more susceptible to extirpation (NMFS 2012). The combination of current anthropogenic constraints caused by development adjacent to the creek mouths, impacts of Pacific Coast Highway and beach bar manipulation, muddle the behavior one would expect from examining past data and color restoration opportunities and constraints. This information will help us to understand how bar built estuaries in the Santa Monica Bay might respond to future climate change and sea level rise.

Systematic studies of the processes driving estuarine seasonal closure dynamics throughout Mediterranean zones worldwide provide some guidance, although observations of the patterns in southern California appear to be somewhat different than those observed elsewhere. McSweeney et al. (2017) developed a classification system for intermittently open/closed estuaries (IOCE) in Victoria, Australia, a Mediterranean climate like southern California. However, lagoons in Australia are tidally influenced, much larger in all ways, and unconstrained by topography so their behavior patterns differ. Northern California

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[3] Southern California Wetlands Recovery Project. 2018. Wetlands on the edge: the future of southern California's wetlands: Regional Strategy 2018. Prepared by the California State Coastal Conservancy, Oakland, CA.

[4] Jacobs, D., E. D. Stein, and T. Longcore. 2011. Classification of California estuaries based on natural closure patterns: Templates for restoration and management. Southern California Coastal Water Research Project Tech. Memo. 619:1-50.

lagoons are much more exposed to wind and wave action due to their west facing orientation, yet many of the lagoons examined in northern California also breach naturally under lagoon-side flow driven processes instead of tidal processes (Kraus et al. 2008). A South African definition for estuaries also echoes processes seen in our study area. Describing a lagoon as "a coastal body of water in intermittent contact with the open sea and within which sea water is measurably diluted with fresh water from land drainage" (Day 1980), takes into account systems that may be dry for periods of time (Cooper 2001). This trait is seen in many of the lagoons in the Santa Monica Bay that dry down completely during summer/fall periods when rainfall is typically absent. Even when lagoon surface area persists through the dry season, connection between a lagoon and upstream habitat is often cut off beginning in the early summer due to subsurface flow in lower reaches (Dagit et al. 2017).

Due to the low coastal exposure of the south/southwest facing beaches, lagoons of the Santa Monica Bay are not strongly influenced by wave action.[4] The Santa Monica Bay coastal area is situated facing south/southwest, which reduces the importance of wind action on beaches by diminishing strong wave action that contributes to longshore sediment processes that help deteriorate berms in higher wave exposure areas.[5] Dominant wave action is due to prevailing northwest winds during spring and summer months, with westerly winds that are common in fall through spring. However, south-southeast winter storm winds can sometimes generate strong waves that cause significant erosion. Overall, wave climate in the area is considered mild due to sheltering from deep ocean waves by the California Channel Islands, although west-facing beaches are more exposed to swell from storms in the North Pacific, and south facing beaches more susceptible to waves generated by southern swell. The lagoons east of Point Dume (including Solstice, Las Flores and Topanga), are generally more sheltered than those west of Point Dume (Zuma, Trancas, Arroyo Sequit and Big Sycamore). Waves greater than 3.5 m are most likely to erode sand from the beach, but these waves have not been found to occur often.[6] Instead, stream input and rainfall are the determining factor of breach potential and surface water presence. Stream flow, which is highly seasonal in California, is a major control on the state of a lagoon's inlet (Elwany et al. 1998).[4] Rich and Keller (2012) examined how watershed size and upstream slope can predict the behavior of small lagoons along the Santa Barbara Coast, determining that watershed size and the size of the associated lagoon are positively correlated.

Additionally, all the lagoons in the study zone are considered hydraulic estuaries that are normally closed to the sea during drier months by a bar that forms across the mouth of the lagoon.[4] Higher storm generated waves and higher tides both occur during the winter and, combined with higher flows associated with storm events, are associated with breaching the sand berms and re-connecting coastal creeks and lagoons with the ocean. Another characteristic that we did not specifically examine is tidal prism, the volume of water in a lagoon that is between mean high tide and mean low tide. Tidal prisms in river-dominated lagoons, where estuary side processes initiate breaches, are too small to maintain a breach against the wave action and tidal influence that the beach faces in the Santa Monica Bay

[5] Moffatt and Nichol. 2013. Broad Beach Restoration Project Coastal Engineering Report Exhibit L to CDP Application 4-12-043. Prepared for Broad Beach Geologic Hazard Abatement District.

[6] Noble Consultants. 2009. Coast of California storm and tidal waves study, Los Angeles Region. Prepared for U. S. Army Corps of Engineers.

typically receive (Cooper 2001). Like coastal exposure and formation process, tidal prism characteristics in the study area lagoons are defined more by morphological constraints that are uniform throughout the study area; additionally tidal prism is usually so small that it is not able to initiate breaches (Cooper 2001).

This study examined how intermittently open bar-built lagoon morphology, specifically breach frequency and volumetric changes, responded to rainfall after a period of drought, and the implications this may have on future restoration efforts to improve *O. mykiss* passage opportunities in the Santa Monica Bay. Seven lagoons within the Santa Monica Bay were selected for evaluation. Historically, Arroyo Sequit, Big Sycamore, Las Flores, Malibu, Solstice, Topanga, Trancas, and Zuma Creeks all supported southern steelhead trout populations (NMFS 2012), but current lagoon conditions restrict passage opportunities at all but Malibu Creek, which was restored in 2012. Malibu Creek is the only antecedent creek that crosses the Santa Monica Mountains from the San Fernando Valley to the ocean; its course remained the same and cut through bedrock despite the uprising of the Santa Monica Mountains. Malibu Creek also receives extensive imported water flows. Due to the recent restoration actions undertaken at this lagoon and its differences from the other coastal creeks, which do not experience either significant inputs of imported water or withdrawal of groundwater resources, Malibu is not further considered in this study. The baseline in-depth data provided for the seven lagoons in this study provide critical context for land use managers and restoration planners as the systems in our study have been identified as a priority watersheds for restoration (NMFS 2012).

Materials and Methods

Based on the watersheds identified in the Southern California Steelhead Recovery Plan (NMFS 2012), the following lagoons and creeks within the Santa Monica Bay were the focus of this study: Arroyo Sequit, Big Sycamore, Las Flores, Solstice, Topanga, Trancas, and Zuma. Although Malibu Creek is the second largest watershed draining into the Santa Monica Bay with present and historic southern steelhead trout habitat, Malibu lagoon was not included in this analysis. Due to the augmentation of flow from Tapia Water Reclamation Facility's discharge in accordance with California Regional Water Quality Control Board Los Angeles Region's NPDES NO. CA0056014, Malibu Creek and lagoon are the only system within the Santa Monica Bay that has a significantly altered hydrologic profile. All the other lagoons and their associated creeks rely on streamflow provided by natural variables such as rainfall and/or the water table. Regional context of these watersheds within the Santa Monica Mountains National Recreation Area and Santa Monica Bay (Fig. 1), along with individual watershed boundaries and limits of anadromy (Fig. 2) for all the study watersheds and lagoons are important to note when considering anthropogenic alterations. All of the systems in our study area have been altered in some way, changing the length of stream available for southern steelhead trout and imposing lagoon constraints due to Pacific Coast Highway (PCH) bridges (Table 1). Other anthropogenic factors include channelization in creek reaches, concrete culverts, multiple bridge constraints, Arizona type instream crossings, and fully restricted lagoons by wall or riprap barriers.

Rainfall metrics were obtained using LA County Department of Public Works, Water Resources Division's "Precipitation" webpage (http://www.ladpw.org/wrd/precip/). Using the "Near Real-Time Precipitation Map", and gauges with closest proximity, daily rainfall was calculated for each lagoon's watershed. The Lechuza gauge (# 454) data was used for Arroyo Sequit, Big Sycamore, Trancas and Zuma watersheds. The Big Rock Mesa

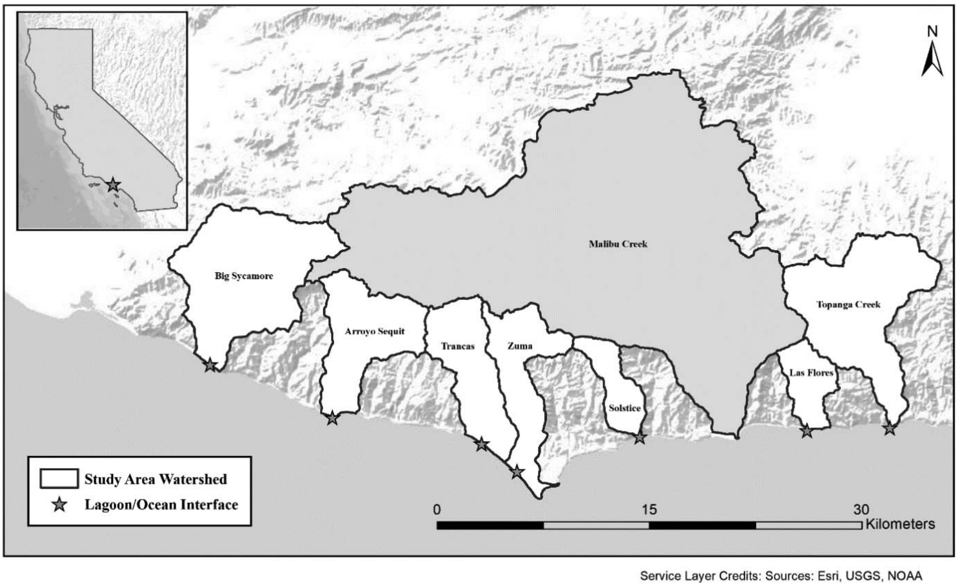

Fig. 1. Watershed boundaries of the northern Santa Monica Bay.

gauge (#320) was used for Las Flores watershed, the Monte Nido gauge (#319) was used for Solstice watershed, and the Topanga Canyon gauge (#318) was used for Topanga watershed. Flow data was obtained for Topanga Creek from the Topanga surface water flow gauge (F54C) maintained by Los Angeles County. Data was available for 2013-2017, but due to changes in thalweg location, the gauge currently sits a couple meters away from the thalweg and does not capture any low flow measurements, despite flow being present. Although we recognize the importance of flow, because this data was so limited and not available for all creeks, it was not incorporated further in this study.

