Central Coast Watershed Studies

CCoWS

Effects of Local Runoff on Water Levels and Water Quality in the Carmel River Lagoon During Dry-River Periods

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Executive Summary

This was a class project conducted by students in the Advanced Watershed Science and Policy (ENVS 660) course at California State University at Monterey Bay (CSUMB).

Coastal lagoons are complex environments that provide essential habitat for fish, macroinvertebrates, amphibians, birds, and terrestrial species. Trout and salmon rely on lagoons to provide a cold, oxygenated, low-salinity environment. Lagoon water quality (WQ) is influenced by the ocean and freshwater inputs from the upper watershed including river discharge, groundwater, and surface runoff.

The Carmel River Lagoon (CRL) is located at the mouth of the Carmel River in Monterey County, California. The mouth of the lagoon opens and closes as a result of wave action and river discharge building and breaching the sandbar. Seasonally the Carmel River is not connected to the CRL, and the only freshwater inputs to the lagoon are groundwater and local runoff. During this period, saltwater enters the lagoon both through and over the sandbar.

The CRL provides rearing and foraging habitat for the federally threatened south-central California coast steelhead. Variations in freshwater sources cause fluctuations in WQ that can impact the optimal habitat parameters for steelhead.

Our goal was to determine how local runoff influences water levels and WQ in the CRL during the river not connected (RNC) season. We investigated five aspects of the CRL system:

1. **Water quality:** We examined current and historical WQ (salinity, temperature, and dissolved oxygen) and observed that the lagoon periodically becomes critically saline during RNC conditions. This justified the need to quantify the potential role of local runoff in mitigating poor WQ.
2. **Lagoon stage and precipitation**: We visually assessed historical changes in lagoon stage with respect to precipitation, river discharge, and wave height. We identified 14 events in which precipitation was the main driver of lagoon stage increase. This provided direct evidence that local runoff has a measurable impact on the lagoon.
3. **Outfall delineation**: To define the RNC-CRL Watershed, we found the upstream extent of local runoff influence, identified 17 stormwater outfalls surrounding the lagoon, and delineated their respective watershed areas.
4. **Runoff model**: We used the U.S. Army Corp of Engineers Hydrologic Engineering Center-Hydrologic Modeling Software (HEC-HMS) to estimate the

volume of precipitation converted to local runoff. We found that observed and predicted stage increases from runoff events matched in magnitude.

5. **Water quality model**: We modeled the effects of local runoff on WQ for given precipitation events. We found runoff from a 1-inch precipitation event will have minimal effect on surface salinity, and 2-inches of rain can potentially drop salinity below critical levels. This gives us the ability to estimate future benefits to the lagoon from quantified changes in runoff management.

Local runoff influences water level and WQ in the RNC-CRL. Managers should keep in mind how their projects will affect surface runoff to the lagoon as it may play an important role in mitigating poor WQ during the dry-river season.

Table of Contents

1 Introduction

1.1 Background

1.1.1 Lagoon Dynamics

Coastal lagoons are shallow water bodies that develop at the interface of terrestrial and marine ecosystems (Elwany *et al.* 1998). They provide essential hydrologic functions including flood relief, coastal protection, sediment trapping, and groundwater aquifer replenishment (Rich and Kellar 2013) as well as essential ecosystem services that support a range of rare and threatened species (EPA 2016).

Lagoons in central and southern California are dynamic systems regulated by watershed processes, precipitation, and wave action (Rich and Kellar 2013). Connectivity with the ocean is seasonally dependent upon river discharge and the presence or absence of a sandbar at the outlet. In periods of low river discharge, wave action builds a sandbar at the mouth and separates the lagoon from the ocean. When the sandbar is closed, ocean influence is reduced to wave overwash events and through-bar flow; freshwater inputs include groundwater exfiltration, river discharge, and local runoff (Smith 1990; Watson *et al*. 2001). During wet seasons, increased precipitation and river discharge fill the lagoon with freshwater. When discharge becomes strong enough, the river forcefully breaches the sandbar allowing direct connection between the ocean and upstream watershed.

Salinity, dissolved oxygen, and temperature in lagoons are moderated by seasonal fluctuations of fresh and saltwater inputs (Atkinson 2010). When the sandbar is open, ocean water and river inflow mix and lagoon water quality (WQ) is highly variable (Perry *et al.* 2006). During periods when the sandbar is closed, lagoon salinity is reduced by freshwater inputs from river discharge and groundwater (Smith 1990). Depending on wind patterns and river discharge, freshwater either mechanically mixes into the water column and reduces salinity throughout, or settles on top, creating a stratified water column (CSUMB ENVS 660 2009).

1.1.2 Biological Significance

California coastal lagoons are ecologically important ecosystems that support diverse habitat and natural resources for a variety of special status species (NMFS 2013; USFS 2002). They provide increasingly rare wetland ecosystems, which are essential habitats for amphibians, birds, and terrestrial species. Lagoon riparian and estuary ecosystems also provide habitat for fish and macroinvertebrates (Casagrande 2006).

Central California lagoons are important rearing and foraging habitat for the threatened south-central California coast steelhead (*Oncorhynchus mykiss*) Distinct Population Segment (DPS, NMFS 2013; Hayes *et al.* 2008). The Carmel River Lagoon (CRL) and upper Carmel watershed provide one of the largest rearing habitats for steelhead (NMFS 2013). Steelhead smolts migrate to the CRL and utilize the calm, brackish waters as a transition zone before continuing to the ocean (Tobias 2006). Smolts reared in lagoon ecosystems have higher growth rates than those reared in the upper watershed due to increased food availability, cover, and backwater habitat (Atkinson 2010; Bond *et al.* 2008; Hayes 2008).

Good WQ conditions for steelhead include low salinity, high dissolved oxygen, and low to moderate temperatures (Alley 1996). Good WQ is maintained when the lagoon has sufficient freshwater inflow to mechanically mix the water column and deconcentrate salinity (Cannata 1998; Bond *et al.* 2008). Steelhead rearing conditions become unfavorable if salinity reaches levels above 10 ppt (Table 1, Alley 1997). In stratified conditions, the freshwater surface layer can become critically thin and habitat for rearing fish is reduced (Atkinson 2010; Smith 1990). Similarly, high winds can mix the water column and increase salinity throughout the system, resulting in stressful conditions for steelhead at all depths, unless there are sufficient freshwater inputs to improve WQ (Perry *et al.* 2006).

Understanding the timing and magnitude of freshwater inputs to CRL is essential for managing steelhead habitat (Casagrande 2006). Groundwater exfiltration, Carmel River discharge, and precipitation have been well documented (Casagrande *et al* 2001; James 2005; Watson and Casagrande 2004).

Table 1. Good, fair, and poor water quality conditions for steelhead in the Carmel River Lagoon (Rhodes 2013; Alley 1997).

Water Quality	Temperature	Dissolved Oxygen	Salinity
Good	$\leq 15°$	≥ 7	≤ 3 ppt
Fair	$\leq 19°$	≥ 5	≤ 10 ppt
Poor	$> 19°$	<5	> 10 ppt

1.1.3 Urban Stormwater

Urban watersheds are common along the central and southern California coast, and many coastal lagoons are in close proximity to urban areas (NOAA 1998). Municipal stormwater runoff is directed to storm drains and outfalls and ultimately discharges into nearby rivers and lagoons. Urban areas along California's coastline are growing rapidly. Increases in urban populations correlate with expansion of impervious surfaces, resulting in higher municipal stormwater runoff to local water bodies (DiGiancomo 2004).

The lower Carmel River Watershed has three urbanized communities that contribute stormwater runoff to the CRL and Carmel River. When the CRL is seasonally disconnected from the upper watershed, freshwater sources from local urban areas could be beneficial to the system by providing supplemental inputs (Watson and Casagrande 2004). However, local runoff to the lagoon from the adjacent urban watershed is one source of freshwater that has not been quantified.

1.2 Project Goals

Our goal was to determine how local runoff influences water levels and WQ in the CRL during the dry-river season with respect to salinity, temperature, and dissolved oxygen. We developed a comprehensive understanding of hydrologic interactions between a well-studied central California lagoon and urban watersheds that surround the watershed. We investigated whether surface runoff has a significant impact on the CRL's freshwater layer when the upper Carmel River is not connected to the lagoon. This research will inform managers about the consequences of management decisions that augment or reduce local runoff to the CRL.

2 Study Area: Carmel River Lagoon

We defined the study area as the CRL during periods when it is not connected to the upper Carmel River Watershed by river flow (Watson and Casagrande 2004); the term "River Not Connected" (RNC) describes this period of discontinuity. The Carmel River is 36 miles long and the watershed encompasses 255 square miles. The area of the RNC-CRL Watershed is 5.9 square miles, approximately three percent of the entire Carmel River watershed.

The CRL is located at the mouth of the Carmel River in Monterey County, California (Fig. 1). Three communities are located near the lagoon, the City of Carmel by the Sea, Carmel Meadows, and Monterey County Community Service Area 50 (CSA-50). The Carmel River Watershed has a Mediterranean climate characterized by mild wet winters and long arid summers (Smith *et al.* 2004). The CRL is an important coastal estuary and provides high quality rearing and foraging habitat for south-central coast steelhead (*O. mykiss*) Distinct Population Segment (DPS, NMFS 2013).

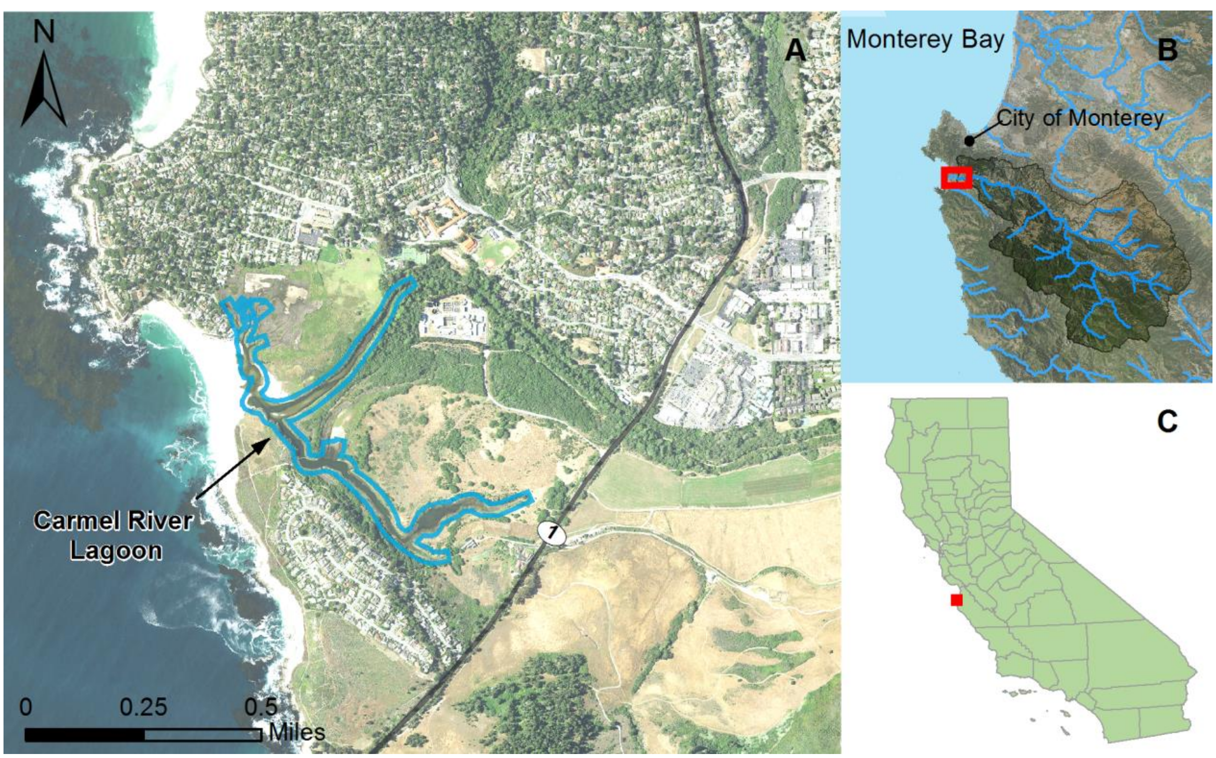

Figure 1. Location of the Carmel River Lagoon (A) in the lower Carmel Watershed (B), Monterey County, CA (C).

Figure 2. Ocean waves entering the Carmel River Lagoon after seasonal breaching of the sandbar. When lagoon and ocean are connected, ocean waves mix the water column and water quality conditions are variable. Photo taken December 16, 2001 by Fred Watson.

When the sandbar is open and the river is flowing, the CRL receives freshwater from the Carmel River and rain events during winter months. The freshwater layer is on top of the heavier brackish water unless mixed by heavy wind or tides and waves entering the lagoon from the ocean (Fig. 2). In winter and spring the sandbar is intermittently open to ocean flows, and the lagoon and ocean exchange water via tidal fluctuations and waves. In early spring, precipitation events become infrequent and by late summer, river flows are minimal or discontinued. Reduction of river flows allows the sandbar to be rebuilt by ocean currents and sand deposition, effectively halting direct ocean interaction through an open channel.

The average stage of the lagoon during the RNC season between 2004 and 2015 was 5.48 ft (NGVD 1929). At a stage of 5.48 ft, the lagoon's average surface area is 32.79 acres (0.05 square miles, RMC 2007). Lagoon surface area, stage, and salinity during the RNC season are initially established by the timing of final lagoon sandbar closure and the intensity of river flow at the time of closure (Larson *et al.* 2005). During RNC conditions, lagoon stage and WQ are influenced by tidal exchange through the sandbar, swell overwash events, groundwater influx, and storm events large enough to generate local runoff. Tidal exchange and wave overwash increase salinity in the lagoon. The influence of these saltwater inputs on salinity profiles might be dampened by groundwater seepage and local runoff (Larson *et al.* 2006).

The Carmel River Lagoon consists of a main river arm, south arm, and north arm. The Carmel River flows through a main embayment toward the mouth opening. The extent of the main embayment varies seasonally and annually, and largely depends upon lagoon water volume, sedimentation and river flow (Casagrande 2006). The north arm is shallow and dendritic during low stages and covered with a wide shallow layer of water when the stage is high. The south arm is a long, deep channel that extends south along the coast before turning inland towards Highway 1. Most of the south arm was constructed in 2004 as part of the Carmel River Lagoon Enhancement Project (CRLEP, Larson *et al.* 2005). The south arm was dredged and expanded to increase available deep-water habitat for steelhead trout (Larson *et al.* 2006).

Following the expansion of the south arm, several survey locations were established for long-term monitoring of WQ parameters in the lagoon relevant to good steelhead rearing habitat (Lumas 2006). The main embayment exhibits "fair" overall WQ year-round and typically maintains a moderately fresh, but shallow column of water in RNC conditions (Rhodes 2013). The water column in the north arm becomes saline and shallow more frequently than other branches of the lagoon (Rhodes 2013). The southern extension of the lagoon provides the best year-round WQ conditions in the lagoon.

Mean annual precipitation in the RNC-CRL Watershed is 18.7 inches (PRISM 2016). The dominant land covers are developed open space, evergreen forest, low-intensity development, and herbaceous (1.78 mi^2, 1.48 mi^2, 0.80 mi^2, and 0.70 mi^2 respectively, Fig. 3, USGSa 2011). Soils in the CRL Watershed are primarily fine to coarse with slow to moderate infiltration rates and are categorized by hydrologic soil groups (HSG) C and B (53.2% and 21.9%, respectively, Fig. 4). Clay (HSG D) and sandy soils (HSG A), comprise 14.2% and 9.8% of the watershed respectively (SSURGO 2016).

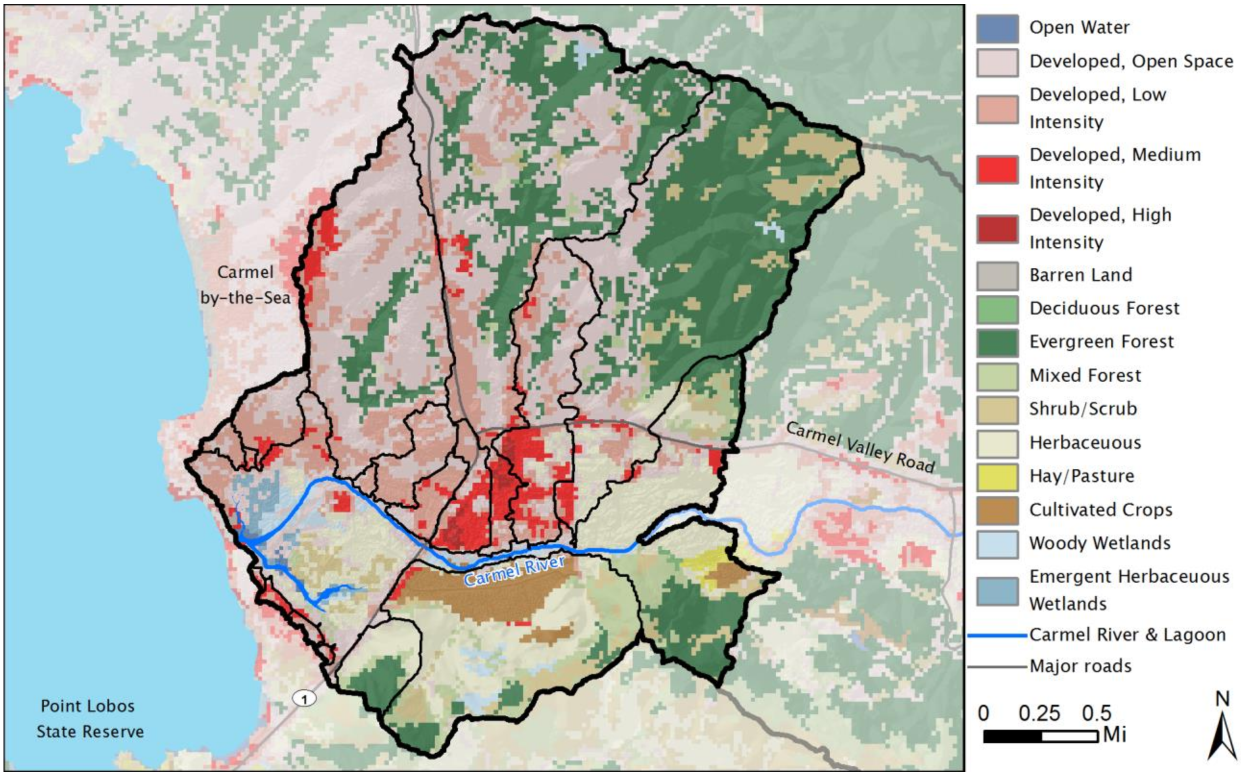

Figure 3. Land use and land cover for the Carmel River Lagoon Watershed (USGSa 2011).