Overwash from high tides and storm event tides can affect passage opportunities for southern steelhead trout into the study area's lagoons. Tide data for the 2013-2017 study period was measured at Los Angeles Station ID: 9410660, (33.7200, -118.2720). Because

Table 1. Descriptive measurements of each lagoon and watershed.

Location	Watershed/ Catchment Area	Limit of Anadromy	PCH Hwy Culvert Dimensions	Mean Annual Rainfall*	Coastal Exposure	Average Lagoon Wetted SA, 2017
Arroyo Sequit	31km²	2.64rkm!	24.2m x 23.75m	14.094	Low	963.3 m²
Big Sycamore	54.4km²	19.3rkm	16.8m x 23.2m	14.094	Low	2009.67 m²
Las Flores	11.7km²	3.2rkm	16.6m x 27.7m	11.874	Low	557 m²
Solstice	11.1km²	3.2rkm	7.17m x 43.02m	13.126	Low	140.33 m²
Topanga	46.6km²	5.3rkm	19.7m x 27.5m	11.2	Low	4561.33 m²
Trancas	26.4km²	10.46rkm	30.5m x 25.8m	14.094	Low	1995.67 m²
Zuma	25.9km²	8.05rkm	30.4m x 23.4m	14.094	Low	9624.33 m²

* Mean annual rainfall calculated by averaging rainfall from 2013-2017 water year data collected.

! Limit of anadromy under low flow conditions.

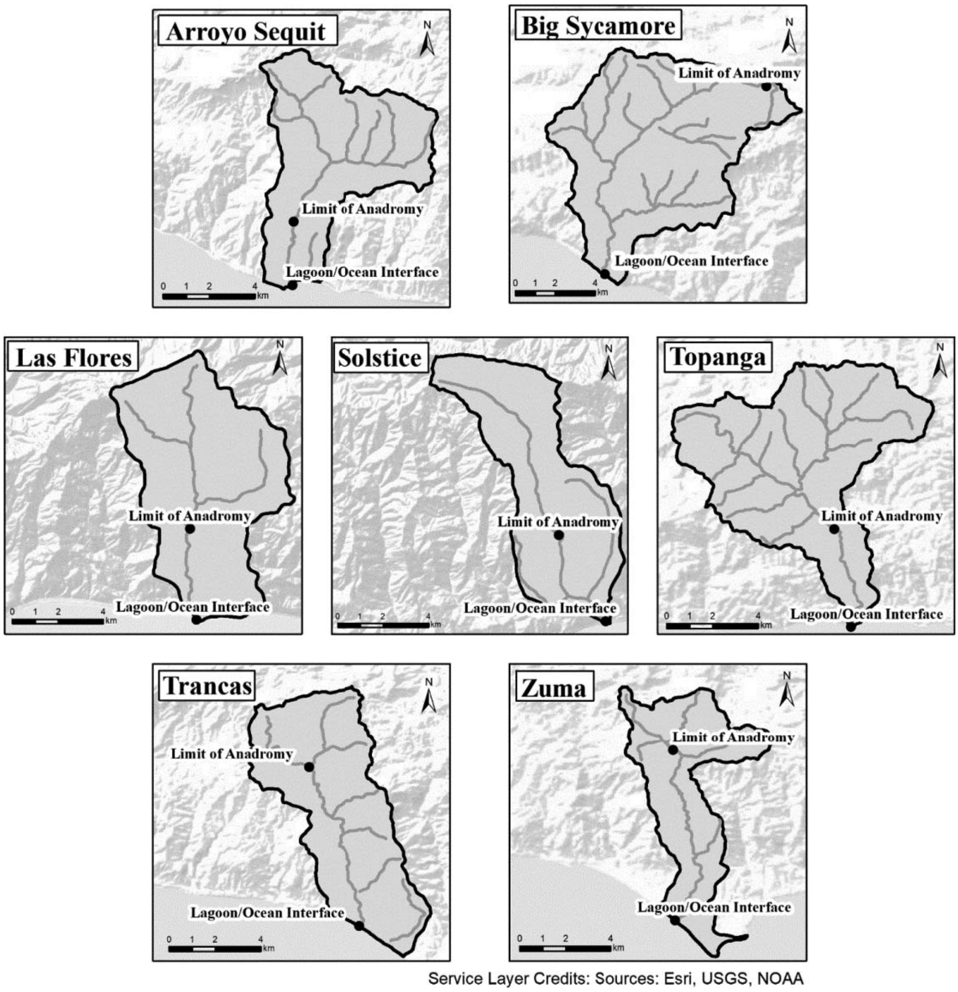

Fig. 2. Individual Watershed boundaries and creek locations.

we describe breach frequency when the connection was both passable and not passable, passable conditions were augmented for times when high tide could allow passage. When a lagoon was breached, any tides over 1.52 m above Mean Low Low Water (MLLW), were noted for potentially passable connection during high tide.

Four comprehensive longitudinal profile lagoon surveys occurred in November 2013 and January, June, and October 2017 at all sites. Lengths and widths of wetted area were recorded at wetted cross sections using hand held 100-meter tapes. Garmin GPS units recorded waypoints of lagoon boundaries (DATUM: WGS84) and GPS locations were uploaded into Google Earth. Lagoon area polygons were then mapped using the waypoints, observable landmarks (such as the PCH bridges), and survey notes. Storm-event related monitoring of the lagoon/ocean interface was conducted from October 2013 through December 2016 in order to document passage opportunities and constraints. In response to large and frequent storms starting in January 2017, weekly lagoon monitoring was conducted by a field team of two or three surveyors. These surveys consisted of visual documentation of lagoon and breach conditions via field notes and photo points to record physical condition (depth, connectivity, etc.) changes over time. Passibility was also recorded at the time of these surveys. Any connection between the lagoon and the ocean, even a steady connected trickle, was considered a breach. Only when flow was of adequate depth and size was the breach considered and noted as passable. A connection was considered passable if there was at least 15-30 cm of depth in the connection between the ocean and lagoon.[7] It is possible for a connection to be passable only at high tide, which was difficult to assess in our surveys since each site was assessed at varying times throughout the tidal cycle. Subsequently, a lagoon was only marked passable if it was clearly accessible at the time of survey. Later tide analysis was performed to predict additional potentially passable opportunities at high tide, a roughly 1-3 hr window. When a lagoon was breached, any tides over 1.52 m (MLLW), were examined for passable connection during high tide. Data from less frequent breach condition surveys from 2013-2016 was included for temporal context.

Field measurements of the lagoons documented conditions in January, June, and October 2017; at the beginning of rains, the beginning of summer, and the end of the water year when the lagoons have been subjected to the entire dry season. Physical measurements were then mapped in Google Earth to create a visual time series of lagoon dimensions and to obtain temporal descriptive measurements of lagoon wetted surface area (SA) and volume (V). SA and V from November 2013 was included in tables for context but not included in analysis since survey methods and measurements were not consistent with the surveys conducted in 2017. Average depths were estimated based on multiple depth measurements taken with a meter stick throughout each lagoon, but this method could be improved by using water level data loggers that would give a continuous timeline of changing lagoon depth over time. This method was not utilized in this study due to limited funding for such loggers.

All data was entered by date and location. Graphs of lagoon breach condition in relation to rainfall on a temporal scale were created for each lagoon. Lagoon volume was calculated by mapping lagoon boundaries via Google Earth mapping software, creating polygons to the specific measurements calculated and recorded in the field. Surface area calculations were coupled with average depth measurements recorded during survey visits to calculate an estimated volume at that particular point in time. An observed rate of rainfall required to cause a breach was calculated by taking the total amount of rain fallen in the watershed from October 1st to first day of breach for each lagoon and dividing it by the number of days until first breach, $\frac{centimeters\ of\ rain}{\#\ of\ days\ until\ 1st\ breach}$. Statistical analysis was performed using JMP statistical software. Continued surveys following the same methods may provide a data set large enough to perform robust statistical analysis in the future.

Results

In the 2016-2017 water year, rainfall throughout the Santa Monica Bay averaged 65.79 cm. Rain data for each watershed can be found in Table 2. Rain data was used to calculate several variables that were used for volume and breach frequency analysis.

[7] Flosi, G., and F. L. Reynolds. 2010. California salmonid stream habitat restoration manual. Second edition. California Department of Fish and Game, Sacramento, CA. http://www.dfg.ca.gov/fish/Resources/HabitatManual.asp.

Table 2. Watershed and rain characteristics of study area for the 2017 water year.

Location	Watershed Area (km^2)	2017 Rainfall (cm)	Watershed Rain Volume (m^3)	Rain Rate (cm/day)
Arroyo Sequit	31	73.81	22,881,800	0.092
Big Sycamore	54.4	73.81	40,153,900	0.162
Las Flores	11.7	56.21	6,576,590	0.076
Solstice	11.1	62.9	6,992,110	0.069
Topanga	46.6	67.03	31,236,300	0.056
Trancas	26.4	73.81	19,486,500	0.082
Zuma	25.9	73.81	19,117,400	0.148

These include the volume of rain fallen (watershed area multiplied by rainfall) over each watershed during the 2017 water year and rain rate, defined in this study as centimeters of rain per day until first breach.

Topanga Creek is the only system that has a flow gauge, but it is currently located in a position that does not accurately measure low flow conditions. According to the available data, Topanga Creek had a mean daily discharge of 0.11 m^3/s, a maximum of 1.66 m^3/s, and a minimum of 0 m^3/s for the 2017 water year. Average daily discharge was 0.024 m^3/s for the 2012 water year, 0.021 m^3/s for 2013, 0.017 m^3/s for 2014, 0.027 m^3/s for 2015, and 0.023 m^3/s for 2016. No flow data was available for any other site. A conceptual hydrology analysis estimated flow rate in cubic feet per second for Trancas lagoon for several potential lagoon restoration alternative designs. Depending on lagoon restoration area size, determined that a two-year storm could produce flows between 0.007-0.033 m^3/s, while a ten year storm could produce flows between 0.028-0.282 m^3/s.[8]

All lagoons showed a time lag between end of breach and end of observed overwash, an expected observation as sediment deposition to rebuild a berm takes several days to weeks, depending on the specific location. Seaward wave action, already of low influence for the study area, became less of a factor on breach potential when a berm barrier was high and wide. When accounting for tidal influence, the amount of time of passable connection was increased by tides when a system was breached. Recorded days of full passibility for each lagoon can be found in Table 4. Due to funding constraints, it was not possible to measure tidal prism as part of this study.

All the lagoons – with the exception of Topanga – were consistently dried down almost completely between 2013 and 2016, highlighting the severity of the California drought (Table 3). Arroyo Sequit had a modest volume throughout the 2017 water year with a maximum of 821 m^3 in June 2017. Volume in Big Sycamore measured less than 100 m^3 during both November 2013 and January 2017 survey, and then increased more than a factor of 20 by June 2017. Anthropogenic constraints limited any lateral movement of water in Las Flores and resulted in a maximum volume of only 337 m^3. Similarly, constraints on Solstice Lagoon from the PCH culvert and manipulation by individuals (placing sand bag, digging small trenches) resulted in a small maximum volume of 125 m^3. Trancas Lagoon had a dramatic volumetric change, quadrupling in wetted surface area and doubling in estimated depth throughout the study period. Topanga lagoon held onto its surface water the longest

[8] Dagit, R., S. Albers, and C. Stevens. 2015. Trancas lagoon restoration feasibility study 2013-2015. Prepared for CDFW and Zuma Beach Properties, LLC. Resource Conservation District of the Santa Monica Mountains, Topanga.

Table 3. Recorded lagoon surface area, depth, and volume including changes in measurements between November 2013, January 2017, June 2017, and October 2017 surveys.

Location	Date of Survey	Wetted Area	ΔWetted Area	Average Depth	ΔAve Depth	Estimated Volume	Δvolume
Arroyo Sequit	11/1/2013	0		0		0	
	11/1/2014	0	0	0	0	0	0
	11/1/2015	0	0	0	0	0	0
	11/1/2016	0	0	0	0	0	0
	1/27/2017	1064	1064	0.55	0.55	585.2	585.2
	6/23/2017	1561	497	0.53	-0.02	821.65	236.45
	10/1/2017	265	-1296	0.41	-0.12	108.65	-713.00
Big Sycamore	11/1/2013	268		0.33		89.04	
	11/1/2014	0	-268	0.00	-0.33	0.00	-89.04
	11/1/2015	0	0	0.00	0	0.00	0
	11/1/2016	0	0	0.00	0	0.00	0
	1/27/2017	569	569	0.1	0.10	56.9	56.90
	6/23/2017	3011	2442	0.68	0.58	2048.27	1991.37
	10/1/2017	2449	-562	0.64	-0.04	1561.24	-487.03
Las Flores	11/1/2013	278		0.32		88.96	
	11/1/2014	0	-278	0	-0.32	0	-88.96
	11/1/2015	0	0	0	0	0	0
	11/1/2016	0	0	0	0	0	0
	1/27/2017	292	292	0.3	0.3	87.6	87.6
	6/23/2017	730	438	0.46	0.16	337.63	250.03
	10/1/2017	649	-81	0.1	-0.36	64.9	-272.73
Solstice	11/1/2013	0		0	0	0	0
	11/1/2014	0	0	0	0	0	0
	11/1/2015	0	0	0	0	0	0
	11/1/2016	0	0	0	0	0	0
	1/27/2017	222	222	0.3	0.3	66.6	0
	6/23/2017	177	-45	0.71	0.41	124.96	58.36
	10/1/2017	22	-155	0.55	-0.16	12.1	-112.86
Trancas	11/1/2013	751		0.34		252.84	
	11/1/2014	0	-751	0.00	-0.34	0.00	-252.84
	11/1/2015	0	0	0.00	0	0.00	0
	11/1/2016	0	0	0.00	0	0.00	0
	1/27/2017	898	898	0.3	0.30	269.4	269.40
	6/23/2017	4419	3521	0.7	0.4	3093.3	2823.9
	10/1/2017	670	-3749	1.1	0.4	737	-2356.3
Topanga	11/1/2013	3453		0.75		2589.75	
	11/1/2014	No Data	No Data	No Data	No Data	No Data	No Data
	11/1/2015	No Data	No Data	No Data	No Data	No Data	No Data
	11/1/2016	No Data	No Data	No Data	No Data	No Data	No Data
	1/27/2017	4298	No Data	0.1	-0.65	429.8	No Data
	6/23/2017	5334	1036	0.75	0.65	4000.5	3570.7
	10/1/2017	4052	-1282	0.75	0	3039	-961.5
Zuma	11/1/2013	813		0.16		130.08	
	11/1/2014	0	-813	0	-0.16	0	-130.08
	11/1/2015	0	0	0	0	0	0
	11/1/2016	0	0	0	0	0	0
	1/27/2017	10148	10148	1.5	1.5	15222	15222
	6/23/2017	11004	856	1.2	-0.3	13204.8	-2017.2
	10/1/2017	7721	-3283	1	-0.2	7721	-5483.8

into the drought with some surface water consistently present (no surface area/volume measurements available) through 2014-2016 and an increase in volume measuring 4000 m^3 during the June 2017 survey. Zuma lagoon was the quickest to recover from drought conditions, drying down almost completely from 2014-2016 and then increasing to an estimated volume of 15,222 m^3 in the January 2017 survey.

Throughout the 2017 water year, a trend in volume changes was observed. Apart from Big Sycamore, all lagoons had a small volume in January 2017 when all lagoons were breached and outflowing, recorded their largest volume measurement in June 2017, and measured the smallest volume in October 2017 because of dry down from high summer temperatures. Big Sycamore was the only location that had a larger volume in October 2017 than in January 2017. Lagoon depth was extremely variable throughout the study area. Some locations increased in depth between each survey in 2017 (Trancas and Topanga); some locations decreased in depth between each survey (Arroyo Sequit and Zuma); and some locations increased depth between January and June, then decreased in depth between June to October (Big Sycamore, Las Flores, Solstice). Fig. 3 and Fig. 4 illustrate the changes in lagoon volume over time at each location in this study. Some mapped surface areas in Fig. 3 appear to extend into the surf. GPS data for these instances were verified for accuracy. Though all surveys were conducted during the day in the same order, some occurred during low tide times, which explains the appearance of some of the maps extending into the ocean. 27 January 2017 was the day of the new moon so neap tides were experienced with an afternoon low tide of 0.027m below MLLW.

Anthropogenic factors affect all the study locations and influence the volume capacity in some way. Instream creek barriers in Arroyo Sequit were recently restored, but the PCH bridge, a concrete pedestrian walkway, and a vehicle driveway line the edges of the lagoon, confining its footprint. Big Sycamore is under similar constraints with a pedestrian bridge running across the upper portion of the lagoon and the PCH bridge along the lower end where riprap holds the banks in place between these two bridges. Las Flores is bordered on either side by tall concrete retention walls with buildings on the east bank, and Solstice has a long culvert under PCH which causes sheet flow into the lagoon and cuts off any upstream migration possibility. Topanga also suffers from constraints due to the concrete retention walls extending from the PCH bridge and fill slopes to a regularly groomed berm. Unlike the other lagoons with more natural channels upstream of the mouth, Trancas Creek has a 600 m concrete trapezoidal flood control channel that begins upstream of the lagoon and channels flow in a way that may affect lagoon morphology. Zuma lagoon has the most unconstrained banks and is by far the largest in our study, but multiple Arizona crossings, regular grooming to maintain the berm for lifeguard vehicle access, and vector control manipulation within the lagoon itself all affect its suitability as potential *O. mykiss* habitat.

Increasing lagoon volume correlated with higher surface areas in the study area lagoons ($R^2 = 0.897$, $p \leq 0.001$). Due to the multi-year drought, all lagoons effectively started the 2016-2017 water year almost completely dry, but the ensuing 2017 rainy season increased surface flows and restored passable conditions into the upper reaches of each system. Santa Monica Bay lagoons with bigger surface areas were more likely to contain a larger volume of water (Fig. 5). There was no significant relationship between watershed area and lagoon surface area. Controlling for differences in rain received over different watersheds in the study area, total rainfall for the 2017 water year was couple with watershed area to get a volume of rain fallen within each watershed (Table 2). Watershed volume in relation to lagoon surface area yielded no significant relationship. A more robust sample size in the

Fig. 3. Mapped surface area of Arroyo Sequit, Big Sycamore, and Las Flores lagoons on surveys conducted on 3 November 2013, 27 January 2017, 23 June 2017, and 5 October 2017 (maps ordered chronologically from left to right). *Las Flores Lagoon dried down completely when observed a week prior to the 5 Octobe4 2017 survey. County employees bulldozed the lagoon, removing all in-channel vegetation as well as several inches of sand revealing sub-surface water that was not previously exposed.

future would improve the confidence in our analysis and be a better indicator of the true relationship between catchment area and lagoon size. Fig. 6 shows how depth in the study area lagoons evolved during a year of average rainfall following a multiyear drought. Depth peaked in the middle of the year, when rains had ceased but before the peak in average high temperatures that Southern California experiences from July to September each year.[9]

A summary of storm events, breaches, and possible fish passage opportunities is provided in Table 4. Passable connection was defined as a breach with enough depth for

[9] US Climate Data 2018, Climate – Los Angeles. https://www.usclimatedata.com/climate/los-angeles/california/united-states/usca1339.