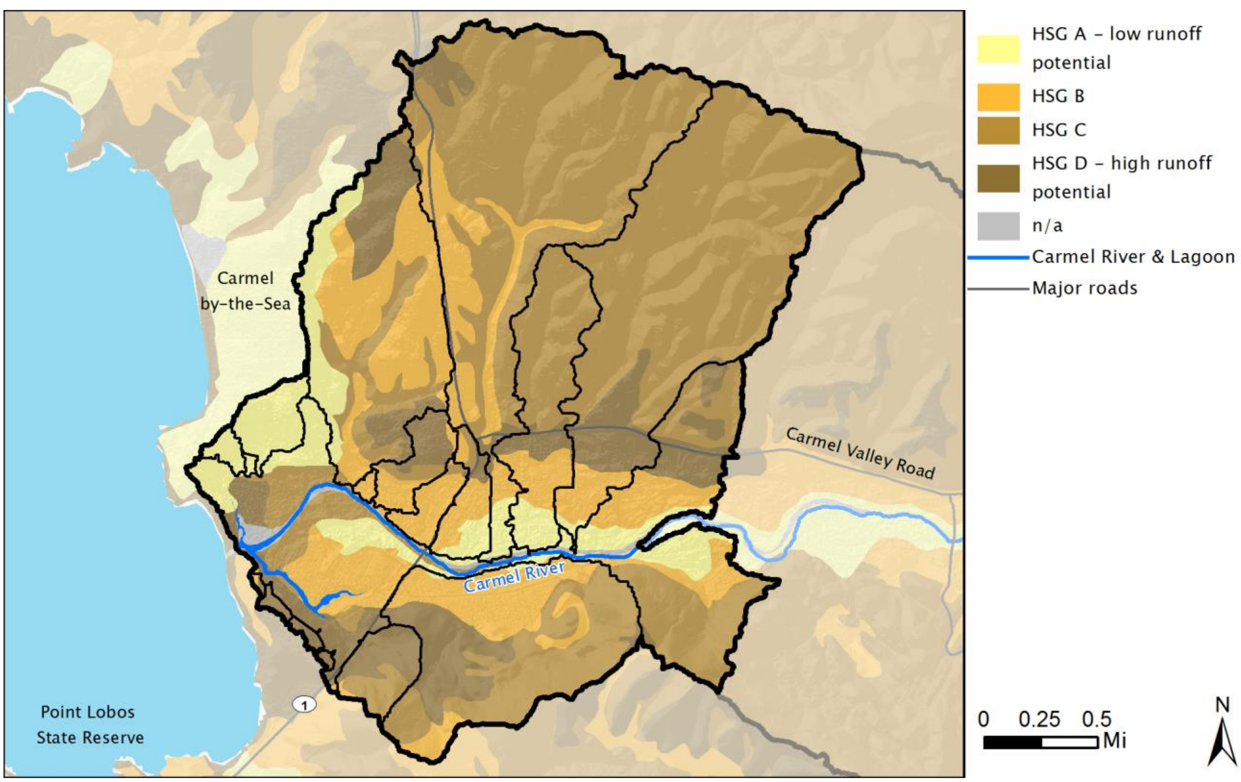

Figure 4. Hydrologic soils groups for the Carmel River Lagoon Watershed (CCRWQCB 2016).

Figure 5. Current and proposed projects around the Carmel River Lagoon as of Fall 2016. Figure inspired by graphic created by MCRMA staff entitled Lower Carmel Area Restoration and Open Space projects.

2.1 Active and Proposed Lagoon-Vicinity Projects

There are several proposed and active projects for the region immediately surrounding the CRL (Fig. 5). The implementation and long term management of these projects may affect watershed processes and ultimately lagoon dynamics and steelhead habitat. In the following section, we summarized components of each project pertinent to the CRL.

Proposed

2.1.1.1 Carmel River Lagoon Ecosystem Protective Barrier (EPB), Scenic Road Protection Structure (SRPS), and Interim Sandbar Management Plan (ISMP) Project

The EPB, SRPS, and ISMP is a project proposed by Monterey County to mitigate potential flooding impacts to low-lying homes and properties north of the CRL. The EPB and ISMP pertain to periods in late fall and early winter when the beach sandbar is closed, river flows increase and the lagoon fills. During this time, water levels can rise to a stage that would flood nearby residences prior to natural breaching of the sandbar (Casagrande *et al.* 2002). The Monterey Public Works Department has frequently used bulldozers to mechanically breach the sandbar prior to flooding, and retained lagoon water rushes into the ocean. The EPB project proposes a constructed sheet piling wall and earthen berm along the northern edge of the lagoon (Denise Duffy & Associates 2014). The wall would provide a buffer allowing lagoon stage to rise to a level where breaching would occur naturally, thereby avoiding issues of non-compliance with the federal endangered species act and unauthorized take of steelhead from the lagoon (Denise Duffy & Associates 2014). The SRPS proposes construction of a wall to protect Scenic Road from erosion by the Carmel River. The road is north of the CRL and when the river meanders in a northerly direction it erodes the bluff fronting Scenic Road. The wall would prevent further erosion of the bluff and allow natural meandering of the river north (Whitson Engineers 2013).

2.1.1.2 Carmel Area Wastewater District (CAWD) Annexation Proposal

The CAWD is a special district governed by an elected Board of Directors that provide wastewater collection and treatment to the City of Carmel-by-the-Sea and portions of the surrounding unincorporated areas of Carmel, Carmel Valley, and Carmel Meadows. CAWD is adjacent to CRL and has the high probability of flooding depending on the surrounding projects. In April 2016, CAWD proposed to increase their sphere of influence to encompass adjacent areas in need of wastewater services. Such areas include east Carmel Valley, Point Lobos, and the Carmel Highlands. District staff estimate an additional 520 connections if the proposed sphere of influence is fully developed in accordance with the county General Plan (LAFCO 2016).

Active

2.1.1.3 Carmel River FREE

The Carmel River Floodplain Restoration and Environmental Enhancement (Carmel River FREE) project is a collaborative effort between the Monterey County RMA, the Big Sur Land Trust (BSLT) and California State Parks. Carmel River FREE will restore connectivity between the Carmel River and the southern historic floodplain by removing sections of the levee. The project proposes a causeway at Highway One to allow flooding events to flow across the floodplain and into the south arm of the CRL. Levee breaks and causeway construction will alleviate flood risk to businesses and residences located in the north bank 100- year floodplain and restore upland and riparian habitats (BSLT 2015).

2.1.1.4 Carmel Area State Parks General Plan – Scheduled for release Summer 2017

The Carmel Area State Park District is creating an updated General Plan, scheduled for release in summer 2017. The Draft General Plan, released in June 2016, proposed two CRL focus areas within the Coastal Area Management Zone: 1) Carmel River Lagoon Wetland Natural Preserve and 2) Lagoon/Wetland zone. Ecological enhancement and protection of habitat for special-status species were listed as top priorities for the existing Carmel River Lagoon and Wetland Natural Preserve (CDSPRa 2016). Objectives for the Lagoon/Wetland zone are to provide areas for natural flooding and promote high quality connected habitat for special status species (CDSPRb 2016). Expanded visitor use is proposed for both zones and will promote activities such as hiking, birding, education and interpretation.

2.1.1.5 Rancho Cañada Acquisition Project

In summer 2016, the Trust for Public Lands, the Santa Lucia Conservancy, and Trout Unlimited partnered to purchase 140 acres of the Rancho Cañada Golf Course for restoration to natural open space. The project aims to restore the property for the sole purpose of protecting species diversity and natural habitat. A major benefit of the project is the transfer of the 300 acre-feet of water per year once used to irrigate the golf course to public agencies. It remains unknown whether riparian well pumping will be reduced or eliminated completely (TPL 2016). Combined efforts to reduce groundwater extraction and enhance riparian vegetation will contribute to prolonged surface water flows in the lower Carmel River.

2.2 Stakeholders

2.2.1 Primary

2.2.1.1 California State Parks (DPR):

The California Department of Parks and Recreation owns the land at the lagoon including Carmel State Beach and is concerned with maintaining good WQ for steelhead. In 2004, DPR restored the Odello Extension in the lagoon to provide more habitat for protected species and reduce flood risk.

2.2.1.2 Monterey Peninsula Water Management District (MPWMD):

The MPWMD co-manages the Carmel River steelhead population by WQ monitoring and stage in the lagoon, restoring riparian vegetation along the Carmel River, performing fish rescues, and rearing steelhead.

2.2.1.3 Monterey County Resource Management Agency (RMA):

The RMA manages stormwater runoff including storm channels and outfalls in CSA-50 near the CRL. A key goal for the RMA is to protect private properties in the CSA from flooding; RMA facilitates breaching the sandbar when the lagoon reaches a critical water level.

2.2.1.4 National Marine Fisheries Service (NMFS):

NMFS regulates critical steelhead habitat, advises local agencies on how to limit impacts to special status species and regulates actions that may result in “take”.

2.2.2 Secondary

2.2.2.1 Big Sur Land Trust (BSLT):

The BSLT initiated several large land transfer and restoration projects near the lagoon including expanding the south arm of the lagoon into the Odello Extension. BSLT is a collaborator on the Carmel River FREE project that will expand the lagoon floodplain beyond Highway 1.

2.2.2.2 Carmel River Watershed Conservancy:

A local organization concerned with protecting natural resources, special status species, and community in the Carmel River Watershed.

2.2.2.3 Carmel River Steelhead Association:

A local organization dedicated to restoring and conserving the threatened steelhead population in the Carmel River Watershed.

2.2.2.4 Carmel Area Wastewater District (CAWD):

CAWD owns and maintains a wastewater treatment facility adjacent to the lagoon. The facility is projected to flood in the event of a 100-year storm (CAWD 2011). CRL vicinity projects could increase flood risk. CAWD is in the process of developing a 15-year master plan that may address strategies for reducing flood hazards (Kennedy/Jenks Consultants 2013).

2.2.2.5 City of Carmel-by-the-Sea

The City of Carmel-by-the-Sea manages its stormwater through outfall pipes that divert urban runoff onto Carmel Beach. Carmel Bay was designated by the State Water Resources Control Board as an Area of Special Biological Significance (ASBS). Only wet weather stormwater discharges are allowed into ASBS; the City may be interested in solutions to prevent local runoff into ASBS including possible diversion to the CRL.

3 Project Overview

Freshwater inputs into the CRL from the Carmel River, groundwater, and precipitation are well documented (Watson and Casagrande 2004); however, freshwater contributions from local surface runoff have not been adequately studied. While stormwater runoff may contain pollutants (Soller *et al.* 2005); if properly managed, it could continue to sustain a freshwater layer in the lagoon when WQ conditions are less than ideal.

We estimated the degree to which local runoff augments freshwater in the CRL during the dry-river season. The elements of the CRL and watershed system that we addressed are summarized in Table 2 and Figure 6. We investigated historic lagoon WQ to determine when conditions have been undesirable in the past for rearing steelhead (Section 5). We searched for evidence linking freshwater additions from local runoff by using historic precipitation and lagoon stage records (Section 6). We predicted surface runoff, sought to reconcile estimated runoff volumes with observed changes in lagoon water level, determined how freshwater augmentation affects salinity in the lagoon, and provided a basis for predicting impacts of future watershed changes on lagoon dynamics (Section 7). Finally, we integrate these components in a discussion of how local runoff affects lagoon WQ, study limitations, and management implications (Section 8).

Table 2. Workflow for investigating the impact of local runoff on the Carmel River Lagoon.

	P →	W →	R →	Q →	Z →	S
	Precipitation	Watershed	Carmel River	Surface Flow	Lagoon Stage	Water Quality
Historical	Sec.6			Sec.6	Sec.6	Sec.5
Observed			Sec.7			Sec.5
Modeled	Sec.7	Sec.7	Sec.7		Sec.7	

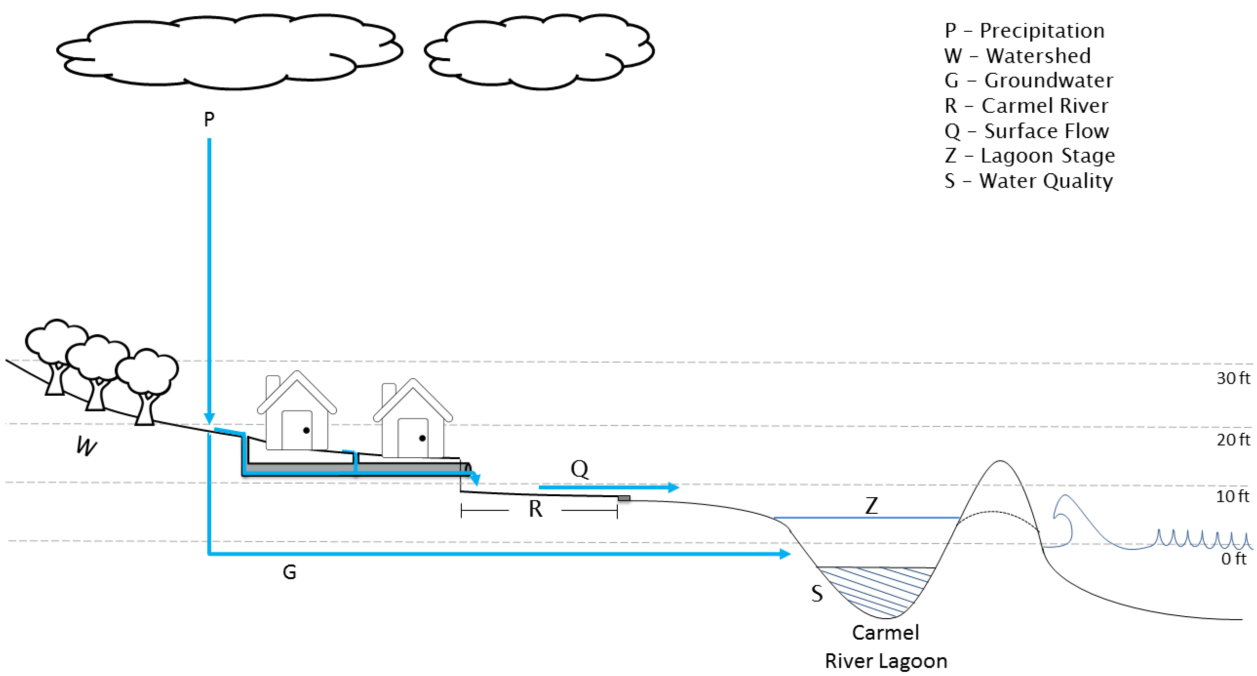

Figure 6. Conceptual model of the Carmel River Lagoon Watershed showing freshwater inputs.

4 Available Data

4.1 Spatial Data

We obtained spatial data from:

- USDA: NRCS Geospatial Data Gateway (NRCS 2016):
    - Mean annual precipitation (MAP) raster, 800 m, PRISM Climate Group at Oregon State University (PRISM 2016)
    - USDA-FSA-APFO NAIP MrSID Mosaic, 1 m: aerial imagery raster for Monterey County, USDA/FSA - Aerial Photography Field Office (2014)
    - Monterey County land cover raster and impervious ground layer, 30 m, US Geological Survey National Land Cover Database (USGSa 2011)
    - Monterey County Percent Developed Imperviousness raster, 30 m, US Geological Survey National Land Cover Database (USGSb 2011)
- Monterey County Resource Management Agency Environmental Services:
    - Monterey County CSA-50, City of Carmel-by-the-Sea, and Carmel Meadows Watershed
        - Inlets and outfalls shapefile (J. Estrada, e-mail correspondence, September 30, 2016)
        - Storm drains, channels, and culverts shapefile (J. Estrada, e-mail correspondence, September 30, 2016)
    - Parcel boundaries shapefile (MCRMAES 2016)
    - City boundaries shapefile (MCRMAES 2016)
- Central Coast Post-Construction Stormwater Requirements page from the Central Coast Regional Water Quality Control Board (CCRWQCB 2016):
    - SSURGO data mosaic for the California Central Coast, Hydrologic Soil Groups (HSG) vector
- United States Geological Survey National Elevation Database (USGS 2016):
    - 2012 National Elevation Dataset, 3 m, 1/9 arc-second tiles

4.2 Hydrologic Data

We obtained hydrologic data from:

- Lagoon water Level:
    - Greg James (MPWMD), NGVD 1929, feet, 15-minute, 08/7/1991 - 09/29/2016
- Precipitation:

- 210 California Irrigation Management Information System (CIMIS) gage, inches, hourly, 12/07/2013 – 10/11/2016,
- Department of Water Resources (DWR), Monterey Airport gage, inches, hourly, 07/01/1995 – 12/07/2013

- Flow Data:
  - USGS, Carmel near Carmel (CAR-VIA), CFS, 15-minute, 2007 – Present
- Wave Height:
  - NOAA National Data Buoy Center (NDBC), Station 46042 (Monterey), feet, 30-minute, 1/1/1996-12/1/2015
- Lagoon Water Quality:
  - MPWMD, salinity, dissolved oxygen, temperature. Monthly. 2006 – Present, Five locations

5 Water Quality

5.1 Field Water Quality – Fall 2016

We measured WQ (salinity, dissolved oxygen, and temperature) in the CRL at five locations before and after a rain event and a wave overwash event in October 2016 to understand the range of habitat conditions that occur during RNC periods (Fig. 7). We emulated the MPWMD sampling protocol at each site by taking WQ samples at 0.25 m depth intervals with a Yellow Springs Instrument (YSI) 85 (Yellow Springs, Ohio) from the surface to the bottom of the lagoon.

Variability in WQ profiles over the 21-day span of the study indicated a fast-changing lagoon environment influenced by precipitation and wave overwash (Fig. 8). Conditions at Site S2 were initially favorable for steelhead with adequate fresh, oxygenated, cool water. A wave overwash event occurred on October 14th, causing stage and salinity to increase by 1.16 ft and 15.28 ppt, respectively, from the previous day. A 1.3-inch rain event occurred on October 15th-16th. Toward the end of the rain event (October 16th), stage increased by 1.12 ft, salinity increased by 8.54 ppt, and dissolved oxygen decreased by 6.9 mg/L. The salinity increase may have been caused by the wave overwash event and intensified saline groundwater seepage into the lagoon. Sites O1 and O4 were difficult to access, therefore we took fewer measurements at those sites.

These observations illustrated how the CRL WQ responded to a rain event and wave overwash event during RNC conditions. The CRL increased in stage and salinity, and decreased in dissolved oxygen which could be considered poor WQ conditions for steelhead. However, there is more habitat with the increase in volume. If steelhead are not acclimated to saltier water, they could have difficulty adjusting to these conditions, if the conditions persist for a long period of time.