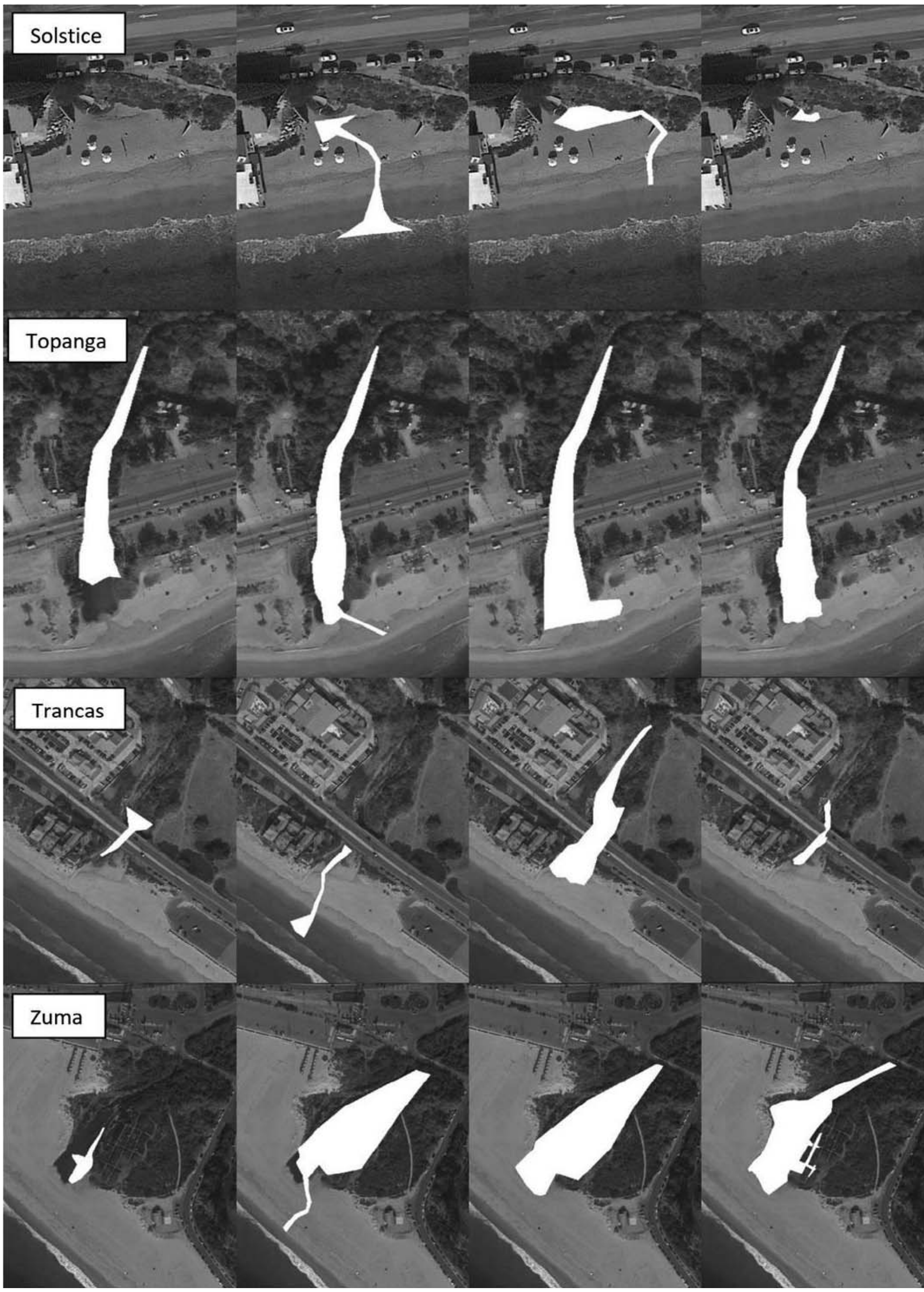

Fig. 4. Mapped surface area of Solstice, Topanga, Trancas, and Zuma lagoons on surveys conducted on 3 November 2013, 27 January 2017, 23 June 2017, and 5 October 2017 (maps ordered chronologically from left to right).

Table 4. Summary of rainfall and fish passage opportunities of monitored lagoons in the Santa Monica Mountains, in alphabetical order.

Lagoon	Water Year*	Rainfall Total** (inches)	Dates Entrance Open	Number of Days Breached	Estimated Number of Days Passable to *O. mykiss*	*O. mykiss* present
Arroyo Sequit	2013-2014	5.87	unknown	0	0	Yes
	2014-2015	17.5	none	0	0	Yes
	2015-2016	9.09	29 Oct 2015	1	1	Yes
	2016-2017	29.06	30 Dec 2016- 14 Jan 2017 18 Jan – 8 Apr 2017	97	51	Yes
Big Sycamore	2013-2014	5.87	none	0	0	No
	2014-2015	17.5	03 Mar 2015 (trickle) 29 October 2015 (storm)	0	0	No
	2015-2016	9.09	none	0	0	No
	2016-2017	29.06	23 – 27 Jan 2017 3 Feb – 8 Mar 2017	39	30	No
Las Flores	2013-2014	5.16	26 Feb – 02 Mar 2014	4	4	No
	2014-2015	17.12	12 Dec 2014 – 3 Mar 2015 (pinched)	10	<10	No
	2015-2016	7.36	6 – 12 Mar 2016	7	1	No
	2016-2017	22.13	24 Dec 2016 – 21 Apr 2017	119	44	No
Solstice	2013-2014	6.31	none	0	0	No
	2014-2015	16.06	12 – 16 Dec 2014 12 Jan 2015	7	<10	No
	2015-2016	9.84	5 – 15 Mar 2016	11	0	No
	2016-2017	24.8	23 Dec 2016 – 3 Jul 2017	193	5	No
Topanga	2013-2014	6.84	27 Feb – 07 Mar 2014 25 March 03 Dec and 12-16 Dec 2014	10	4	Yes
	2014-2015	13.76	10 – 19 Jan and 3 Mar 2015 03 Mar 2015	17	<10	Yes
	2015-2016	8.31	6 March – 6 April 2016	32	5	Yes
	2016-2017	26.39	21 – 26 Dec 2016 11 Jan – 16 May 2017	132	36	Yes
Trancas	2013-2014	5.87	none	0	0	No
	2014-2015	17.5	3-8 Dec 2014 (overwash) 16 Dec 2014 (pinched)	5	<5	No
	2015-2016	9.09	6 Mar 2016	1	0	No
	2016-2017	29.06	24 Dec 2016 – 12 Jan 2017 19 Jan – 18 Apr 2017	110	61	No
Zuma	2013-2014	5.87	none	0	0	No
	2014-2015	17.5	none	0	0	No
	2015-2016	9.09	none	0	0	No
	2016-2017	29.06	20 Jan – 1 Mar 2017	41	39	No

* *Water year, as used by the USGS: October 1 through September 30 of the following year.*
** *Rainfall data from gauge stations managed by Los Angeles County Department of Public Works.*

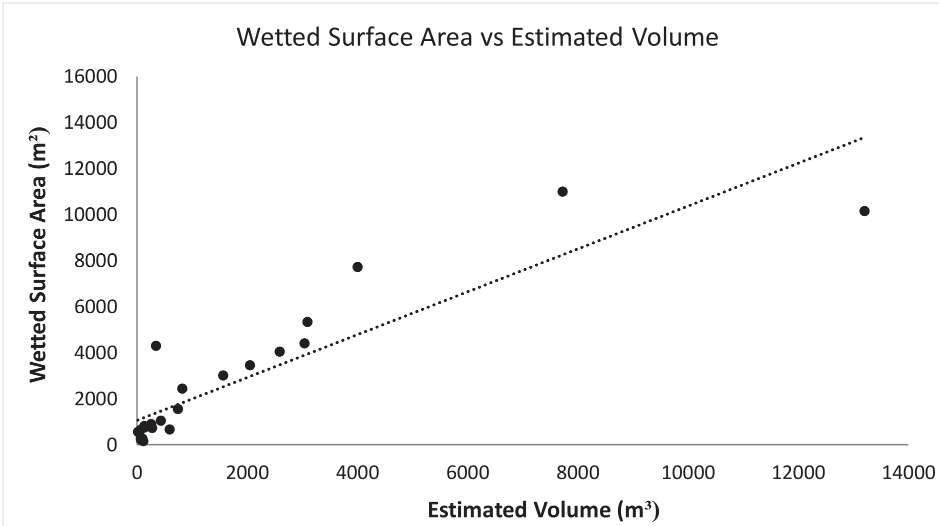

Fig. 5. Wetted surface area measurements are positively associated ($p < 0.001$) with increased volumes for all lagoon surveys conducted post-rain in 2017.