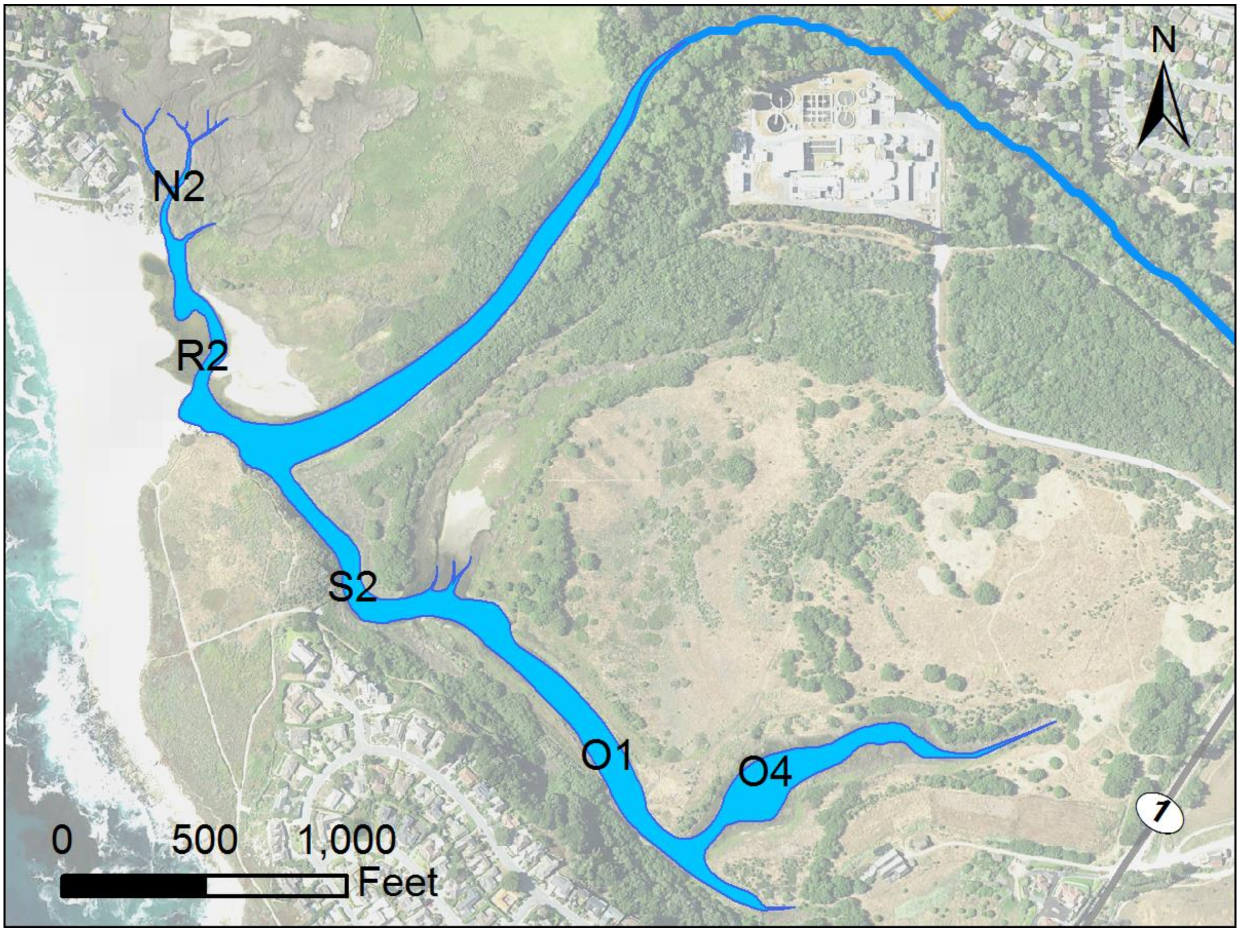

Figure 7. Locations of MPWMD monthly WQ sampling in the Carmel River Lagoon.

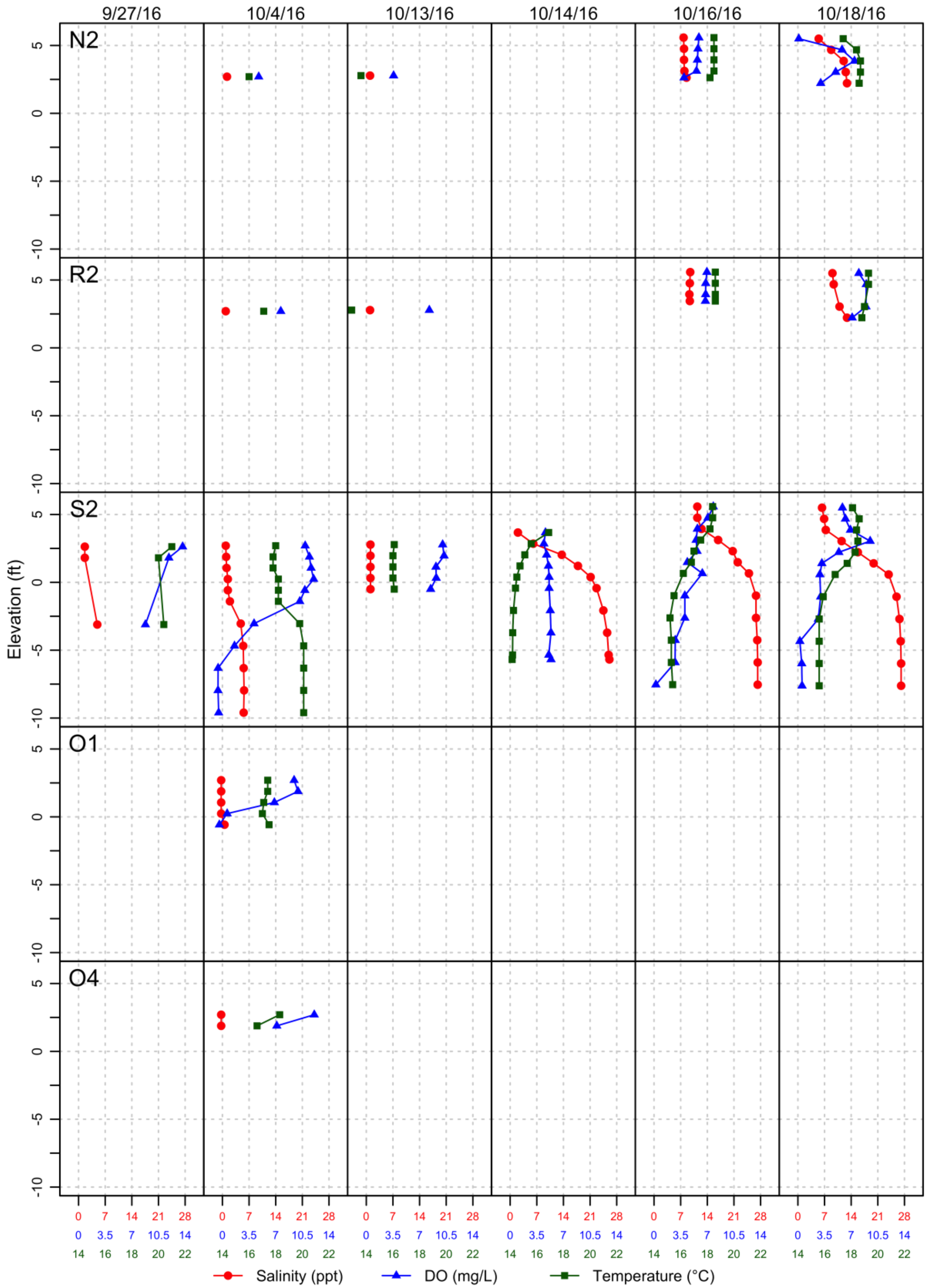

Figure 8. WQ profiles before (9/27–10/13/16), during (10/14–10/16/16), and after (10/18/16) a wave overwash and rain event in the CRL.

5.2 Historical Water Quality

We reviewed the historical WQ record (Mar. 2006 to Sept. 2016) at Site S2 measured by MPWMD to identify periods of good and sub-optimal steelhead habitat during RNC periods (Fig. 9). We considered good WQ conditions for steelhead to be defined by low salinity, high dissolved oxygen, low to moderate temperature, and sufficient depth to enable predator evasion. We found periods of poor WQ in 2010, 2011, 2014, and 2015 during the dry-river season; these were often followed by improved WQ conditions.

We examined precipitation, wave height, and Carmel River discharge to assess potential sources of poor WQ during RNC conditions and to investigate why WQ subsequently improved (Fig. 10). We concluded that wave action led to high surface salinity, which subsequently reduced over time even though the Carmel River was not flowing. There must be freshwater sources that caused this recovery such as groundwater, surface runoff, or a combination of the two. This justified the need to quantify freshwater inputs to the CRL during RNC periods.

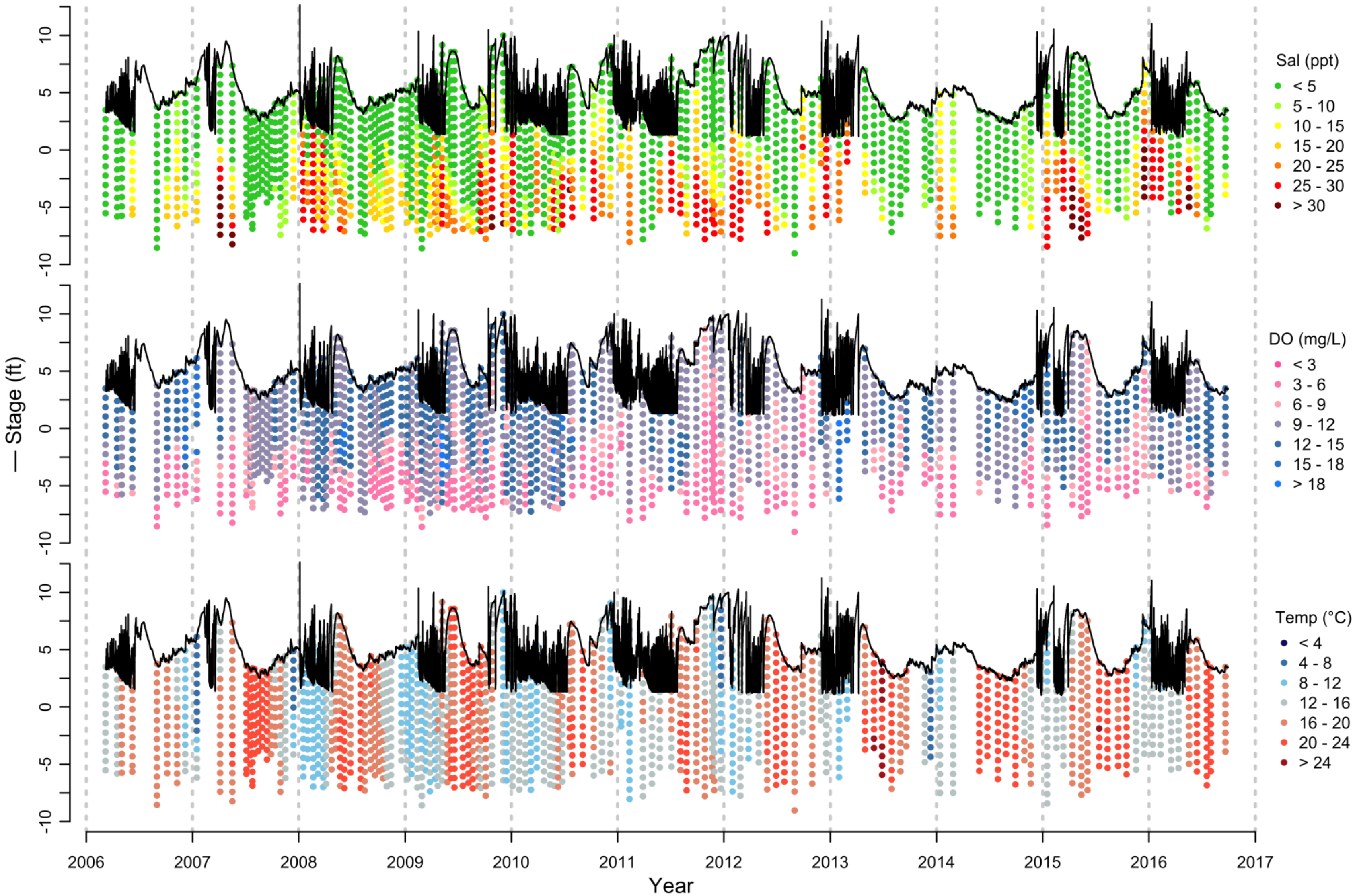

Figure 9. Stage, salinity (Sal), dissolved oxygen (DO), and temperature (Temp) from 2006-03-08 to 2016-09-20 in CRL. Periods of large fluctuations in stage indicate the lagoon was connected to the ocean.

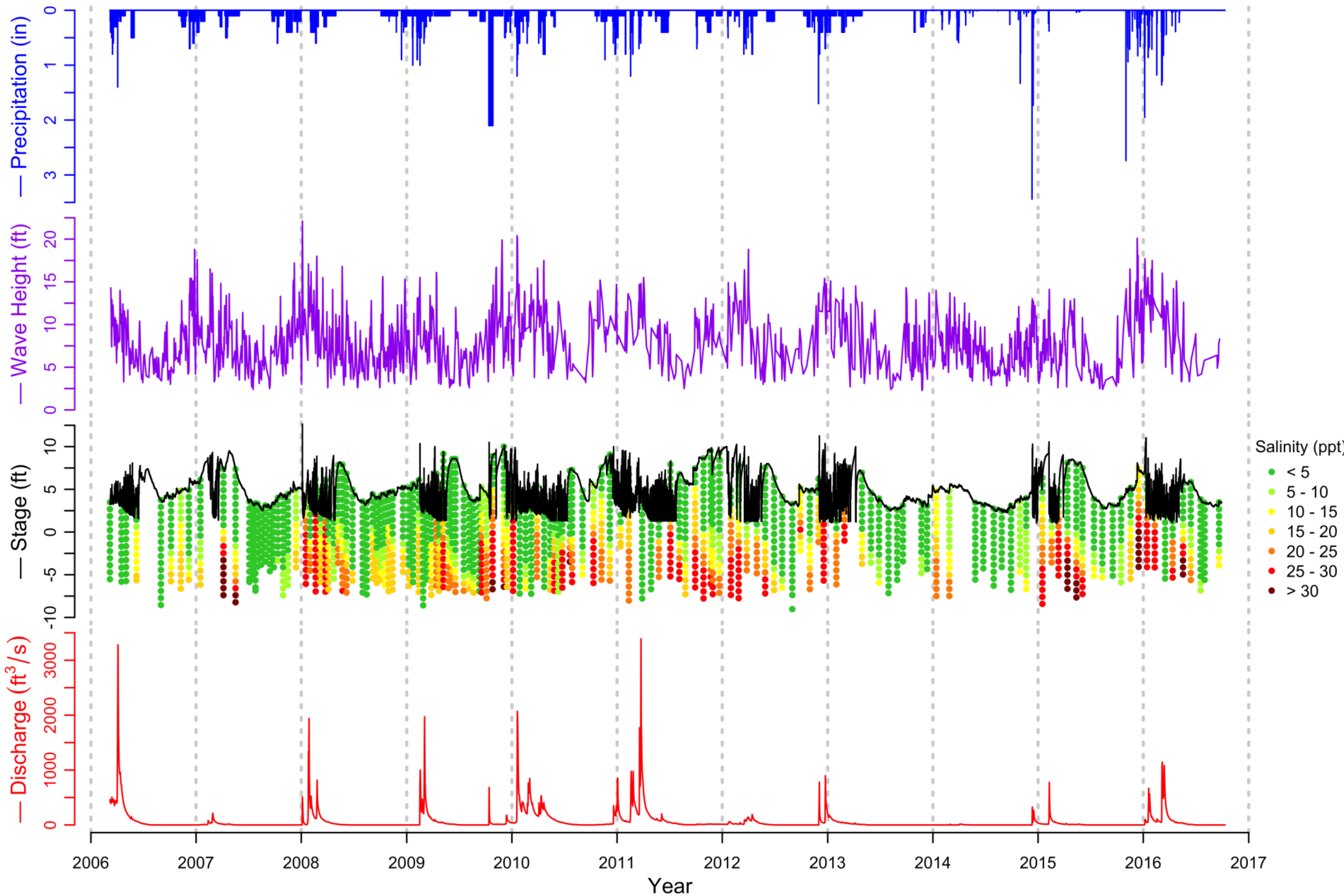

Figure 10. Daily cumulative precipitation, 15-minute lagoon stage, wave height, salinity at Site S2, and daily mean discharge at Highway 1 from 2006-03-08 to 2016-09-20.

6 Precipitation and Lagoon Connectivity

6.1 Methods

Precipitation events during RNC conditions have the potential to augment freshwater in the lagoon. A fraction of the precipitation during the storm is converted into surface runoff, while some of the precipitation will percolate into groundwater aquifers and eventually exfiltrate to the lagoon. We chose to focus on quantifying the amount of precipitation that is converted to surface runoff and drained into the lagoon. If local runoff does in fact influence freshwater in the lagoon, it could play a significant role in stabilizing WQ during RNC conditions.

To determine whether local runoff influenced CRL water level during RNC conditions, we created graphs that overlaid annual lagoon water levels, local precipitation, Carmel River discharge and wave height over time. We visually assessed the changes to lagoon surface elevation dating back to 1996. We inferred local runoff had an influence on CRL water level if there was an increase in lagoon stage during or immediately after an RNC storm event that was not clearly attributable to wave overwash. If runoff increased lagoon stage, we related lagoon stage values before and after precipitation to lagoon volume using a stage-volume relationship that we modified from RMC Water and Environment (2007) data. We fit a model to lagoon stage and the natural log of lagoon volume data providing a power equation which converts lagoon stage to volume. We did not account for and changes in lagoon topography over the last two decades in the analysis such as the construction of the south arm in 2004. The model for the current logarithmic relationship between lagoon stage and volume is:

$$\ln(V) = -0.0145Z^2 + 0.5841Z + 1.5798$$

where V is lagoon volume and Z represents lagoon stage.

We compared volumetric lagoon increases to the approximate volume of precipitation that fell in the RNC-CRL Watershed to provide an implied runoff coefficient for each identified storm.

6.2 RNC Increases in Lagoon Stage

We identified 14 events between 1996 and 2015 that had sufficient evidence of a connection between local runoff and lagoon water level (Table 3, Fig. 11). This analysis suggests that on average, 3.9% of local precipitation is converted to lagoon storage during RNC conditions. For a typical storm of 1-inch rainfall, the lagoon increases in volume by approximately 12.3 ac-ft, or eight percent of the average lagoon volume. The magnitude of lagoon surface elevation increase via local runoff was dependent on the lagoon's previous elevation (Fig. 12). Precipitation into the lagoon when stage was high led to a minimal increase and vice versa.

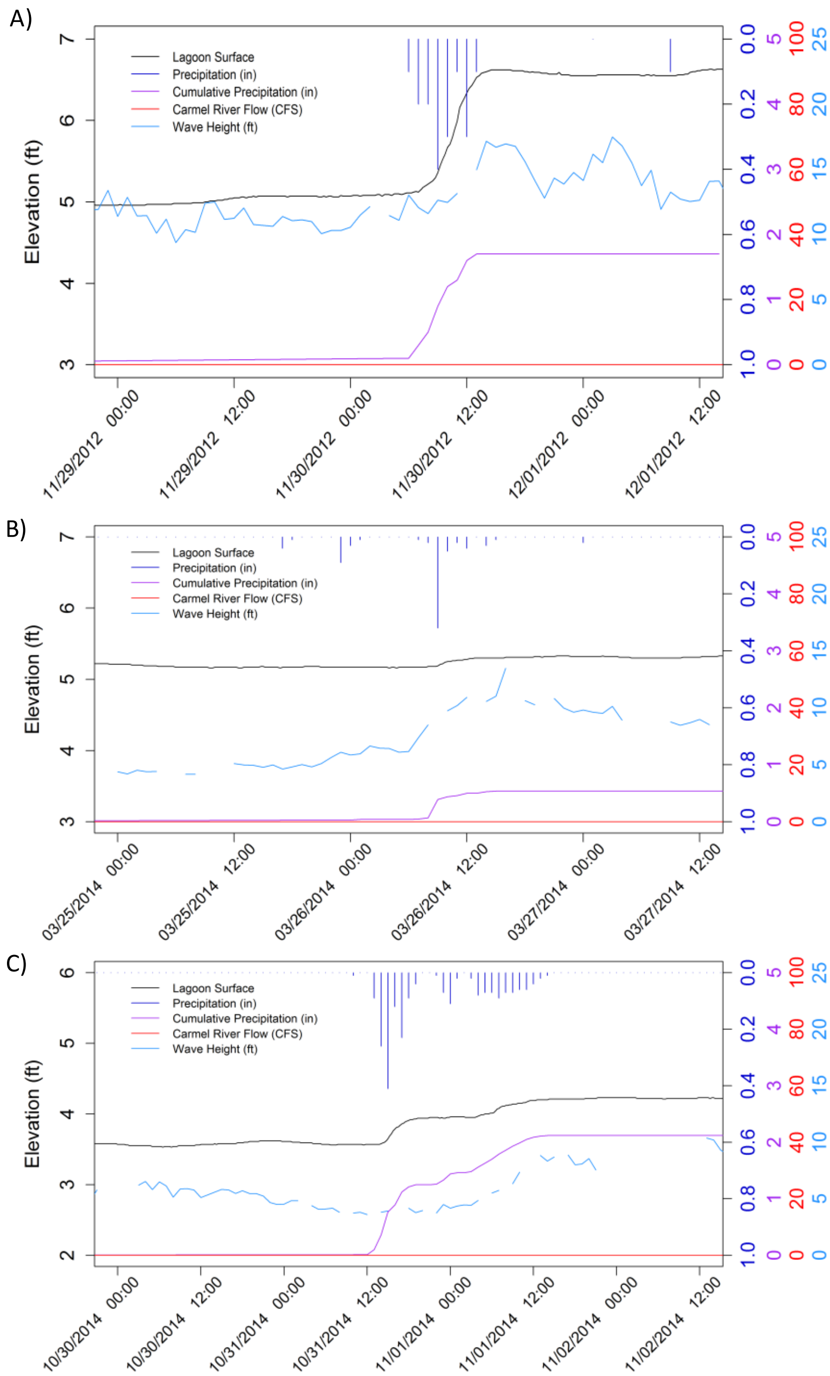

Figure 11. Water surface elevation of the Carmel River Lagoon during storm events. We can infer from plots A, B, & C that there is a connection between local runoff and lagoon stage. Additional storm event graphs can be found in Appendix B.

Table 3. Storm events during RNC conditions and subsequent increase in lagoon water depth and Implied Lagoon volumetric increase derived using the stage-volume relationship for the CRL published by RMC Water and Environment in 2007.

Date	Initial lagoon stage (ft)	Lagoon stage increase (ft)	Implied Lagoon volume increase (ac-ft)	Total Precip (in)	Implied Volumetric Precip (ac-ft)	Implied runoff coefficient (%)
11/27/2004	5.21	0.07	2.8	0.2	63	4.4
12/9/2002	6.9	0.07	4.6	0.3	95	4.9
11/25/2005	5.12	0.09	3.5	0.3	95	3.7
11/20/2011	9.44	0.07	7.3	0.4	127	5.8
10/24/1998	7.97	0.12	9.9	0.5	158	6.3
3/26/2014	5.17	0.15	6.0	0.5	158	3.8
10/29/1996	4.86	0.24	8.6	0.6	190	4.5
11/13/2006	4.88	0.2	7.2	0.6	190	3.8
12/21/2006	5.55	0.19	8.7	0.6	190	4.6
10/10/2007	3.57	0.33	5.5	0.6	190	2.9
12/14/2008	5.08	0.27	10.6	0.9	285	3.7
11/30/2012	5.07	1.55	76.0	1.7	538	14.1
10/31/2014	3.57	0.66	12.6	2.12	670	1.9
11/2/2015	4.46	0.62	20.2	2.7	854	2.4

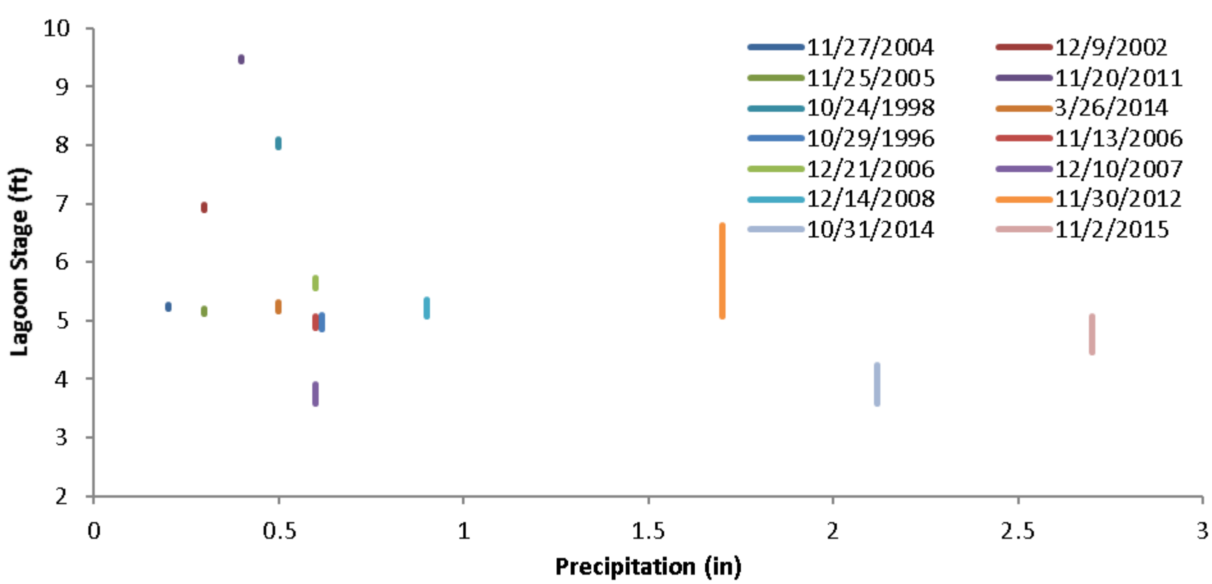

Figure 12. Precipitation versus lagoon stage increase. Magnitude of precipitation has the largest influence on lagoon stage increase; however, stage increase is also dependent on initial lagoon stage.

7 Watershed Delineation and Runoff Modeling

7.1 Outfall Delineation

We delineated the RNC-CRL Watershed and its subwatersheds to quantify its processes and provide a basis for evaluating the role of the local subwatersheds in lagoon dynamics. We surveyed the lower 2.1 miles of the Carmel River during early October (pre-rain) to determine the point above which the river was dry for at least a half a mile and disconnected from the larger CRL Watershed (Fig. 13). We determined that the upper limit of the RNC-CRL Watershed at the time of the survey was the Rancho Cañada Golf Course. We walked the lower Carmel River again after a 1.35-inch rain event on Oct. 16, 2016 and confirmed that outfalls 10-15 were connected to the lagoon with flowing water (Fig. 13). We assumed that outfalls 16 and 17 were also connected.

We mapped 17 outfalls- some of which were conventional stormwater drains and others were dead-end roads and their flow paths in the RNC-CRL Watershed (Fig. 14 & 15). We used a 1/9 arc second (approximately 3 m) digital elevation model (DEM) and ArcGIS spatial analysis tools to delineate the watershed boundary for the RNC-CRL. We incorporated stormwater infrastructure by burning storm drains and channels into the DEM before running the pit-filling algorithm. This allowed water to flow in through specified "channels" to the outfalls (CSUMB Class ENVS 660 2011). We used the Spatial Analyst tools in ArcGIS to delineate watershed areas for each outfall within the RNC-CRL Watershed before incorporating it into the runoff model (Fig. 15).

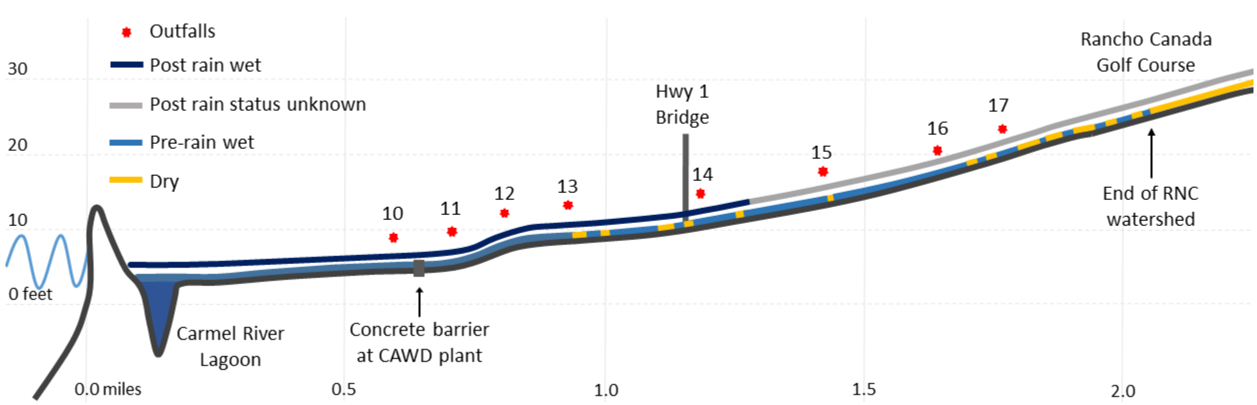

Figure 13. Profile of wet and dry portions of Carmel River before and after the October 15, 2016 rain event. Profile is adapted from Figure 3.1 in Watson and Casagrande (2004).

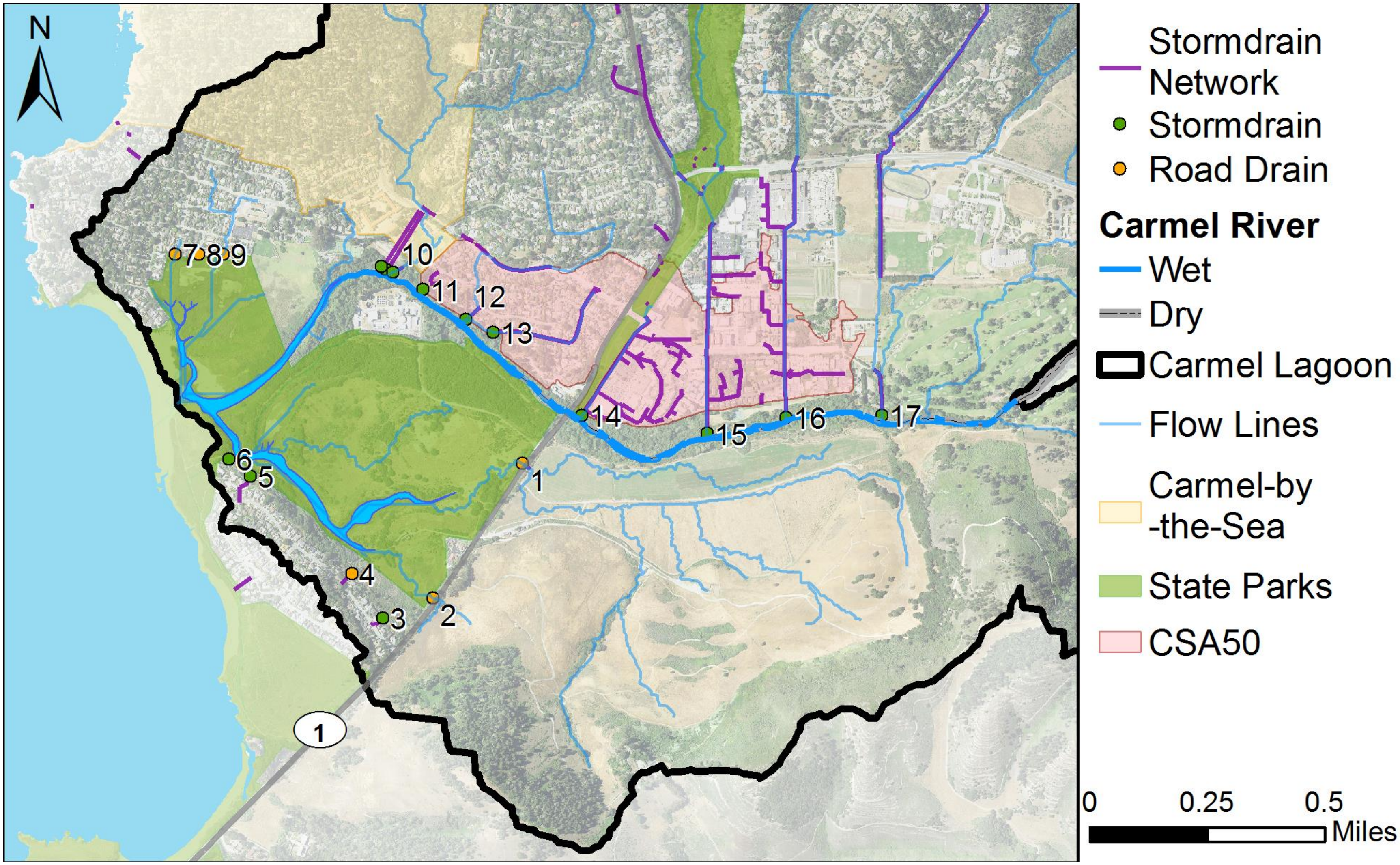

Figure 14. Identification numbers of local outfall and road drains within the RNC-CRL Watershed. See Appendix C for photographs and descriptions of all outfalls.

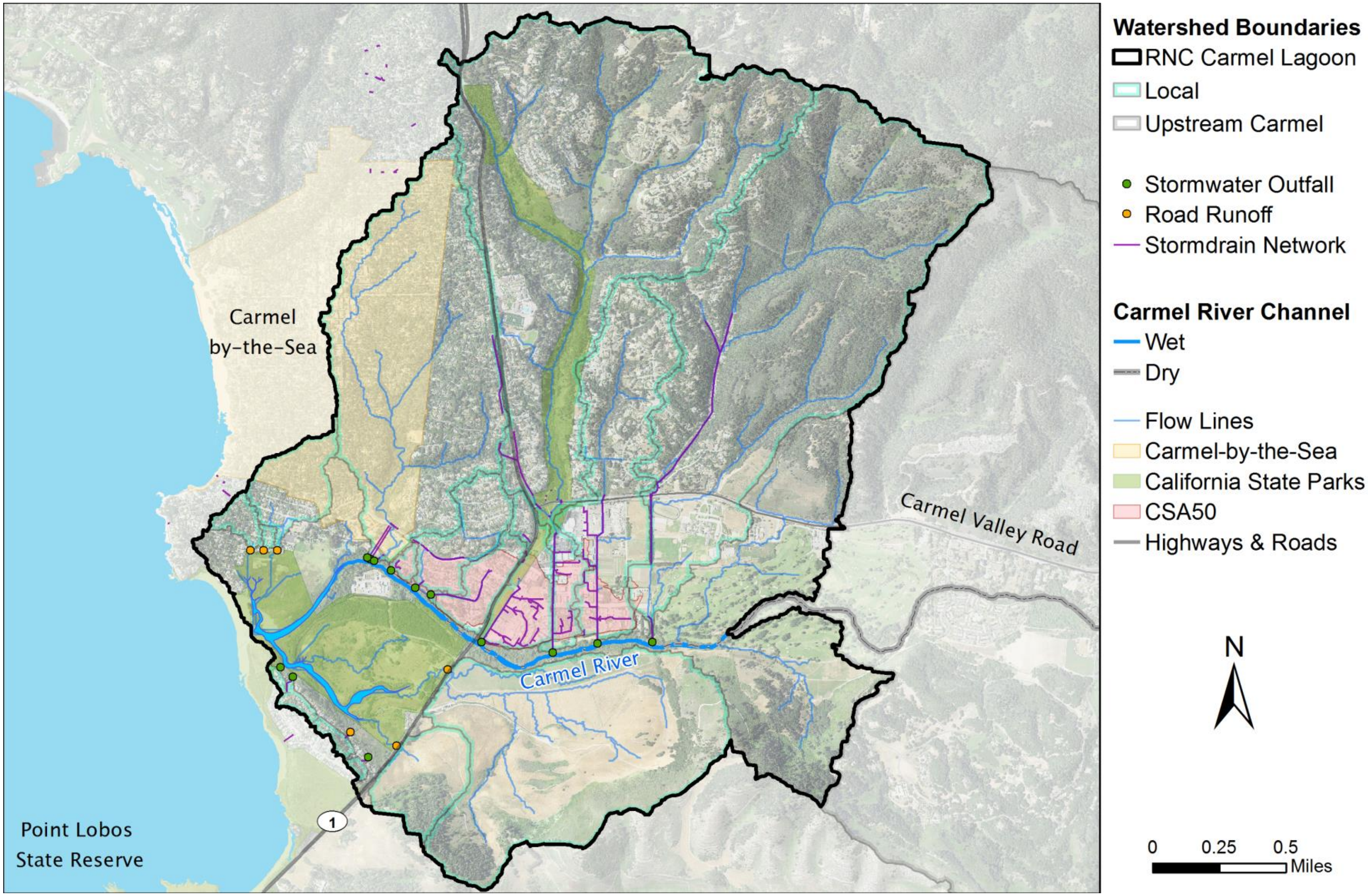

Figure 15. RNC-CRL Watershed and major subwatersheds from stormdrains and road ends.

7.2 Runoff Model

We modeled local runoff into the RNC-CRL Watershed to determine the contribution of local surface water to freshwater in the lagoon. We used the U.S. Army Corp of Engineers Hydrologic Engineering Center-Hydrologic Modeling Software (HEC-HMS) to estimate the volume of precipitation converted to runoff (USACE 2015). We modeled 10 different hypothetical storm events with precipitation depths ranging from 0.25-3.0 inches.

We compared several approaches to the HEC-HMS RNC-CRL Watershed model including: 1) a Single Curve Number (SCN) model with runoff regulated by a single weighted-average SCS curve number (CN), 2) a Multiple-subwatershed Curve Number (MCN) model with a separate CN for each watershed, and 3) an Impervious Area (IA) model with runoff determined by the mapped percentage of impervious ground. For Approach 1, we generated a mean CN for the entire RNC-CRL Watershed using soil type and land cover, based on the Soil Conservation Service methodology (CCRWQCB 2016; Cronshey *et al.* 1986; USGS 2011). We determined a composite CN by calculating an area weighted average CN for the RNC-CRL Watershed based on HSG soil type and NLCD raster pixel values (Tables 4 & 5, USGSa 2011). For Approach 2, we created a composite CN for each outfall watershed using the TR-55 Report methodology. For Approach 3, we calculated the average percentage impervious ground for the RNC-CRL Watershed from the NLCD Percent Developed Imperviousness raster using Zonal Statistics in ArcGIS (USGSb 2011). We configured HMS to estimate runoff using the rational method, where runoff is a constant fraction of precipitation, as determined by the mapped percentage of impervious ground (Boulos *et al.* 2006).