O. mykiss to migrate to or from the ocean to the lagoon during all tides. Breach patterns for lagoons with larger surface areas such as Big Sycamore and Topanga were strongly influenced both by rain events and by the constraints of the PCH bridges and fill slopes that border these lagoons. Breaches closed rapidly after storms in the beginning of the

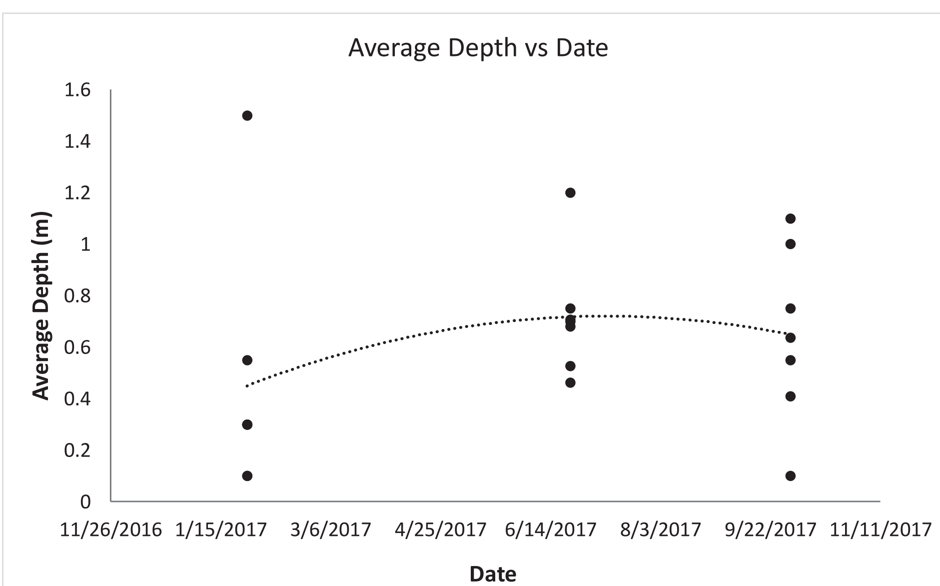

Fig. 6. Average depth measurements of each lagoon during 27 January 2017, 23 June 2017, and 5 October 2017 survey. Includes mean depth (line curve; cm) and confidence of fit (background shading).

season, but once reopened, the lack of ability to spread out helped sustain subsequent breaches. Zuma lagoon was more influenced by rain events, as this location lacked lagoon bank constraints. It took less cumulative rainfall to cause a breach in Topanga and Big Sycamore than in Zuma, but once breached, Zuma's connectivity to the ocean was sustained. Breaches for the lagoons with smaller footprints tended to occur more quickly during the rainy season and lasted for months. Small windows of closure occurred in Arroyo Sequit and Trancas, but they did not close for long. It should be noted that passibility in this study refers specifically to the lagoon–ocean connection, whereas the ability of fish to move upstream from the lagoon through the mainstems of the creeks is usually of much shorter duration and more difficult to document. Documented windows of passibility during a site visit, when a breach was clearly passable for *O. mykiss,* were recorded and later analysis of tides resulted in an estimation of possible passable windows during high tide to give a detailed evolution of breach at each location over the span of the 2017 water year (Fig. 7). No relationship was identified between watershed volume and number of days of passable connection. There was more significance to the relationship between watershed volume and the number of days a system was breached.

The open period for all lagoons ranged from 39 d (10.68% of the year) to 193 d (52.88%) in the 2016-2017 water year, with an overall average time breached at 104 d (28.61%). Comparing the number of days breached with the average lagoon surface area measured on 27 January, 23 June, and 5 October 2017, there was a slight trend showing that larger surface area lagoons were open for fewer days, and smaller surface area lagoons were open for more days over the water year. Since the surface area values for each location were averaged between the three survey events, there are only seven data points to work with and no significance was calculated in this relationship.

Calculated rain rates ranged from 0.143 to 0.412 cm/d with a median of 0.221 cm/d. Comparing the rate of rainfall/d needed for first breach by the average lagoon surface area as measured on 27 January, 23 June, and 5 October 2017, larger lagoons needed more rain to initiate first breach, whereas smaller lagoons were able to breach with less accumulated rainfall. When examining the effects of lagoon surface area and watershed volume on rain rate needed for first breach (Fig. 8), both were positively correlated. Increasing average surface area or watershed volume predicted an increase in rain rate (i.e. an increased amount of rain required for first breach to occur), though linear regression revealed a higher confidence in the line of best fit between rain rate and watershed volume. A significant negatively correlated relationship between rain rate and the number of days a system was breached was discovered. Locations that were breached the longest also had lower rain rates, while shorter breach windows required a higher rain rate ($R^2 = 0.763$ and $p = 0.01$).

Discussion

Restoration planning is in progress for many of the lagoon systems in the Santa Monica Bay and design for these efforts not only must account for site-specific conditions, but also address regional wetland restoration and species recovery goals. When considering restoration options, it is critical to evaluate the implications of lagoon size because breaching frequency may depend on it (Rich and Keller 2012). Data on the presence/absence of steelhead, as well as information regarding the existing lagoon breach patterns, was compiled in order to identify the appropriate regional archetypes and lagoon classification patterns, which can help guide restoration designs. The challenge for restoration planners is to provide the right balance between connectivity during the winter months when stream

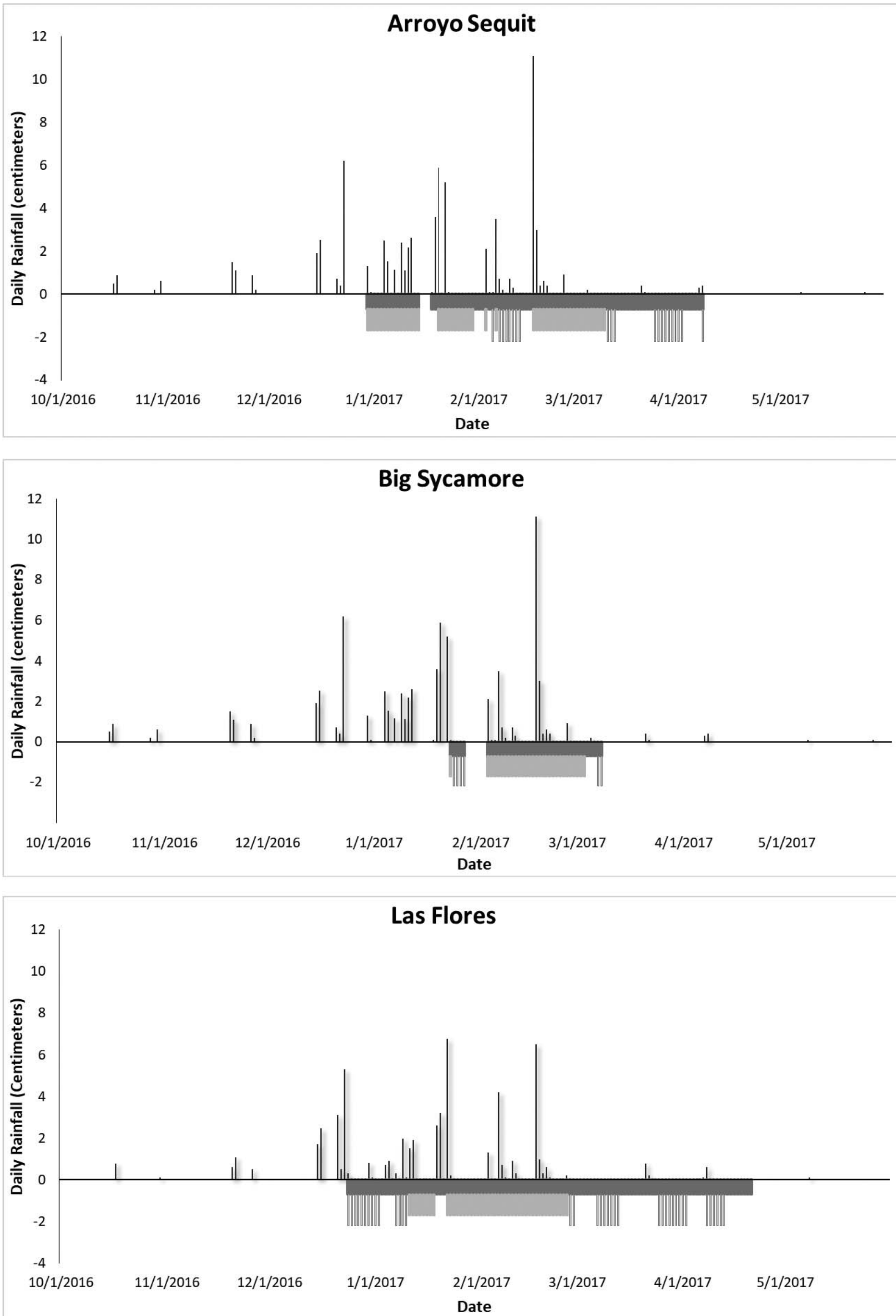

Fig. 7. Lagoon breach condition related to rainfall over the 2017 water year. (Breach = dark grey bar; Passable Connection = light grey bar; Rainfall = dark line columns).