We modeled a 24-hour, Type 1 storm event in the RNC-CRL Watershed (Table 6, SCS 1972). A high CN translates to more runoff potential; if the CN is 100, then 100% of precipitation is converted to runoff. If the CN is less than 100, then some initial precipitation is "lost" before it is converted to runoff.

We calculated lagoon stage increase by dividing estimated runoff (ac-ft), provided by HEC-HMS modeling, by an assumed lagoon surface area of 32.79 acres. We calculated surface area by finding the average stage (5.48 ft) during 14 RNC events in which lagoon stage increased after precipitation and computing the derivative of an exponentiated polynomial fit to volume-vs-stage (Table 7, Fig. 16). Section 6.1 includes a more detailed explanation of calculating lagoon volume from stage.

Table 4. Summary of watershed characteristics for 18 subwatersheds that drain into the Carmel River Lagoon during the RNC period. Refer to Figure 15 for map of watershed.

Watershed	Area (mi^2)	Area (acres	% of total RNC area	CN	Ave. imperv.	Impervious area (acres)	MAP (in/yr	HSG (acres) A	B	C	D	NA
1	0.666	426.0	11.2%	71	1.3%	5.3	17.9	4.9	135.9	188.5	96.9	0.0
2	0.105	66.9	1.8%	77	47.0%	27.4	17.0	0.0	2.1	25.4	39.3	0.0
3	0.005	3.0	0.1%	85	47.8%	3.2	16.0	0.0	0.0	0.0	3.0	0.0
4	0.010	6.3	0.2%	86	27.3%	1.7	16.0	0.0	0.0	0.0	6.3	0.0
5	0.010	6.6	0.2%	90	27.4%	16.0	16.9	0.0	0.0	0.0	6.5	0.0
6	0.004	2.7	0.1%	80	32.1%	11.9	17.0	0.0	1.1	0.0	1.6	0.0
7	0.022	14.2	0.4%	56	10.2%	86.4	19.5	14.4	0.0	0.0	0.0	0.0
8	0.005	3.0	0.1%	43	24.9%	53.3	17.7	3.0	0.0	0.1	0.0	0.0
9	0.087	55.5	1.5%	53	3.6%	27.9	18.9	54.9	0.0	0.1	0.0	0.0
10	0.717	458.6	12.1%	69	31.8%	2.0	16.6	74.5	202.0	87.8	95.2	0.0
11	0.009	6.1	0.2%	71	27.3%	0.8	17.0	0.0	6.0	0.0	0.0	0.0
12	0.091	58.2	1.5%	80	0.7%	0.5	17.4	0.0	20.8	9.4	27.6	0.0
13	0.058	37.1	1.0%	74	26.9%	14.9	16.1	0.0	34.3	2.5	0.4	0.0
14	0.091	58.2	1.5%	78	46.2%	1.4	16.0	16.9	31.0	5.6	4.6	0.0
15	1.327	849.2	22.4%	72	27.9%	4.0	16.0	15.5	153.4	642.7	35.5	1.3
16	0.335	214.2	5.6%	76	16.8%	77.0	17.7	24.6	35.3	131.5	22.4	0.4
17	1.208	773.0	20.4%	76	31.7%	0.8	16.0	4.1	32.5	663.5	73.4	0.2
Direct to lagoon	1.177	753.4	19.9%	64	5.7%	42.7	17.1	157.9	176.5	260.4	126.7	32.7
Totals	5.925	3792.1	100.0%	70	9.9%	376.9	17.0	370.7	830.9	2017.4	539.4	34.7

Table 5. Summary of land cover by outfall watershed. Land cover codes: DO, developed open space; DL, developed low intensity; DM, developed medium intensity; DH, developed high intensity; EF, evergreen forest; MF, mixed forest; DF, deciduous forest; SS, shrub/ scrub; H, herbaceous; WW, woody wetlands; EH, emergent herbaceous wetlands; CC, cultivated crops; HP, hay/ pasture; OW, open water; BL, barren land. Totals are land cover values for the entire RNC-CRL Watershed.

	Land use & land cover (acres)														
Watershed	DO	DL	DM	DH	EF	MF	DF	SS	H	WW	EH	CC	HP	OW	BL
1	6.7	4.9	4.4	0.0	30.9	75.6	0.0	50.5	145.9	16.7	0.0	92.1	0.0	0.0	0.0
2	4.0	0.0	0.0	0.0	24.0	8.9	0.0	0.4	29.4	0.0	0.0	0.0	0.0	0.0	0.0
3	1.1	1.1	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	2.2	2.9	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.2	2.0	3.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.4	0.9	0.9	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0
7	3.3	10.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	1.8	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	22.2	28.9	3.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	276.9	109.4	21.1	0.0	51.6	0.0	0.0	0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0
11	1.1	4.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	18.2	39.8	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13	8.9	24.0	5.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	10.0	18.7	23.8	5.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	388.3	118.1	24.5	4.2	284.7	8.2	2.4	8.2	8.2	4.9	0.0	0.0	0.0	0.0	0.0
16	95.9	55.2	36.3	3.1	16.9	0.0	0.0	0.0	8.2	0.4	0.0	0.0	0.0	0.0	0.0
17	151.7	23.1	14.2	0.0	448.3	14.9	0.0	78.5	44.0	2.9	0.0	0.0	0.0	0.0	0.0
Direct to lagoon	142.1	63.8	18.5	0.4	97.0	52.3	2.4	62.5	213.7	42.7	26.0	11.6	12.9	10.2	2.4
Total	1133.3	509.5	159.9	13.3	953.4	159.9	4.9	200.2	451.5	67.6	26.0	103.6	12.9	10.2	2.4

Table 6. Model parameters used to simulate runoff in the RNC Carmel River Lagoon Watershed for Approaches 1-3: single watershed runoff model using curve number (SCN), multiple subwatershed runoff model using curve number (MCN), and impervious area runoff model (IA).

Parameter	**Method**		**Model Approach**		
			1. SCN	2. MCN	3. IA
Drainage		Area (mi2)	5.93	variable	5.93
HEC- HMS 'Loss'	SCS Curve Number	Initial Abstraction (in)		0	
		Curve Number	70	variable	0
		Impervious (%)	0	0	9.9
SCS Storm	Type 1	Depth (in)		increments (0.25")	
Runoff Transformation	SCS Unit Hydro Graph	Graph Type		Standard PRF 484	
		Lag Time (min)		100	

Estimated stage increases were of the same order of magnitude as observed stage increases. The IA model estimated a higher, linear runoff potential while the SCN and MCN models underestimated stage height increase until 1.75 in of precipitation (Table 7 & 8, Fig. 16). The general concurrence between modeled and observed changes provided further evidence that observed lagoon stage increases during the dry-river season were a result of runoff events, and established a mechanism for quantitatively linking lagoon dynamics to watershed processes.

Although it was encouraging that model results bracketed observed stage increases, the disagreement among respective modeling approaches and between models and observed lagoon stage leaves substantial room for improvement in model accuracy. A better runoff model might use 50% of the mapped IA instead of the CN (Fig. 16). Disagreements between model results and observed increases in lagoon stage could be a result of the assumption that increases were only affected by precipitation events and our use of a single stage-surface area-volume curve for all events in Figure 16 B and a single surface area for Figure 16 C.

A more accurate model could incorporate the effects of:

- wave action and tide,
- sandbar elevation,
- saltwater intrusion through the sandbar,
- groundwater exfiltration,
- more accurate mapping of IA,
- a Soil Moisture Accounting (SMA) approach to modeling,

- collection of actual runoff data, in order to calibrate the runoff model directly, and not via an indirect relationship with lagoon stage (Watson *et al.* 2016), and
- antecedent conditions before events when estimating runoff.

Table 7. Modeled runoff volumes for the CRL Watershed generated using the SCS Storm method and three model configurations: multiple curve number (MCN), single curve number (SCN), and impervious area (IA) models. Potential increases in freshwater depth assumed that the surface area of the lagoon was 32.79 acres.

Precipitation (in)	Runoff (in)			Runoff Volume (ac-ft)			Lagoon Height Increase (ft)		
	MCN	SCN	IA	MCN	SCN	IA	MCN	SCN	IA
0.25	0.00	0.00	0.02	0.00	0.00	7.70	0.00	0.00	0.23
0.50	0.00	0.00	0.05	0.00	0.00	15.30	0.00	0.00	0.47
0.75	0.00	0.00	0.07	0.60	0.00	23.20	0.02	0.00	0.71
1.00	0.02	0.00	0.10	5.20	1.10	30.90	0.16	0.03	0.94
1.25	0.05	0.03	0.12	16.20	9.30	38.60	0.49	0.28	1.18
1.50	0.11	0.08	0.15	33.70	24.40	46.30	1.03	0.74	1.41
1.75	0.18	0.14	0.17	57.00	45.50	54.00	1.74	1.39	1.65
2.00	0.27	0.23	0.20	85.40	71.70	61.70	2.60	2.19	1.88
2.25	0.37	0.32	0.22	118.00	102.40	69.50	3.60	3.12	2.12
2.50	0.49	0.43	0.24	154.50	137.00	77.20	4.71	4.18	2.35
2.75	0.61	0.55	0.27	194.20	175.10	84.90	5.92	5.34	2.59
3.00	0.75	0.68	0.29	236.90	216.20	92.60	7.22	6.59	2.82

Table 8. Runoff generated by subwatershed for a 1-inch storm event.

				IA		MCN		SCN
Watershed	**Area (mi^2)**	**Area (acres)**	**% total RNC Area**	**Runoff Volume (ac-ft)**	**Relative to total (%)**	**Runoff Volume (ac-ft)**	**Relative to total (%)**	**Runoff Volum (ac-ft)**
1	0.67	426.0	11.2%	0.5	1.6	0.2	3.8	
2	0.10	66.9	1.8%	0.0	0.0	0.2	3.8	
3	0.00	3.0	0.1%	0.1	0.3	0.0	0.0	
4	0.01	6.3	0.2%	0.2	0.6	0.1	1.9	
5	0.01	6.6	0.2%	0.3	1.0	0.2	3.8	
6	0.00	2.7	0.1%	0.1	0.3	0.0	0.0	
7	0.02	14.2	0.4%	0.3	1.0	0.0	0.0	
8	0.00	3.0	0.1%	0.1	0.3	0.0	0.0	
9	0.09	55.5	1.5%	1.2	3.9	0.0	0.0	
10	0.72	458.6	12.1%	6.3	20.3	0.1	1.9	
11	0.01	6.1	0.2%	0.1	0.3	0.0	0.0	
12	0.09	58.2	1.5%	1.3	4.2	0.4	7.7	
13	0.06	37.1	1.0%	1.0	3.2	0.1	1.9	
14	0.09	58.2	1.5%	2.2	7.1	0.3	5.8	
15	1.33	849.2	22.4%	7.1	22.9	0.7	13.5	
16	0.33	214.2	5.6%	4.4	14.2	0.6	11.5	
17	1.21	773.0	20.4%	2.3	7.4	2.3	44.2	
Direct to Lagoon	1.18	753.4	19.9%	3.5	11.3	0.0	0.0	
Totals	**5.93**	**3792.1**	**100.0%**	**31.0**	**100.0**	**5.2**	**100.0**	**1.**

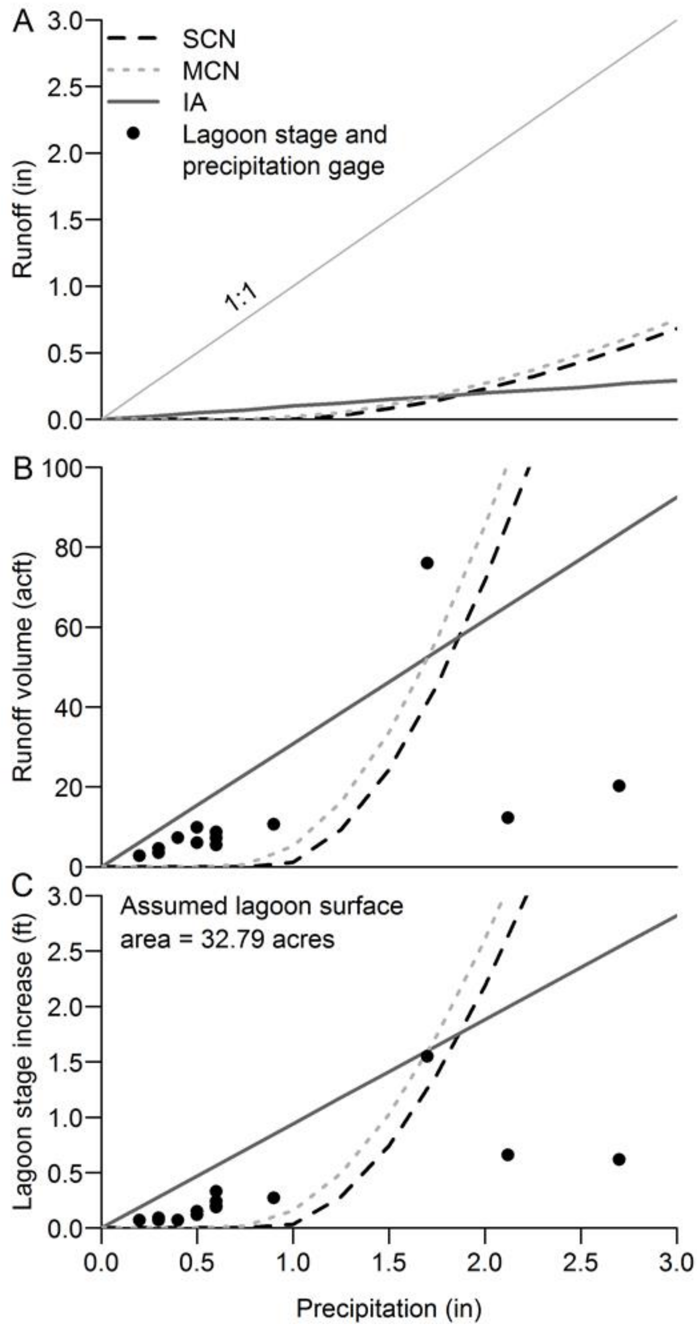

Figure 16. Estimated and observed changes in lagoon water level resulting from individual precipitation events. Modeled stage increases matched the order of magnitude of observed increases: the IA model approach over-predicted the stage increase and the CN model approaches under-predicted stage increases for smaller events and over-predicted them for larger events. Observed lagoon stage and precipitation data are from Table 3, Section 6.2.

7.3 Water Quality Model

We modeled the way in which the addition of surface runoff would influence the freshwater layer in the RNC-CRL when the surface waters were saline (i.e. not optimal for steelhead). We selected dates during the RNC season where surface salinity was near or greater than 10 ppt (Alley 1996). We averaged estimated stage increase from the MCN and IA models for 1 and 2-inch storm events and assumed that local runoff would only mix with the layer above the halocline.

To model the addition of runoff to the lagoon, we augmented historical salinity profiles with estimated runoff volumes and calculated the resulting change in salinity and thickness of the surface layer. We defined the surface layer as comprising all water above the halocline, which in turn was subjectively defined as the point at which salinity increased suddenly. Then we divided the surface layer into sub-layers represented by each of the measurements that occurred within the surface layer. The top sub-layer was assumed to be 12.5 cm thick, and the lower sublayers were assumed to be 25 cm thick (Fig. 17). We used the following equation to augment each salinity measurement above the halocline:

$$S_1 = \frac{S_0 \times T_0}{T_0 + T_A}$$

where S_1 is augmented salinity, S_0 is initial salinity, T_0 is initial thickness of the sample's freshwater layer, and T_A is the augmentation of freshwater to that layer (Fig. 17). Full derivation of the equation can be found in Appendix D.

The estimated effect of freshwater additions on the salinity of surface layers was substantial (Fig. 18). Salinity on Sept-2009 and Dec-2012 was near or above 10 ppt at the surface initially and was reduced by 2.82 and 3.92 ppt respectively after modeling a 2-inch storm event. This provides one explanation of how the lagoon recovered to fresh levels after historical wave overwash events and it gives us the ability to estimate future benefits to the lagoon from quantified changes in runoff management (Fig. 9).

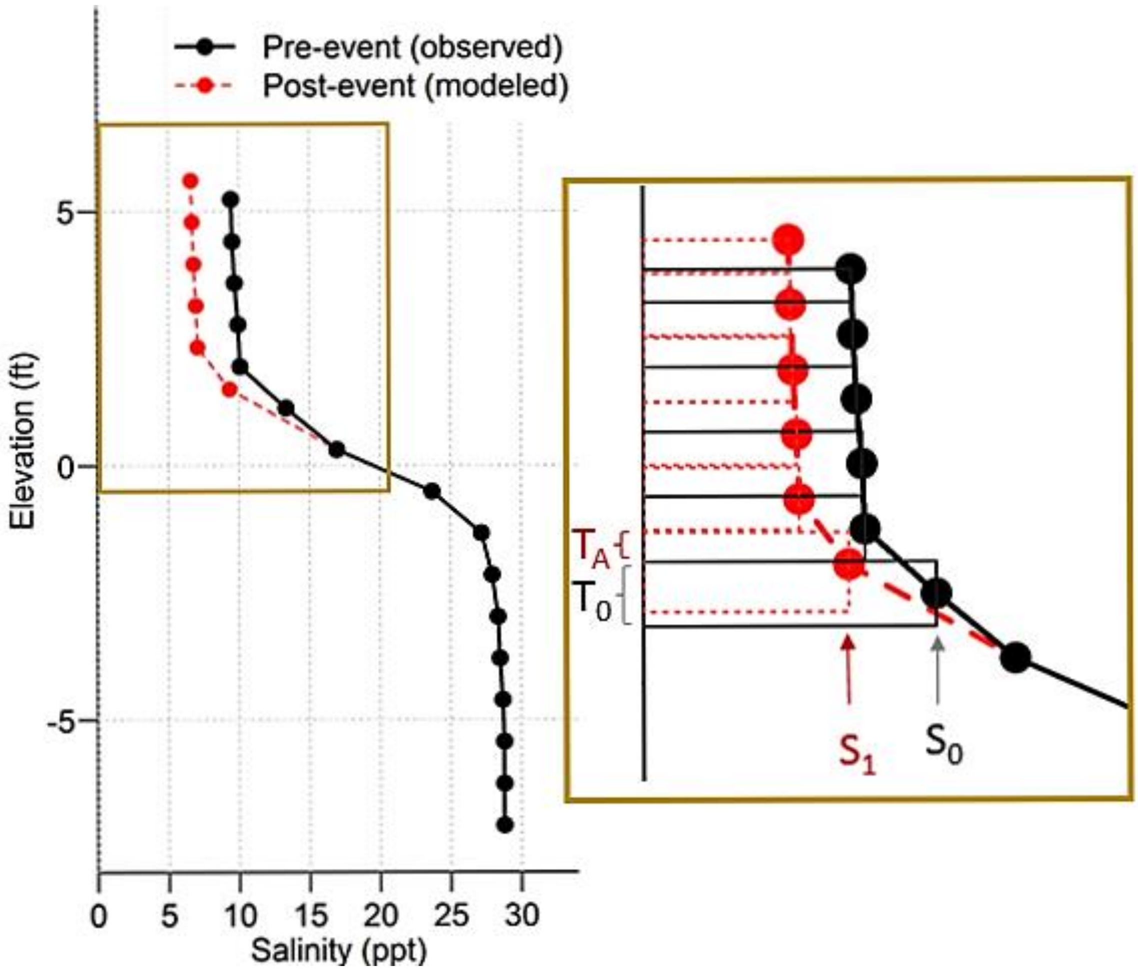

Figure 17. Predicted effect of freshwater runoff augmentation on salinity profiles in the Carmel River Lagoon. This diagram explains the spatial structure of the WQ model. See Appendix D for derivation.