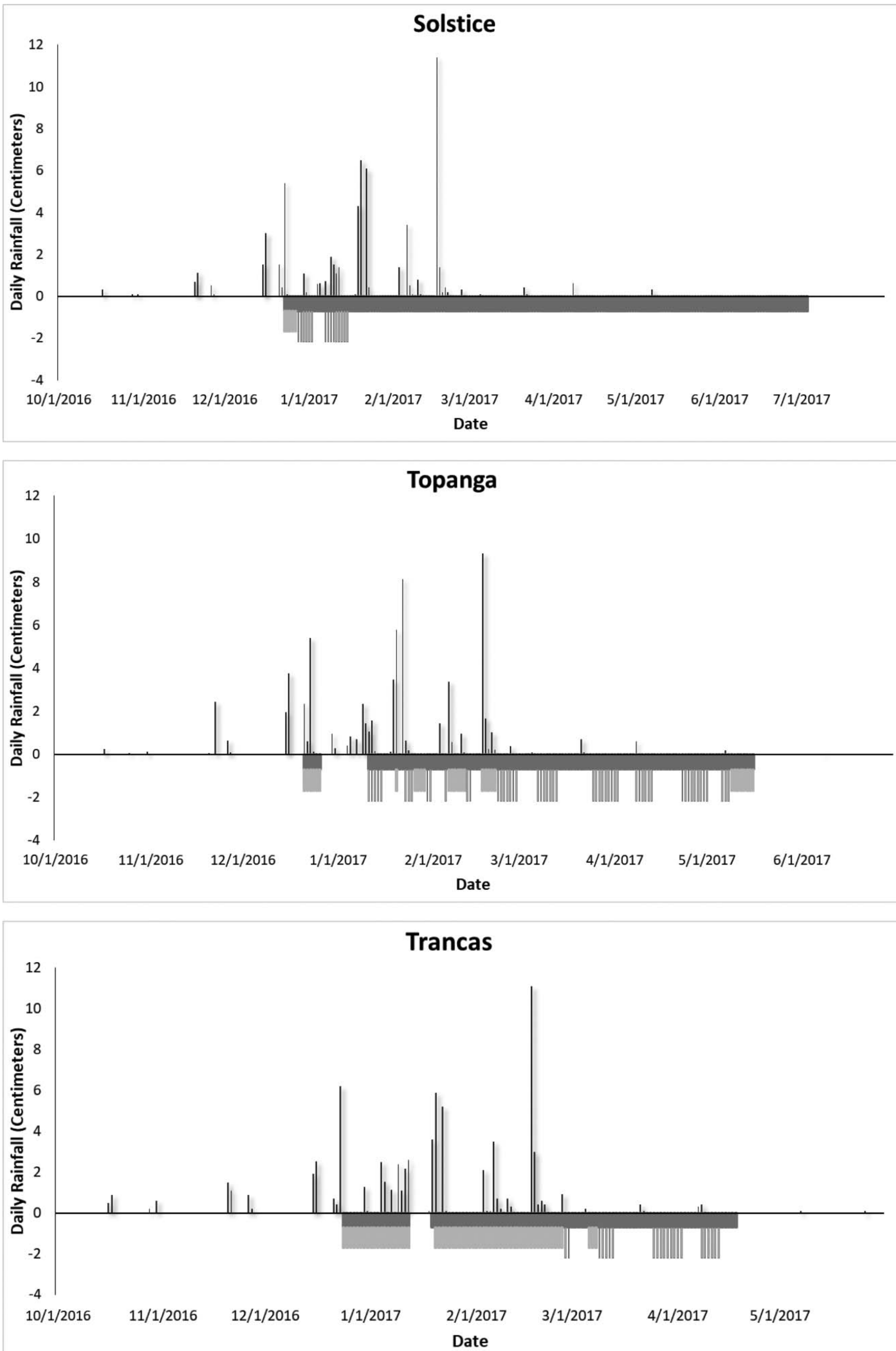

Fig. 7. Continued.

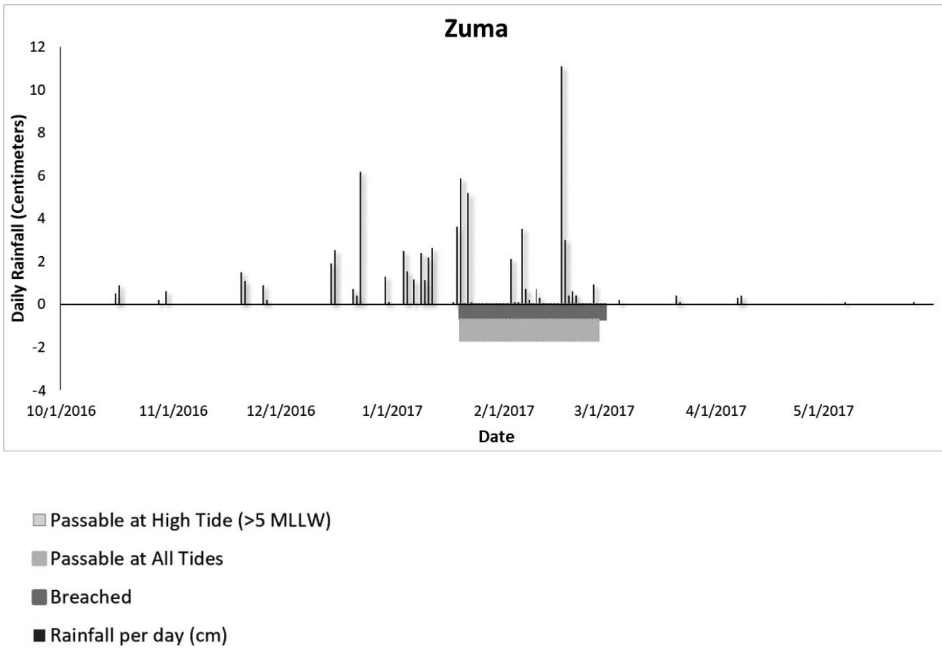

Fig. 7. Continued.

flows typically drive lagoon breaches (McLaughlin et al. 2014)[4], versus accommodating more wetland habitat and transition zones that will provide flexible response to projected and measured sea level rise (Nerem et al. 2018). When stream flow is a limiting factor, the general assumption that larger systems remain open for longer periods of time when compared to their smaller counterparts was not observed during our study.[4]

All seven of the lagoon-creek systems examined in this study fit the "small creek" archetype, and while similar patterns were observed in regard to breach dynamics, further classification was confounded by the unique constraints particular to each system. Rich and Keller's (2012) analysis of small coastal lagoons near Santa Barbara, CA, a similar coastal area, found that the size of an estuary was directly related to watershed size. In their study, larger watersheds produced larger creek channels which in turn resulted in larger lagoons. While this relationship could not be confirmed in our study area, other observations from locations with similar characteristics were also seen in the Santa Monica Bay. As has been observed in several Mediterranean regions, breaching was initiated by processes on the lagoon side of the berm, namely the lagoon/ocean water elevation difference and the width of the barrier beach (Kraus et al. 2008). Berm closure was initially caused by wave driven sediment import that occurred at a rate slightly higher than sediment export from tides and creek flow (FitzGerald 1996). Behrens et al. (2013) also observed that the amount of closed days is more dependent on river flow and less related to wave condition. These observations closely match the patterns documented in this study. Despite differences in volume capacity, the drought reduced the lagoons in our study area to meager puddles or completely dry channels that no *O. mykiss* were able to access for years. Evaporation rates and water seepage due to the porosity of substrate are factors that can contribute to lack of surface water in lagoons, and the lowering of the water table likely

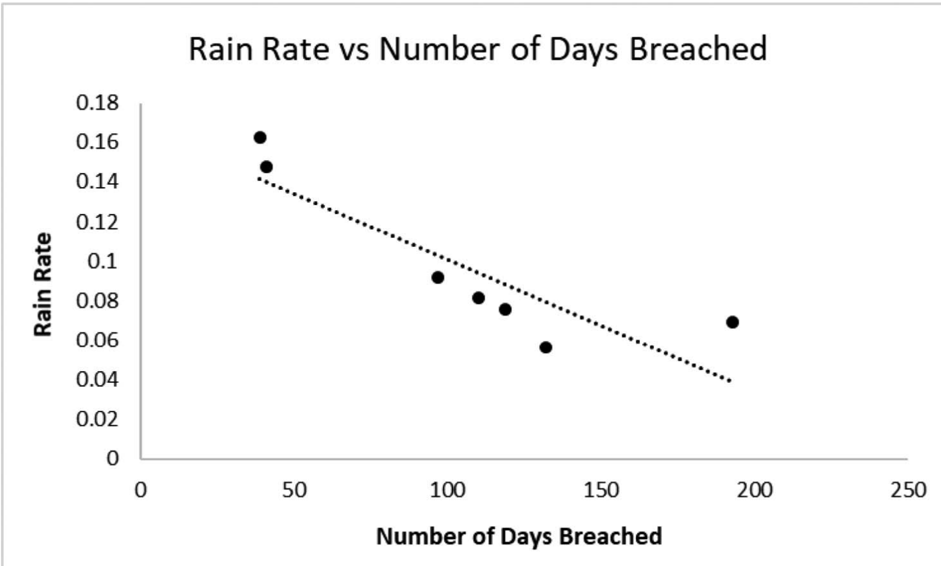

Fig. 8. Rate of rain/d versus number of days breached.

contributed to an overarching dry down that extended upstream from the lagoons during the drought period.

Of significance for *O. mykiss* in particular, the duration of a breach often exceeded the window of possibility when there was sufficient depth for either returning anadromous adults or emigrating smolts. Adequate depth is necessary to allow for *O. mykiss* passage, with a minimum 0.305 m required for anadromous adults and 0.152 m required for migrating juveniles (Flosi and Reynolds 2010). Sustaining adequate depth for migration of *O. mykiss* both in and out of a creek system is a key factor that needs to be taken into consideration when restoration planning occurs for a lagoon in the Santa Monica Bay.

Southern steelhead trout life history cycles require three important habitat conditions: connection from the ocean into the lagoon, suitable lagoon conditions for smolts to transition from freshwater to saltwater (Bond et al. 2008), and connection from the lagoon upstream to upper creek habitats allowing passage for both smolts and anadromous adults (NMFS 2012). Recovery of this species relies upon all of these elements being functional simultaneously in numerous coastal streams. Connectivity both to the ocean and upstream was extremely limited during the study. Depths measured in these lagoons were on the lower limit of the preferred ranges for supporting smolt growth or transition within the lagoon itself, and the limited wetland and transitional habitat in most of these locations provide limited support for smolts.

The observed ability of larger lagoons in our study area to retain water through the summer and into the following water year has important implications for *O. mykiss* smolts. Smaller smolts with an average fork length of 112 mm were found to stay in a central coast estuary and wait until the following winter to emigrate when they were much larger (Bond et al. 2008). Smolts would not have this opportunity in the smaller lagoons in the Santa Monica Bay, as Arroyo Sequit, Solstice, and Las Flores lagoons dried down to uninhabitable levels as the study period progressed into summer 2017. Data examining the average fork length of smolts in Topanga Creek indicate that most emigrating smolts are larger than 170 mm (Bell et al. 2011), which suggests that environmental cues in the Santa Monica Bay may favor larger smolt sizes for emigration. Even with adequate surface water remaining present throughout the summer in lagoons like Big Sycamore, Topanga, Trancas, and Zuma, connection to upstream habitat was cut off very early in the dry season, between May and June. This phenomenon had been observed consistently in Topanga Creek for many years (Dagit et al. 2017). The lower reach of Topanga Creek has been drying down earlier each successive year of drought, with the length of reach dry also increasing each year.