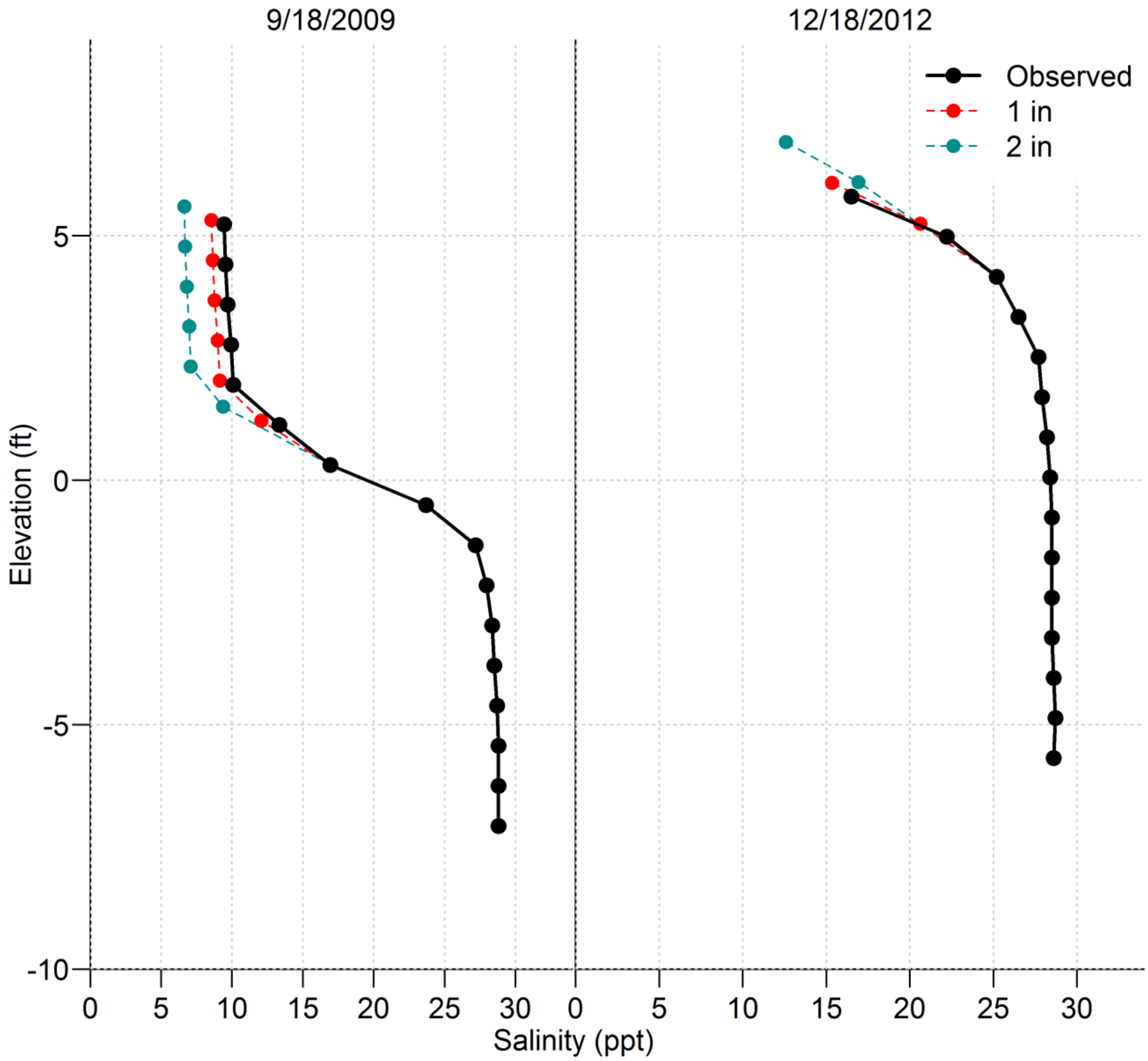

Figure 18. Observed pre-rain and modeled post-rain salinity profiles for 1 and 2-inch precipitation events.

8 Integration

The purpose of this study was to determine whether local runoff had any influence on lagoon WQ during RNC conditions. We approached the problem by addressing the following questions:

- Do current historical WQ data show any positive responses following precipitation events?
- Is there a noticeable increase in lagoon stage after precipitation events?
- How large is the lagoon's effective watershed during RNC conditions and what is the propensity for runoff to be generated from this area based on land cover and soil type?
- Are local watershed runoff sources hydraulically connected to the lagoon during RNC conditions?
- How does a given watershed runoff volume translate into changes in water level and WQ in the lagoon?

Water quality in the CRL did not positively respond to the rain event on Oct 28th 2016; however, historic records show there are instances where local runoff increases lagoon freshwater. We determined that the increased salinity on Oct 28th 2016 was due to wave overwash, which diminished the impact of local runoff on lagoon WQ. Freshwater inputs are still valuable by way of mitigating the amount of salination that occurs in the CRL. Historical WQ records support this by showing instances in Mid-2009 and Late-2012 where conditions improved following precipitation (Fig. 10).

We looked at historical stage and precipitation and found 14 incidents when stage increased during precipitation events in a manner that was not readily attributable to Carmel River flow or wave events (Table 3, Fig. 12). This gave us direct evidence that local runoff has a measurable impact on the lagoon, even when the river is not connected. The magnitude of the influence of local runoff depended primarily on cumulative precipitation and initial lagoon stage.

We determined the effective area of the CRL Watershed during RNC as 3792 acres with 377 acres as impervious area. Using this approximated area, we created surface runoff models to predict the amount of runoff generated by specific precipitation events in the CRL Watershed and we corroborated predicted stage increases with historical data (Fig. 16). The ensemble of predictions by the three different approaches approximately matched runoff volume for a given precipitation event and effectively linked local runoff to specific watersheds and drainage pathways.

We then used the runoff models to show how precipitation events affect salinity. The models estimated runoff from 2- inches of precipitation can reduce critically high salinity levels by 2.8-3.9 ppt (Fig. 18). This provides one explanation of how the lagoon can recover to fresh levels after historical wave overwash events and it gives us the ability to estimate future benefits to the lagoon from quantified changes in runoff management.

8.1 Project Limitations

This study made simplifying assumptions to model changes in lagoon dynamics from stormwater runoff to the lagoon during the dry-river season. We used a single stage-surface area-volume curve and assumed a static surface area (32.79 acres) when surface area actually increased with lagoon stage (RMC 2007). Predictions of lagoon dynamics could be improved by collecting local runoff data to calibrate the runoff model directly, instead of through an indirect relationship with lagoon stage (Watson *et al.* 2016). In addition, effects of groundwater exfiltration were not incorporated into stage or WQ models. Models could be improved by studying the influence of adjacent freshwater sources on stage and salinity.

Our ability to accurately predict how local runoff affects lagoon WQ would be improved by integrating past and present research to create a more holistic model. Events such as wave overwash, saltwater intrusion through the sandbar, groundwater exfiltration, and fresh and saltwater mixing have been well documented (Casagrande *et al.* 2001 & 2002; Watson and Casagrande 2004; CSUMB Class ENVS 660). Further studies are needed to combine these interactions with local runoff.

8.2 Implications

All freshwater contributions to the CRL during times of poor WQ potentially aid in steelhead survival. The WQ model suggested that local runoff can shift salinity from critical to more favorable conditions, thereby improving steelhead survivorship in otherwise lethal circumstances. Steelhead are subject to predation by birds when the freshwater layer is thin and fish are forced to the surface (Alley 2014). Increases in lagoon stage submerge vegetation and woody debris, allowing fish to evade predators. The lagoon became so shallow during some RNC seasons that LWD installations in the south arm were exposed and essentially non-functional, therefore water sources that deepen the lagoon are important.

Increasing drought frequency is expected to prolong the RNC season and minimize groundwater exfiltration (Lake 2003); both will likely worsen WQ conditions for steelhead. These results imply local freshwater contributions to the lagoon have the potential to buffer impacts of climate change.

Other sources of runoff may have the potential to benefit lagoon WQ. At present, stormwater generated by the City of Carmel-by-the-Sea discharges into the Pacific Ocean in an Area of Special Biological Significance (ASBS) Watershed Protection Area. Diversion of this runoff to the lagoon would help to augment the lagoon freshwater layer. Future population growth will lead to additional impervious surfaces and potentially a more significant runoff contribution during RNC conditions.

Local runoff, though a valuable freshwater source, can be contaminated with pollutants that may detriment the CRL. Past studies have shown that urban runoff could contain a variety of harmful pollutants such as sediments, nutrients, pathogens, petroleum hydrocarbons, heavy metals, polycyclic aromatic hydrocarbons (PAHs), pesticides, and herbicides which could degrade an already stressed habitat and create toxic environments for steelhead (SWRCB 2012). The runoff models identified CRL subwatersheds with the highest runoff potential, providing managers with a tool to focus contaminant mitigation efforts.

Polluted runoff can be mitigated by various treatment options. Treatment wetlands and runoff diversions to the CAWD water treatment facility are two plausible options to remove pollutants from surface runoff in the CRL Watershed. Artificial treatment wetlands have been shown to effectively remove certain pollutants in stormwater (Tanner and Headley 2011). Also, dense wetland vegetation in the northern portion of the lagoon could ameliorate poor WQ by removing pollutants from runoff at road drains that currently goes untreated.

Resource management agencies in the area should consider the implications of altering watershed processes on lagoon dynamics. Any local project which changes the local hydrology has the potential to increase or decrease freshwater availability within the lagoon. Overall annual and seasonal variation in lagoon health should be taken into account when designing and implementing projects within the RNC-CRL Watershed.

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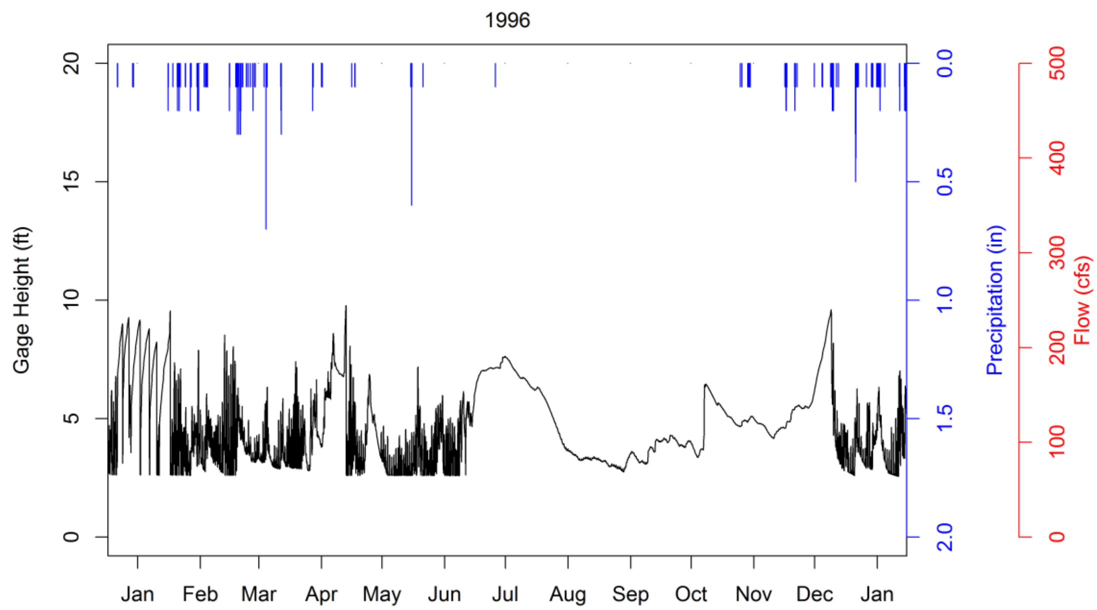
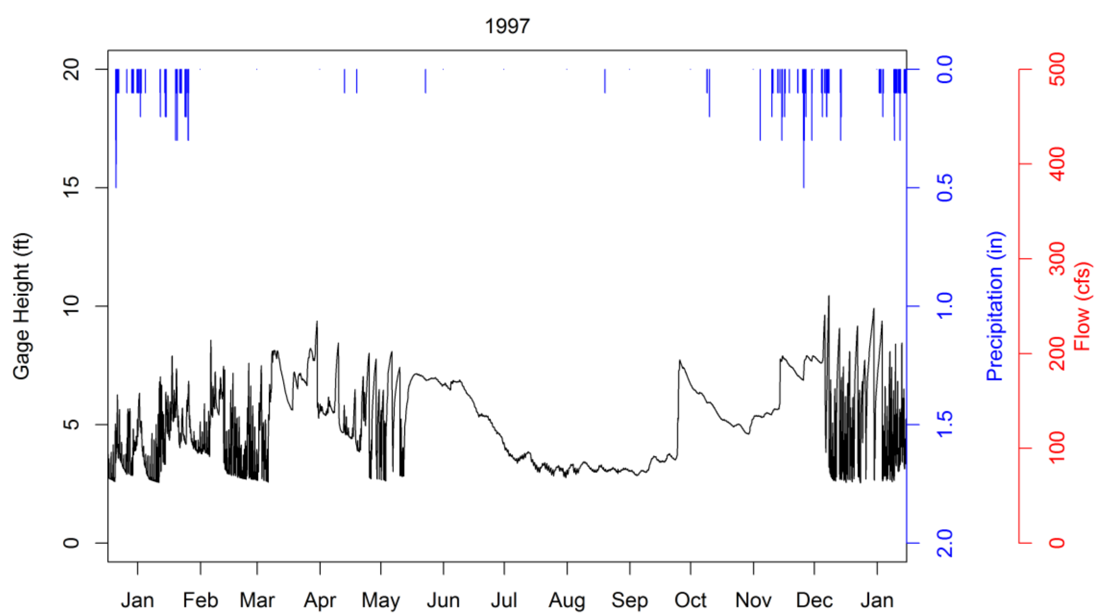
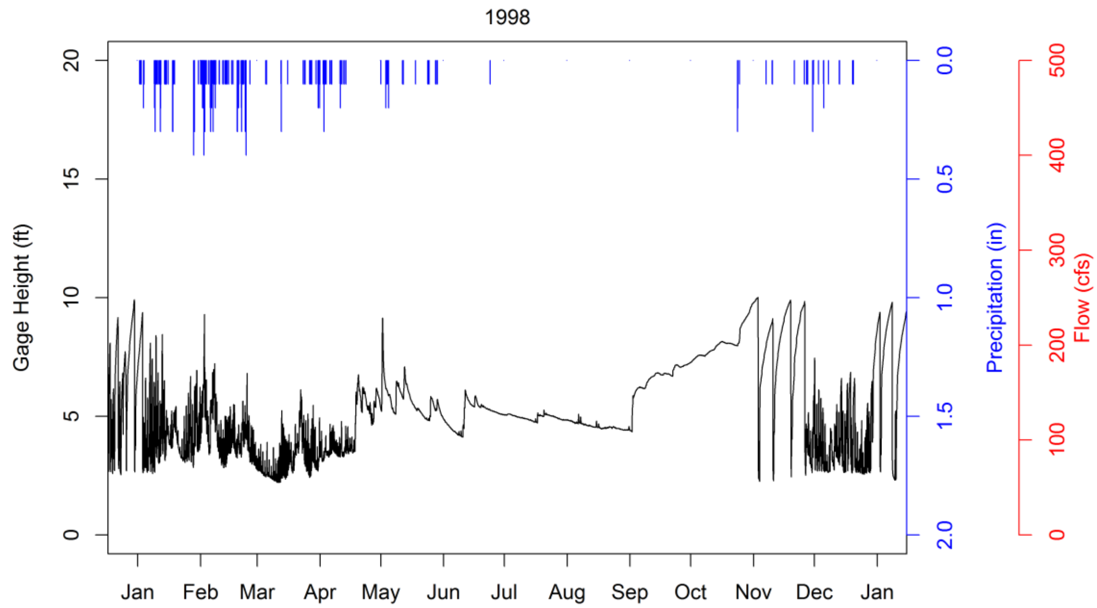
10 Appendix A: Carmel River Lagoon Stage and Precipitation

Annual CRL water level height (ft) compared with precipitation (in) and river discharge (cfs).



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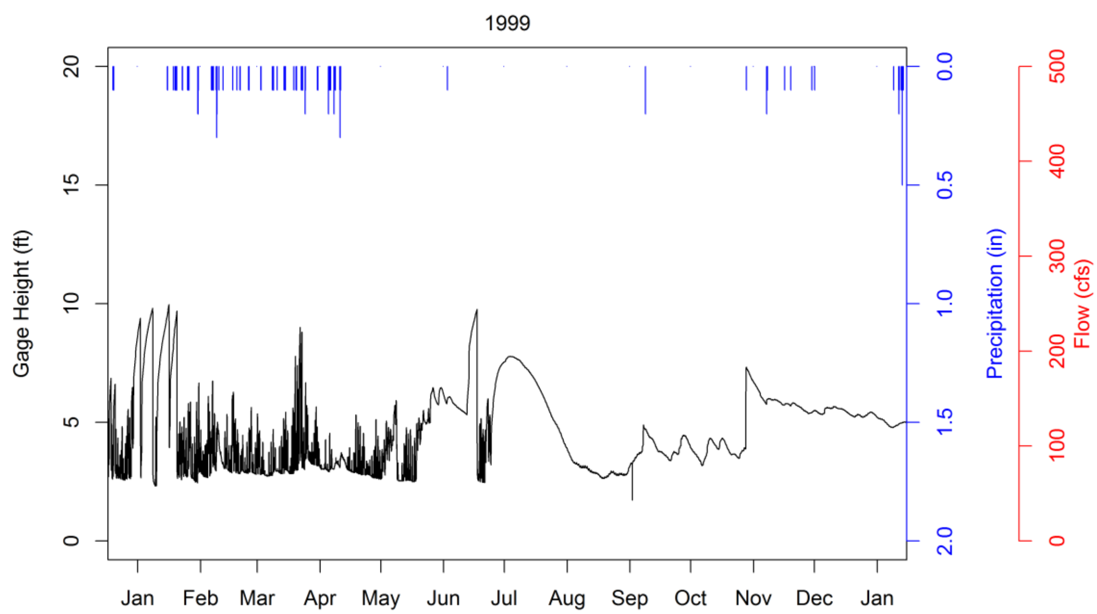
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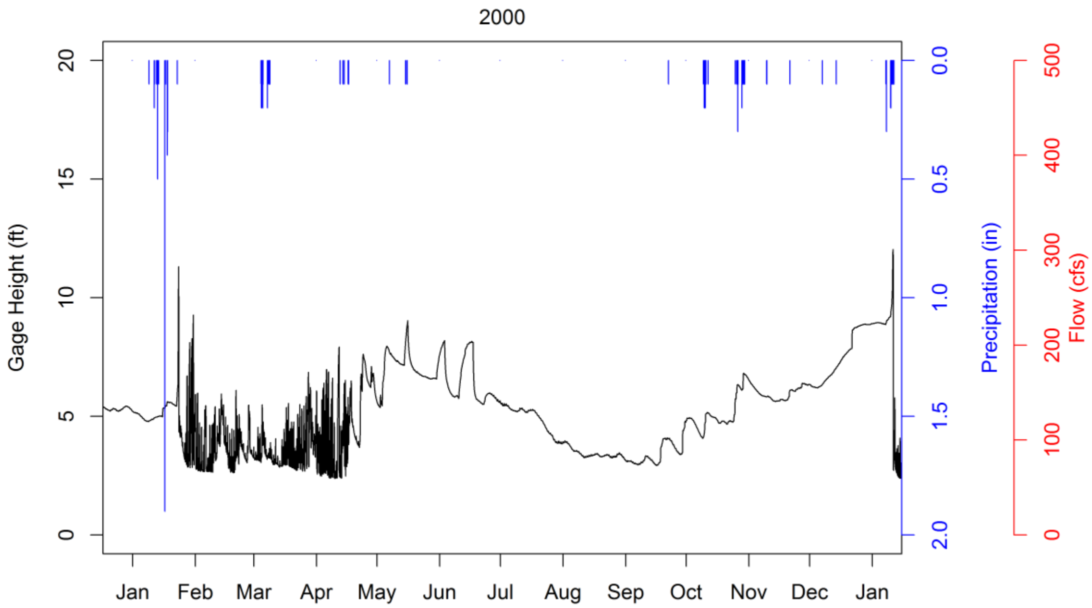
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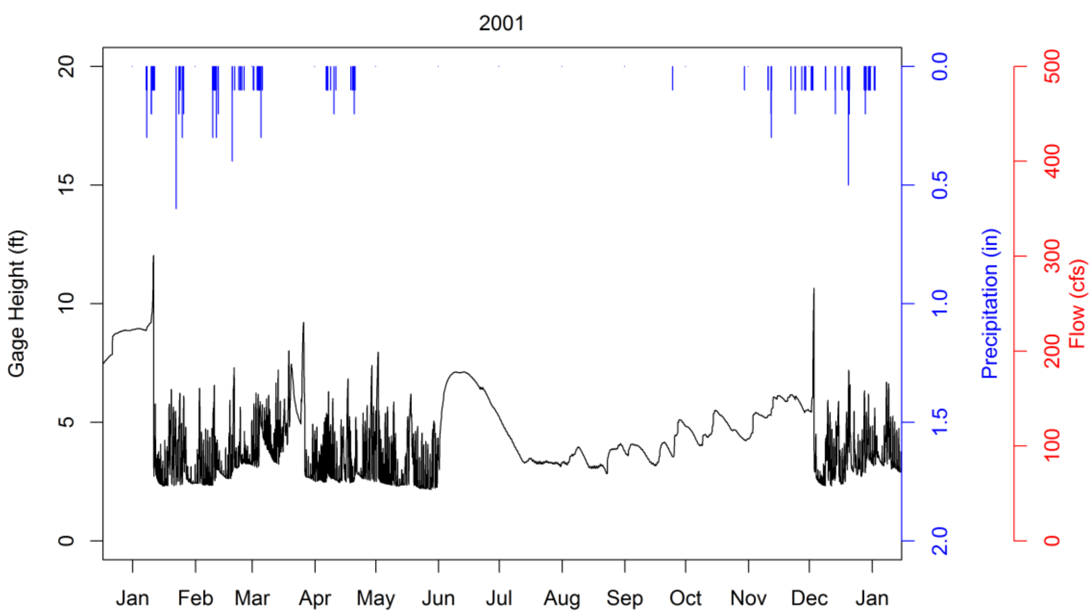
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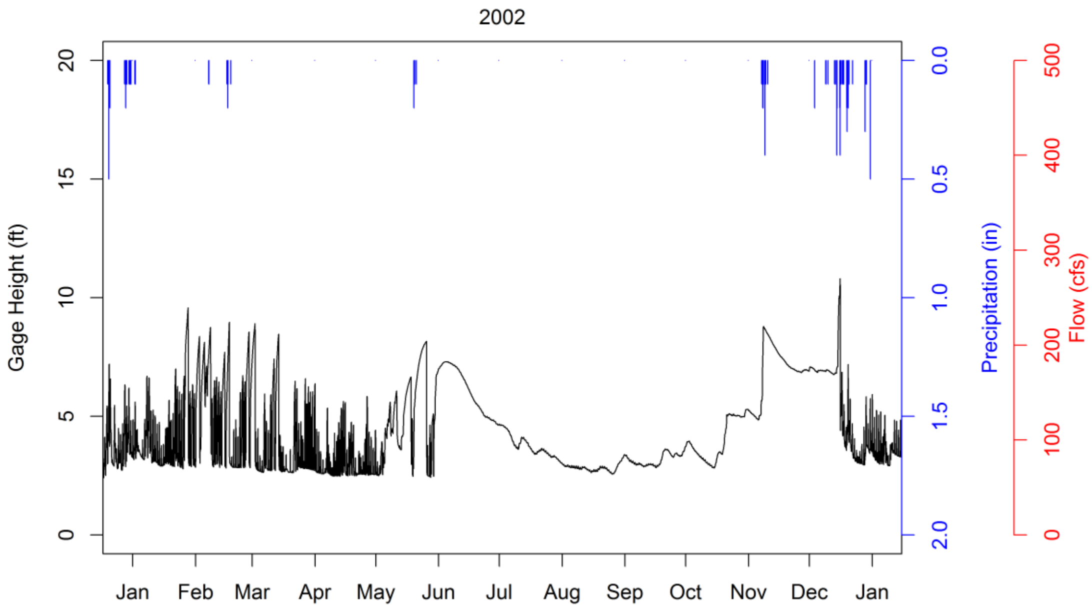
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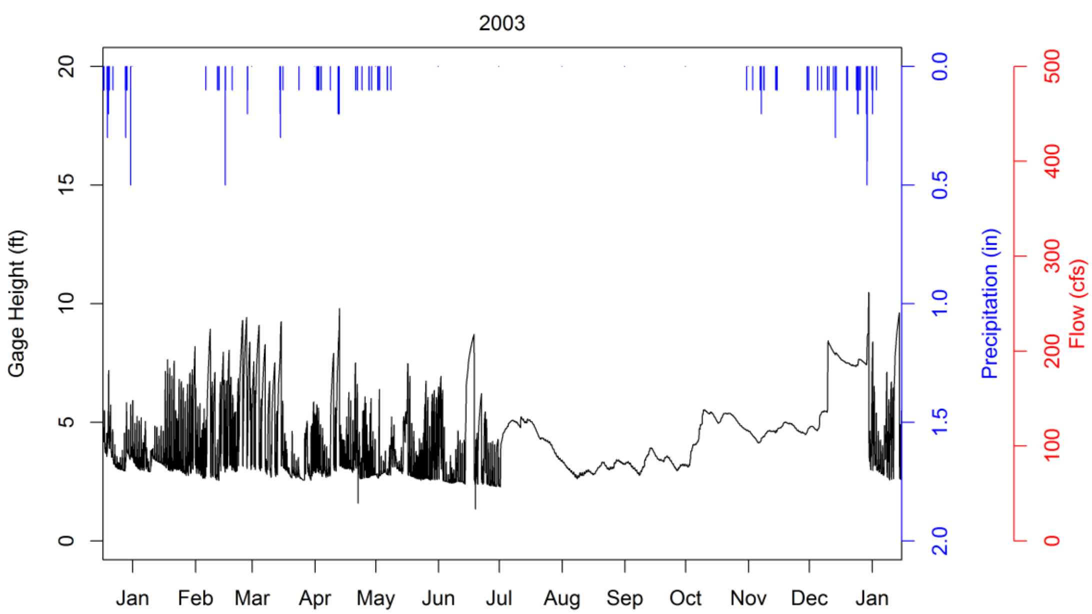
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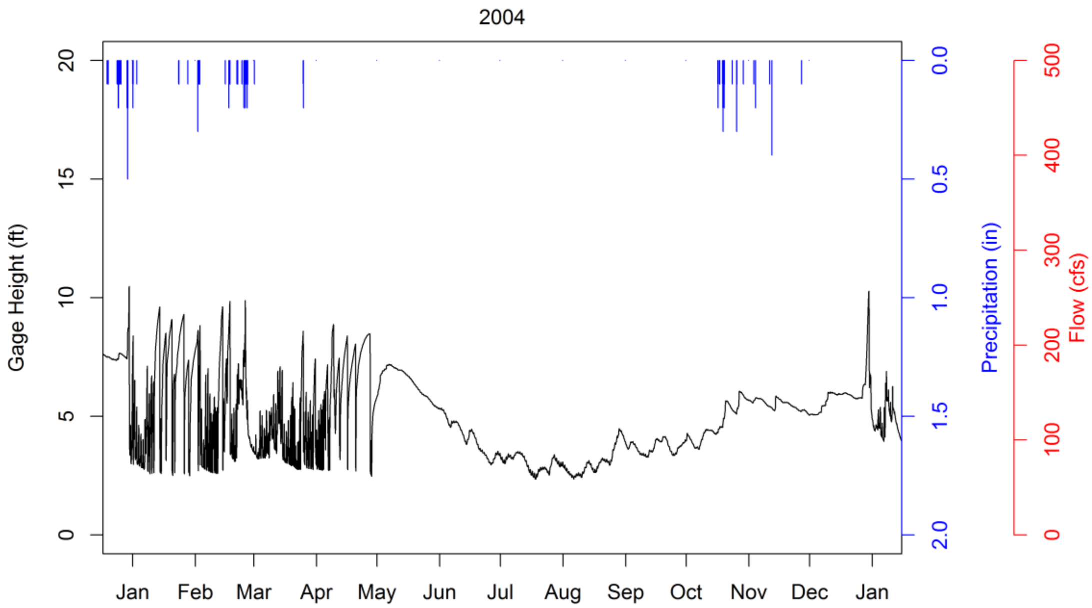
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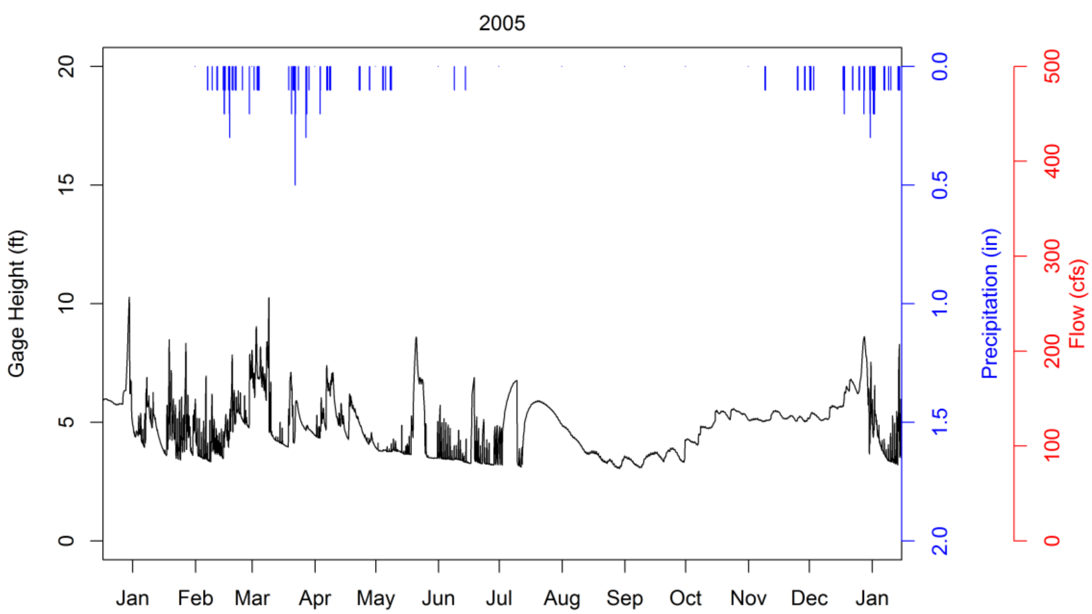
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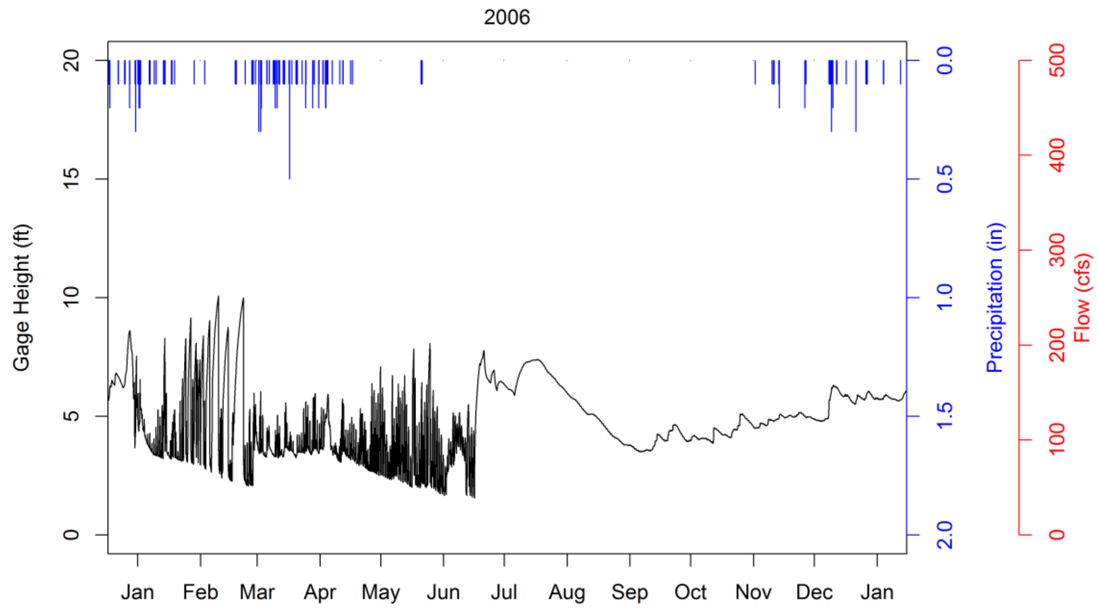
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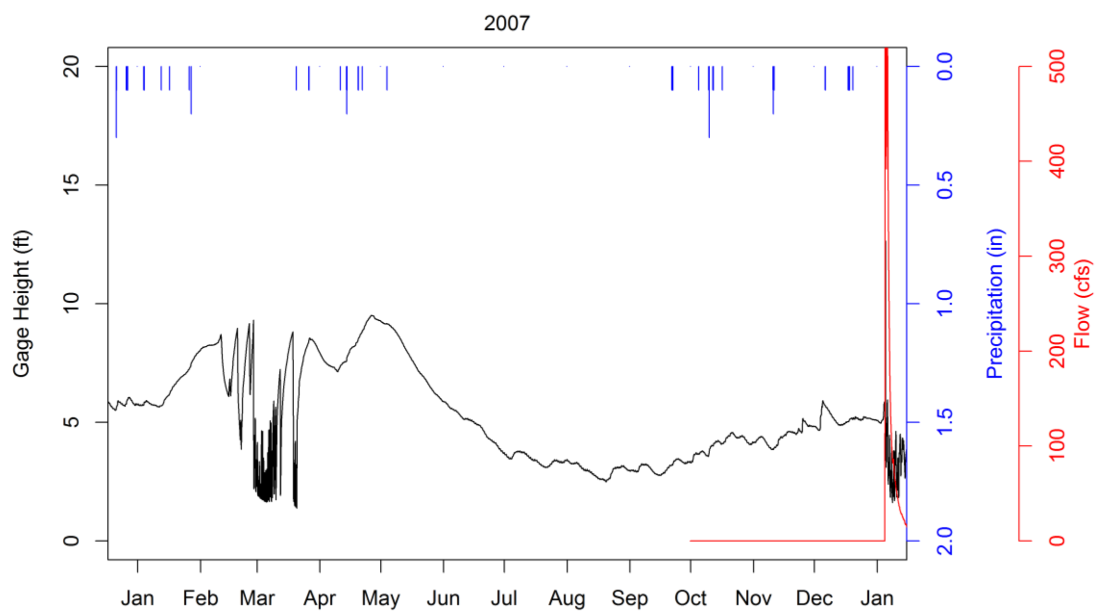
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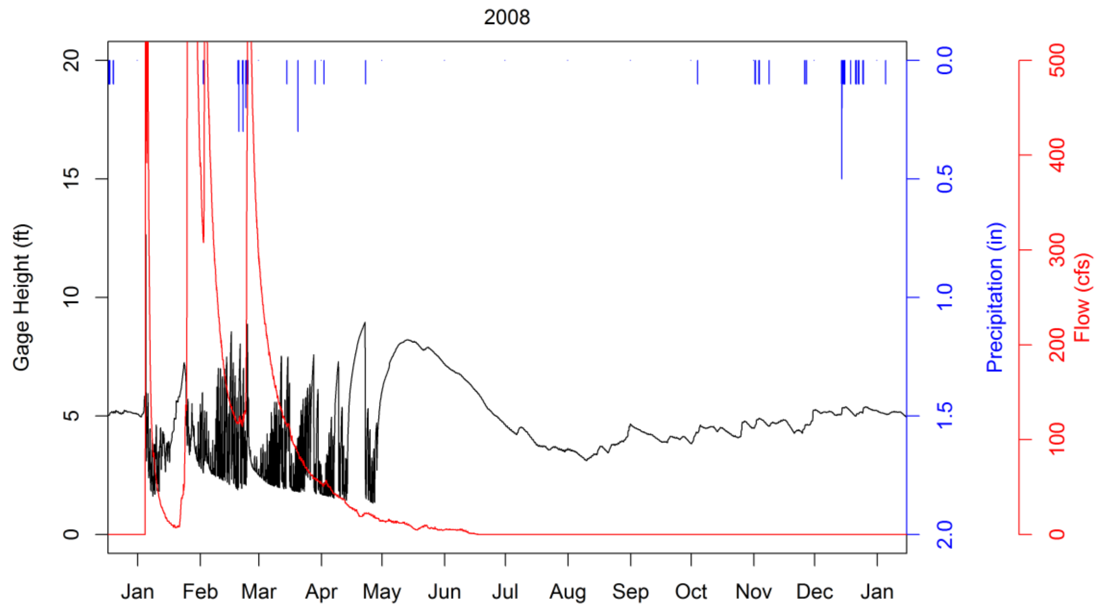
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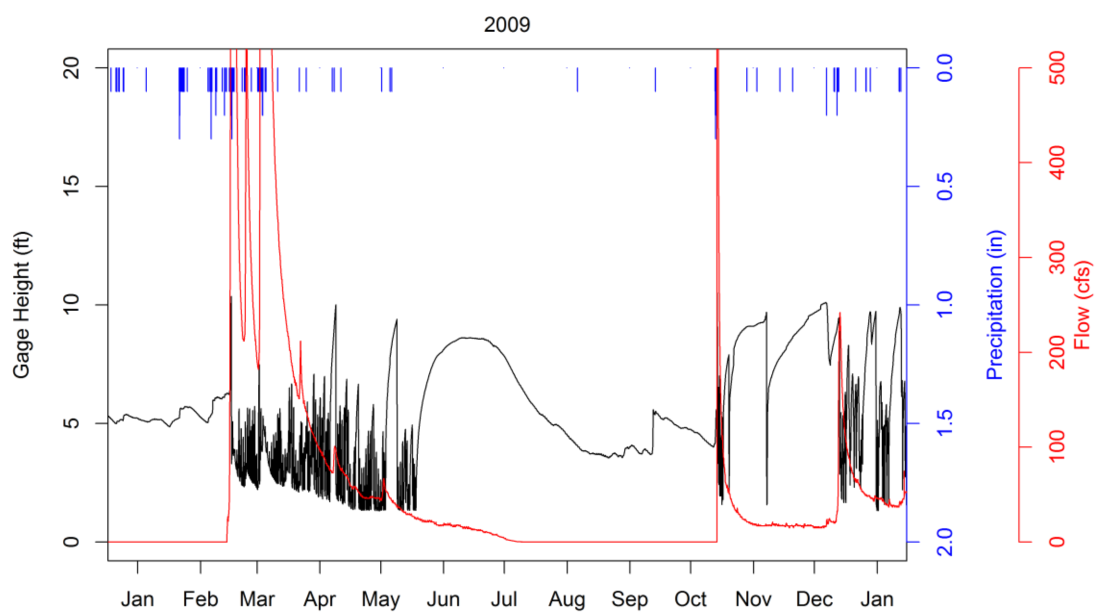
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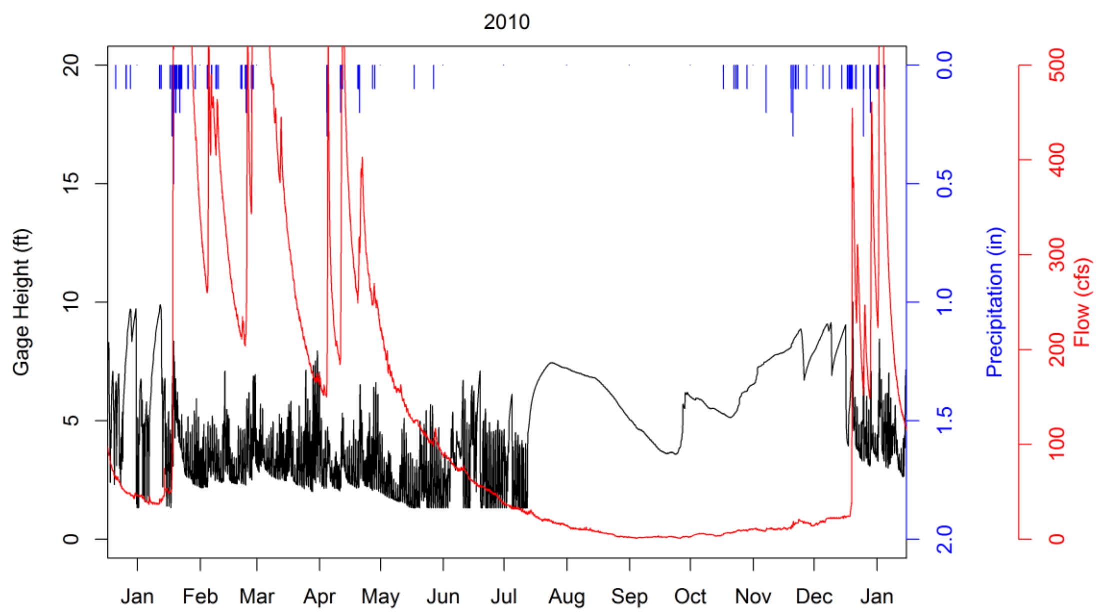