Previous habitat assessment and barrier identification work in the Santa Monica Bay documented watershed size and geomorphology, both natural and anthropogenic fish passage barriers and habitat quality (CalTrout 2006). Based on an integrated assessment of these factors, CalTrout (2006) prioritized restoration actions to focus on recovery of *O. mykiss.* Their recommended ranking prioritized Topanga, Arroyo Sequit, Trancas, Big Sycamore, Zuma, Las Flores and Solstice. Our study builds on that effort by providing both qualitative and quantitative data on the evolution of breaching and lagoon conditions. Based on the results of this study, the unique challenges and constraints of each system are discussed, with ranking based on all of the above metrics, as well as documented presence of *O. mykiss* since 2000 (RCDSMM unpublished data).

Because it has the best average habitat quality and the third largest habitat quantity in kilometers, as well as supporting the only reproducing population of *O. mykiss* remaining in the Santa Monica Bay, restoration of Topanga lagoon is considered to be the highest restoration priority. Topanga lagoon's unique system sustains a steady pool of surface water throughout the year despite interrupted flow upstream in the low gradient reach during the dry season. The Topanga watershed has a high water table relative to the creek and receives groundwater recharge in most reaches of the creek throughout the entire year (Tobias 2006). The Topanga Canyon rain gauge (#318) measured 11.73 cm of rainfall from October- December 2016, which was sufficient to breach the lagoon on 21 December 2016, but the breach was not sustained. Another 6.91 cm fell before the lagoon breached again on 11 January 2017. With an additional 42.11 cm of rain between January and February, Topanga Lagoon remained breached for a total of 132 d. It was the longest breach period for a larger surface area lagoon in this study and included an estimated 30 d of passable connection. The berm closed on 16 May 2017 and remained closed for the remainder of the study period.

Topanga Lagoon is constrained on all sides by fill slopes, and PCH bridge abutments, which laterally constrain the lagoon's physical features. This caused quicker and longer breaches than might have historically occurred, since the lagoon is not able to expand and spread out naturally to take up a larger surface area and volume.[4] Topanga Lagoon consistently maintained surface water throughout the drought period and required the second smallest amount of rain to breach in the 2017 water year. Tidewater gobies (*Eucyclogobius newberryi*) are supported in this lagoon, and while in-stream vegetation is limited to a small patch on the east side of the lagoon downstream of PCH, these are two potential food sources for smolts.

Restoration that removes constraints on the sides of the lagoon above and below PCH would allow more area for important wetland and transitional upland bank vegetation in addition to potential for sea level rise accommodation. This must be balanced by preserving enough thalweg constraint to continue maintaining a breach. Careful analysis of breach flows needed to connect to the ocean, while expanding the duration of suitable flows that support fish migration will be needed. During the 2017 water year, two anadromous adults entered the system and one of them is confirmed to have spawned (RCDSMM unpublished data). Recent genetic analysis indicates that anadromous genes in this population are currently present, retaining the potential to produce anadromous individuals despite years of limited passage opportunities and purely residential spawning (RCDSMM unpublished data). Restoration planning was initiated in 2004 with the preparation of required documents for replacing the PCH bridge, which continues to date.

Removal of three fish passage barriers in Arroyo Sequit in 2016 restored access to four kilometers of high-quality spawning and rearing habitat for *O. mykiss*, which was utilized by two anadromous adults in January 2017. Arroyo Sequit lagoon saw variable conditions throughout the drought period between 2013 and 2016, with consistent pooling under the PCH bridge associated with a high water table in that area. This relatively small watershed (31 km^2) receives no imported water and is sustained only by groundwater flows from the upper watershed. The lagoon pool was not connected either upstream to the dry creek channel or downstream to the ocean except for one day on 29 October 2015 following a storm. The lagoon had ponded surface water during the winter of 2016, as well as in September-December 2016. After a combined 18.92 cm of rain fell from October-December 2016, the first breach occurred on 20 December 2016. The breach closed for a brief period from 15-17 January 2017 but re-connected following a storm and remained breached through a combined 40.51 cm of rainfall over the following three months. Arroyo Sequit's breach closed on 9 April 2017, but the lagoon remained subject to input daily with high tide overwash through the end of June 2017. The lagoon was breached for a total of 97 d with an estimated 51 d of passibility. Schools of stripped mullet (*Mugil cephalus*) and Topsmelt (*Atherinops affinis*) were documented in the lagoon but were not able to survive as the depth decreased to less than 30 cm (RCDSMM unpublished data). There are no proposals to make any changes to the lagoon at this time.

In Trancas, the grade and concrete pylons/walls at the PCH bridge severely constrain the lagoon, and a channelized portion of the creek just upstream of the lagoon likely contributes to its current tendency to funnel water to the west side of the lagoon, aiding in a quicker breach. The current configuration of the PCH bridge severely limits the ability of the lagoon to move as the bridge pylons redirect flow in a way that has built up sediment on the eastern side of the lagoon. Surface area of Trancas lagoon was in the mid to high range in our study, but also sustained a long breach period. The Trancas Lagoon Restoration Feasibility Study (Dagit et al. 2015) analyzed lagoon restoration alternatives to better understand these relationships and found that there were significant trade-offs between increasing lagoon and wetted area versus increasing or maintaining breach frequency. A larger lagoon footprint decreased the potential for breach, but in the face of sea level rise, adequate lagoon size will be necessary to buffer shoreline recession. While there are currently no *O. mykiss* present in this system, there is historic documentation of *O. mykiss* caught in the 1980's (CalTrout 2006), the upstream habitat is good to excellent and most of the watershed is owned and managed by the National Park Service.

Trancas lagoon experienced brief breaches during the 2014-2015 (5 d) and 2015-2016 (1 d) water years. From October-December 2016, 17.63 cm of rain fell before Trancas lagoon breached on 24 December 2016. The breach was sustained as other storms dropped another 14.86 cm of rain from 30 December 2016 through 12 January 2017. The lagoon closed on 12 January 2017 but reopened again 8 d later with a new storm on 19 January

2017. The breach then remained connected until 18 April 2017, at which time the lagoon closed for the remainder of the water year. Trancas lagoon was breached for a total of 110 d and passable for an estimated 61 d. The berm continued to build vertically as ponded water remained within the lagoon and under the PCH bridge through the end of the water year. Grooming of the berm by LA County Department of Beaches and Harbor occurred immediately after the breach ended.

Restoration of Trancas lagoon is in the planning stages associated with the pending replacement and expansion of the PCH bridge. This process is complicated by both landowner reluctance on the north side of PCH and the proposed re-nourishment of Broad Beach along the ocean. This project could potentially expand the width of the beach berm to almost 60 m, approximately twice its current width. Finally, the upstream concrete trapezoidal flood control channels identified as the keystone passage barrier to the approximately 10 km of upstream habitat are being studied to potentially restore a natural bottom that could facilitate fish passage opportunities.

At Big Sycamore lagoon, both the PCH bridge at the ocean and a pedestrian bridge over the upper end of the lagoon connected by fill slopes on both sides entirely constrain the lagoon area. Waves actively deposit sand under the PCH bridge, creating a vertical berm that inhibits connectivity. The water is thus forced upstream above the pedestrian bridge and into the mainstem of the creek. Substantial vegetation lines the banks above the pedestrian bridge but no vegetation is present either in the lagoon or on the banks of the lagoon between PCH and the pedestrian bridge. The extent of the berm is exacerbated by the concrete walls flanking the PCH crossing. Waves are able to deposit sand, but removal processes are hindered by the southern wall. Big Sycamore was ranked second in total habitat score for the Santa Monica Mountains (CalTrout 2006), but since then the Springs Fire in 2013 devastated much of the upper watershed and subsequent mudslides and sediment deposition further degraded the habitat (NPS pers communication). Regrowth and improvement has occurred, and the 2017 water year showed promise in Big Sycamore creek, but access upstream 19 km to the limit of anadromy was minimal. The lagoon filled and a large reach of the creek upstream remained wetted well past the rainy season. There are currently no *O. mykiss* in this watershed.

Big Sycamore lagoon completely dried down during the 2013-2016 drought period, with occasional puddles appearing in the lagoon due to sporadic overwash or a small rain event. In December 2016, the Lechuza rain gauge recorded 13.13 cm of rainfall, but Big Sycamore lagoon remained disconnected from the ocean. It was not until another 28.37 cm of rain fell over two storm events that the lagoon finally breached on 23 January 2017. After 5 d of connection, the berm closed, but was reopened one week later with another series of rain events that totaled 24.38 cm over a 31-d span. Despite this large amount of rainfall in the watershed, Big Sycamore lagoon closed on 8 March 2017. Small rain events in March and April 2017 were unable to cause another breach; the berm remained intact for the remainder of the year. An estimated 39 d of breach were recorded, the minimum for our entire dataset, with only 30 d of passable connection, most often at times of high tide. Once closed on 8 March 2017, the berm began to substantially build up.

The PCH–pedestrian bridge complex has been identified as the keystone passage barrier in this system and has recently been placed on the priority restoration list by Caltrans District 7 (Caltrans pers. communication). Efforts are underway to obtain funding for the feasibility study needed to examine overall watershed processes post fire and develop a restoration plan.

The restoration challenges at Zuma lagoon are exacerbated by over 20 fish passage barriers extending from the Zuma Beach driveway and Arizona crossing, upstream through numerous private properties to the public area owned by National Park Service.[10] Planning has been in progress since 2005 to replace the Arizona crossing with a bridge, and to restore passage under PCH, but implementation funding is still missing. NPS restored over five acres of tules and transitional upland vegetation on the east side of the lagoon in 2010, but management for mosquito abatement resulted in creation of paths through the tules that has fragmented that habitat and attracted transients.

Habitat quality in Zuma lagoon was documented prior to the drought. Despite the added natural wetland vegetation, high water temperatures, dissolved oxygen level limitations, and extensive eutrophication would make this a challenging habitat for *O. mykiss* (McLaughlin et al. 2014). Zuma lagoon almost completely dried down during the 2013-2016 drought period and did not breach at all. Only a small fraction of the lagoon area had surface water in October and November 2016. It took a combined 42.09 cm of rainfall from October-January for Zuma lagoon to breach on 20 January 2017. Two more large rain events, with a combined total of 29.49 cm of rainfall recorded, sustained the breach for a total of 41 d with 39 d of passibility into the lagoon, dependent on high tide conditions. Once rain events ceased, the lagoon closed on 1 March 2017 at very high-water capacity, and the 200 m wide berm seen at this location built back up rapidly. Grooming and beach manipulation by LA County Department of Beaches and Harbors, who maintain the berm closure to provide lifeguard vehicle access across the beach, assisted in the rapid berm buildup.

Almost all the upstream fish passage barriers in Solstice have been removed during the past decade by the city of Malibu and National Park Service. The final constraint is a Caltrans box culvert under PCH that has been the subject of much restoration analysis for years; it creates a steep >1 m drop-off with no jump scour pool that precludes fish passage during much of the breach period. Final planning for a bridge to replace the culvert is in progress but there is no current timeline for implementation. While there is historic documentation of *O. mykiss* in Solstice (Dagit et al. 2005; NMFS 2012), lagoon development and presence is currently ephemeral and constrained by PCH and houses. Sometimes there is kelp washed up to the pool, but otherwise there is no vegetation and habitat is marginal at best. Flow through the culvert rarely exceeds 5 cm depth, although riparian cover and suitable habitat is available from the upstream end of the culvert to the limit of anadromy approximately three kilometers upstream.

Solstice lagoon experienced breaches in the 2014-2015 (7 d), and 2015-2016 (11 d) water years. During 2016-2017, the first breach occurred on 23 December 2016 after a combined 14.73 cm of rain fell from 1 October 2016 through the day of first breach. With an additional 49.02 cm of rain recorded over the 2017 rainy season, the breach remained connected until closure on 4 July 2017. Solstice lagoon remained open for the longest period out of all the locations in our study area but was completely impassable. When the breach was first initiated, there was a short window before enough sand had washed away that would have allowed passage from the ocean to the culvert, but not further upstream. Sub-

[10] Kelley, E., E. Wallace, and M. Stoecker. 2013. Southern California steelhead recovery and barrier removal recommendations for Zuma Creek, Santa Monica Mountains National Recreation Area. Prepared for Santa Monica Mountains Foundation and the Southern California Research Learning Center, Thousand Oaks, CA.

sequent sheet flow across the beach face and the smooth concrete bottom of the culvert also restricts passibility. Additional human interference was a constant occurrence at this location. Sandbags were found within the culvert and obvious trenches appeared dug into the sand to divert flow.

Although Caltrout (2006) and NMFS (2012) recovery plan both identify Las Flores as having potential *O. mykiss* habitat, there is no historic record of fish in this system and the anthropogenic constraints at the beach pose significant barriers. Las Flores lagoon has an extremely constricted channel bordered by concrete walls on either side both up and downstream of the PCH bridge, which funnels flows to the beach. Due to the fire hose funneling effect of these constraints, it breached every year despite drought conditions in the 2013-2016 water years. These breaches were variable in length, lasting 4, 10, and 7 d, respectively. A combined 16.51 cm of rain fell from 1 October 2016 until the first breach occurred on 24 December 2016. The breach was sustained throughout the rest of the rainy season, with an additional 39.12 cm of rain recorded, until its closure on 22 April 2017. Total breach time in 2017 equaled 119 consecutive days with an estimated 44 d of passibility into the lagoon but the lack of connected surface flow in the upstream channel precluded any further movement. Berm buildup occurred over the month of May 2017, and at the end of the 2017 water year what remained of the lagoon sat dry, 1-3 m below the height of the completely closed off berm.

In addition to the site-specific constraints found at each lagoon system, the global effects of sea level rise also need to play a role in developing restoration scenarios. According to a Los Angeles County Public Beaches Sea Level Rise Vulnerability Assessment (Noble 2009), most beaches in the western portion of the county are expected to be eroded under a high sea level rise scenario by 2040. Topanga beach is expected to erode completely and Zuma beach is projected to erode by ~70%. By 2100, Zuma beach and Topanga beach are expected to recede by 184 feet and 190 feet respectively. While the other lagoons in our study were not included in the LA County Assessment, we can infer that erosion and recession could be similar under high sea level rise conditions. Explicitly evaluating the ecological trade-offs between ensuring adequate connectivity and increasing transition zone habitat in the face of sea level rise, as well as examining the best way to develop a realistic, self-sustaining mosaic of ecosystem habitat types and services, is necessary but difficult (Southern California Wetlands Recovery Project 2018). Continued monitoring of lagoon volume over time can help inform management decisions by providing accurate knowledge of how a given lagoon responds to rainfall, and how it provides habitat to emigrating smolts and anadromous adults returning to riparian headwaters. It will be critical for managers and restoration planners at all lagoon sites to balance the need for breach connectivity with lagoon footprint as restoration plans move forward.

Conclusions

The recovery of anadromous adult steelhead trout to headwaters of southern California creeks is contingent on open and passable lagoon conditions. Our analysis of lagoons in the Santa Monica Bay indicates that lagoon surface area correlated positively with the amount of rain needed for the first breach to occur but negatively with the number of days a breach persisted. Larger lagoons in our study area tended to open later and close more quickly than smaller lagoons. At the same time, larger lagoon footprints could offer sea level rise protection to estuarian vegetation and other wildlife that is critical to the overall health of the ecosystem (Southern California Wetlands Recovery Project 2018). As observed during the study period, lagoons with smaller footprints have little potential to provide smolt rearing habitat and provide limited anadromous adult passage. At this point in time, all of the lagoons in our study region would be considered unsuitable for rearing smolts. While it has been continually observed that *O. mykiss* smolts do not linger for very long in estuaries[11] (Welch et al. 2004), insufficient lagoon volume can also lead to increased predation risk by birds (Kelley 2008; Osterback et al. 2015). Lagoons with larger footprints have better potential to be utilized as smolt habitat with decreased predation risk since they retained volume the longest through the summer and into the next water year. Adequate depth played a role here, as larger surface area locations were deeper overall, providing habitat that is more protected than shallower areas. The problem is that these lagoons also tend to breach less frequently, restricting anadromous adults from entering to spawn, which can result in fewer fish overall (NMFS 2012).

The last important part of restoring connectivity for *O. mykiss* is for fish to have access from the lagoons upstream to headwater spawning and rearing habitat. Dry down of lower reaches in these creeks poses a significant barrier for both adult and juvenile migration to and from the lagoon. As extensively documented in Topanga Creek, the stream channel dries down from 200 to ~1700 m every summer (Dagit et al. 2017), effectively rendering the lagoon habitat useless to any anadromous adults or smolts that failed to enter the creek or ocean during a short period of passable connection. This pattern was also observed in all the other watersheds. Water temperatures in the study area lagoons consistently reach stressful levels during the summer months and these already high temperatures increased over time (RCDSMM unpublished data). Additionally, instream vegetation, which provides habitat for benthic macroinvertebrates and terrestrial insects, and provides a major food source for juveniles (Krug et al. 2012), is virtually nonexistent in every lagoon of our study area (RCDSMM unpublished data).

The measurements recorded and analyzed in this study provide insight into the volumetric characteristics that small creek archetypal lagoons display in southern California's Mediterranean climate. With the Santa Monica Bay predicted to face more extreme conditions due to climate change and sea level rise, maintaining sufficient volume in the lagoons in our study area as well as managing them to support connectivity will become increasingly more important to the recovery of southern steelhead trout. Unfortunately, due to the small data set with only three points in time measured for each lagoon, robust statistical analysis was not possible to further illuminate the complex dynamics that need to be understood in order to develop self-sustaining long-term restoration plans.

Passage limitations due to drought are a key limiting factor affecting adult steelhead in the Santa Monica Bay, and despite the ability to spawn multiple times anadromous adult movement is hindered by flashy peak flows characteristic of southern coastal streams (NMFS 2012). In both Topanga and Arroyo Sequit, anadromous adults were able to migrate upstream in 2017, despite the short window of opportunity for passage. They were not able to return to the ocean due to low flow conditions in the creeks. If climate predictions for low flow conditions continue and further restrict migration opportunities, *O. mykiss* may have no choice but to remain in freshwater refugia pools. Resident *O. mykiss* are typically smaller and less fecund than ocean-going steelhead (NMFS 2012). The

[11] Kelley, E. 2008. Steelhead trout smolt survival: Santa Clara and Santa Ynez River estuaries. Report for California Department of Fish and Game Fisheries Restoration Grant Program, University of California, Santa Barbara, CA 61 pp.

implications of reduced connectivity and migration opportunities could decrease resiliency of southern *O. mykiss* by increasing the risk of local extirpations and restricting genetic flow among neighboring systems (NMFS 2016). As sea level rise is projected to inundate wetland habitat across southern California in the next 100 years (Thorne et al. 2018), now is an opportune time to set up management plans to ensure adequate estuarine and transitional habitat remains resilient in the face of climate change and anthropogenic stressors. This study provides insight into how the lagoons in the study area rebounded from drought conditions and subsequently evolved over a wet period followed by the hot and dry season.

With the current population of southern steelhead trout at record lows, the importance of passage opportunities in the Santa Monica Bay are more important than ever. Increased fire risk and uncertain precipitation levels that have come along with climate change will be an important consideration for management in the future as populations have the potential to be completely extirpated during a single natural hazard. Enhancing the ability of southern steelhead trout to move not only within their own watershed, but also between watersheds, could be vital to preserving this population. Finding the balance between lagoon volume and breach potential will be critical.

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