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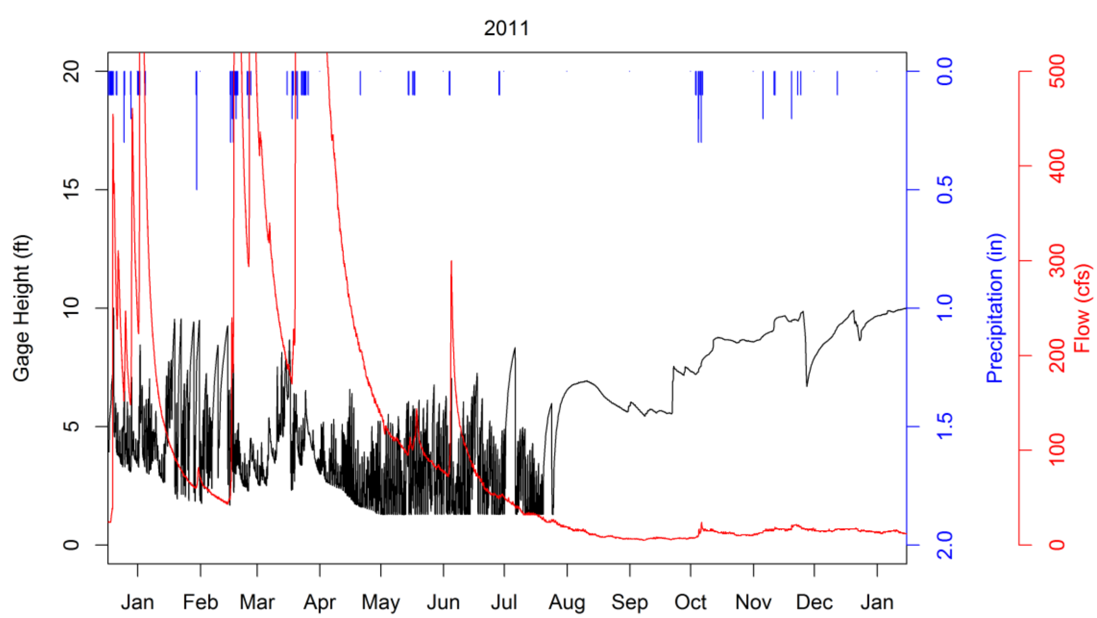

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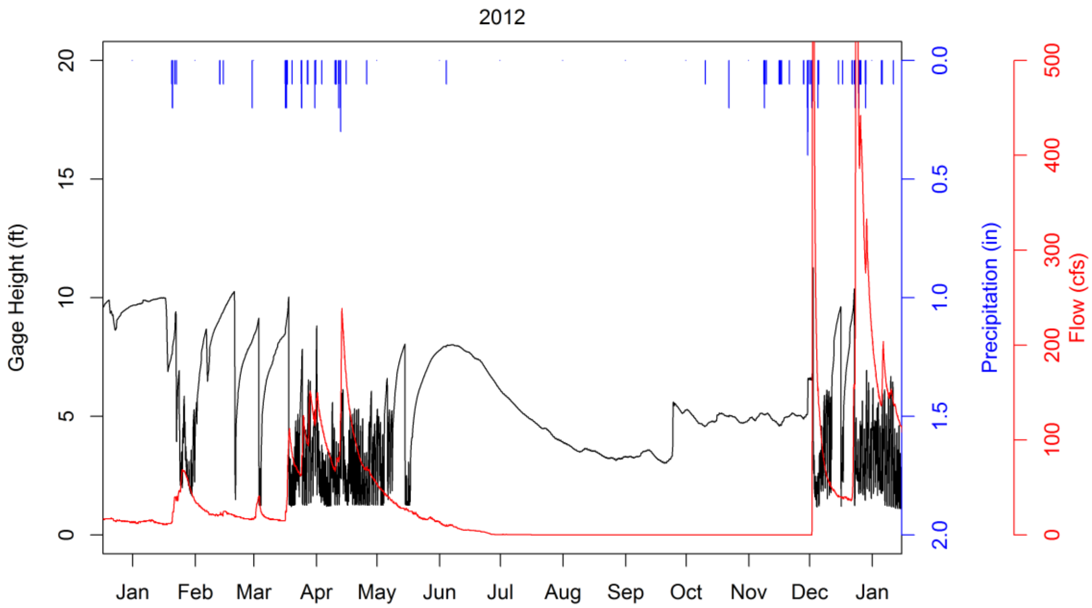
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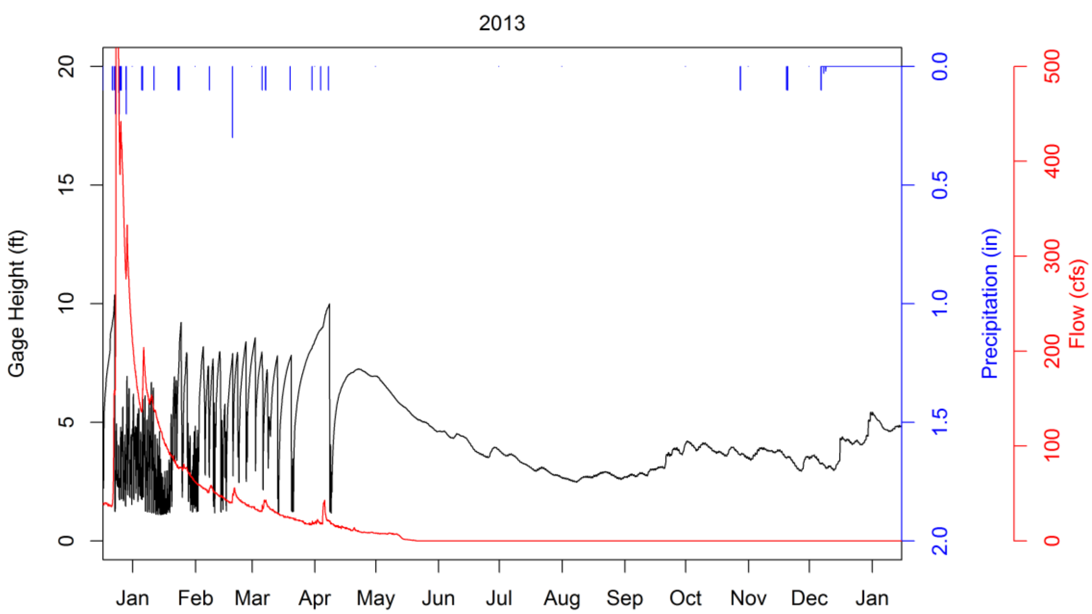
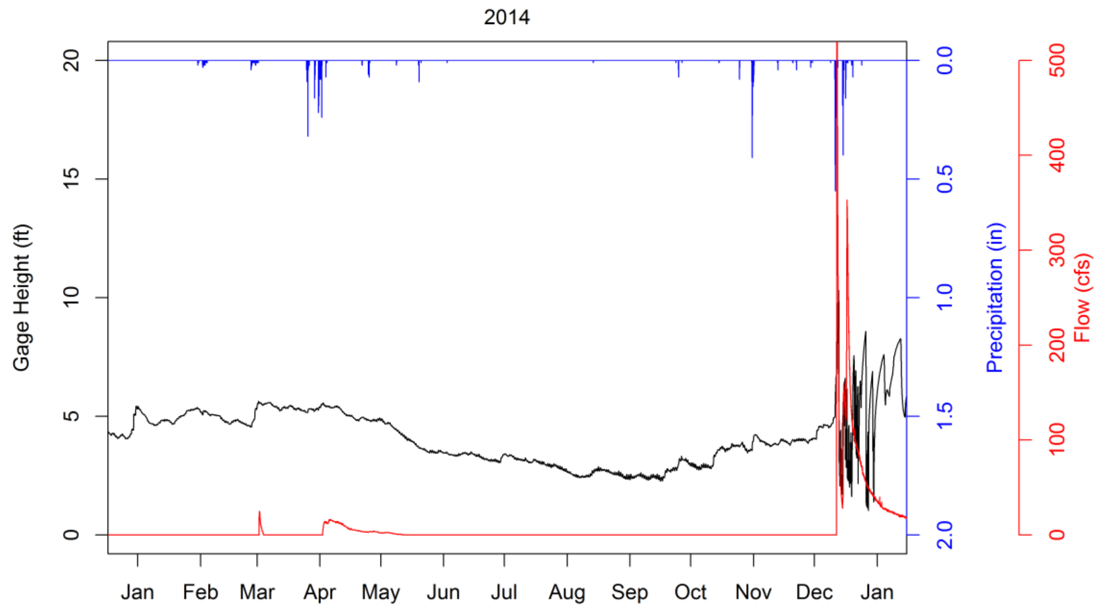
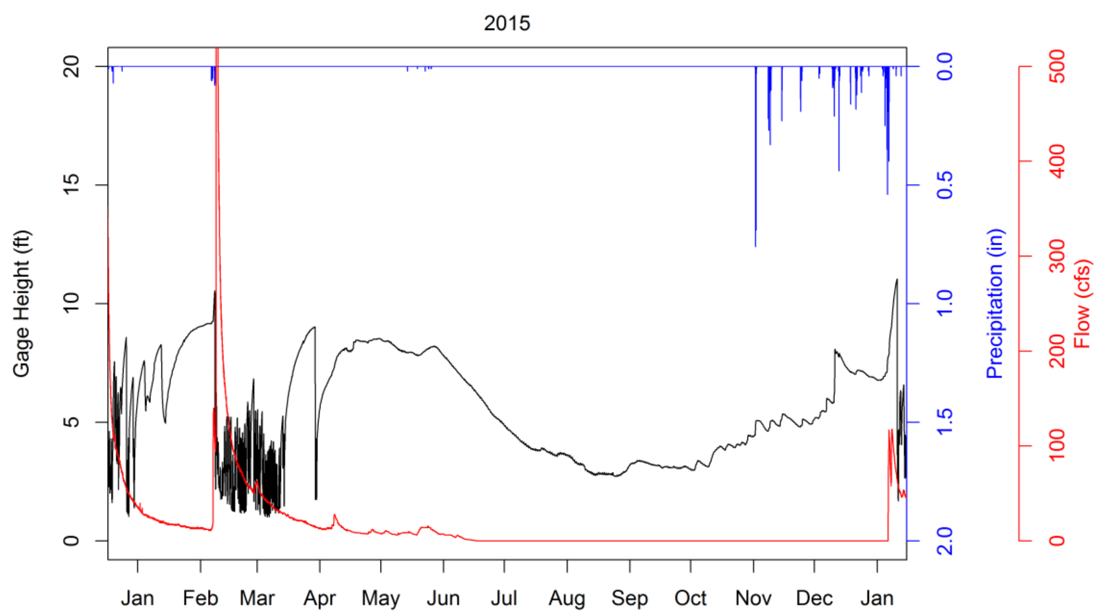
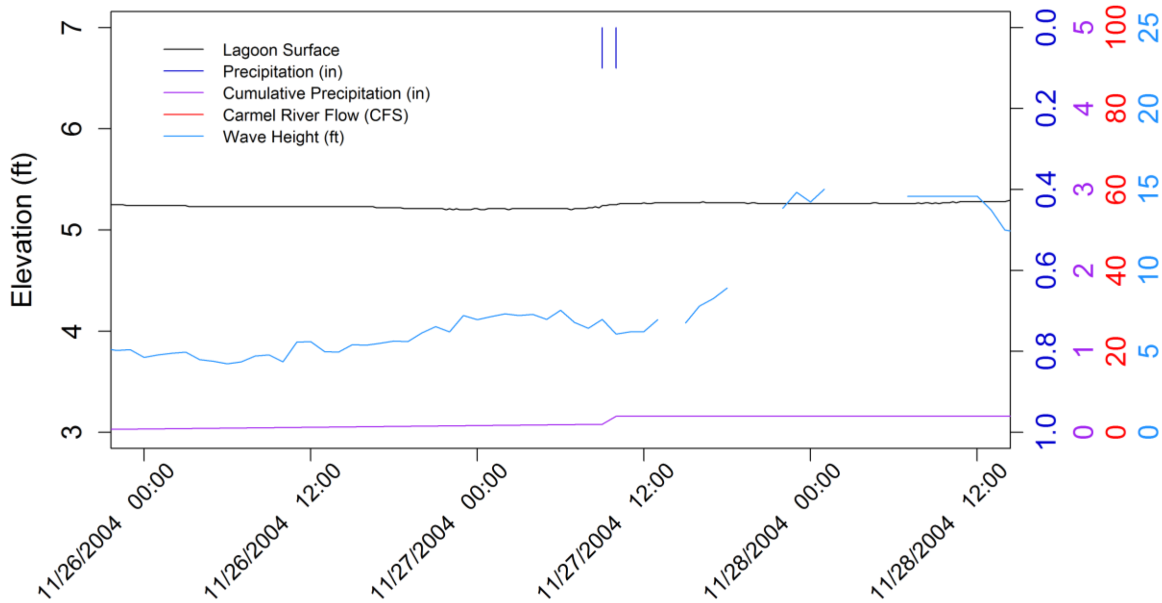
0.0
0.5
1.0
1.5
2.0
0
100
200
300
400
500
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan

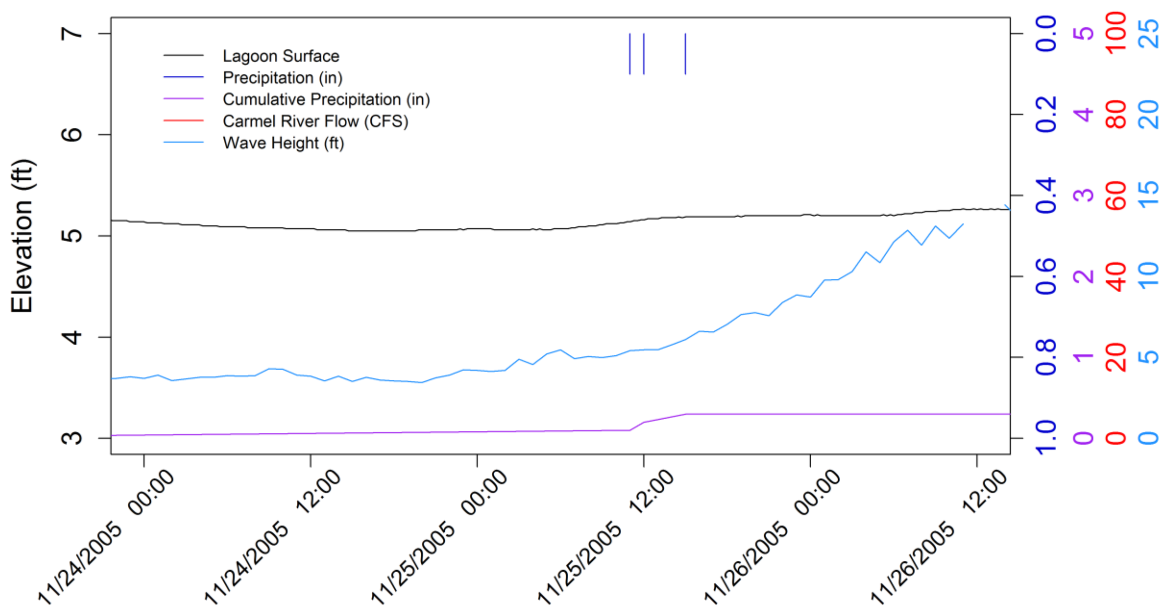

2013
Gage Height (ft)
Precipitation (in)
Flow (cfs)
0
5
10
15
20
0.0
0.5
1.0
1.5
2.0
0
100
200
300
400
500
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan

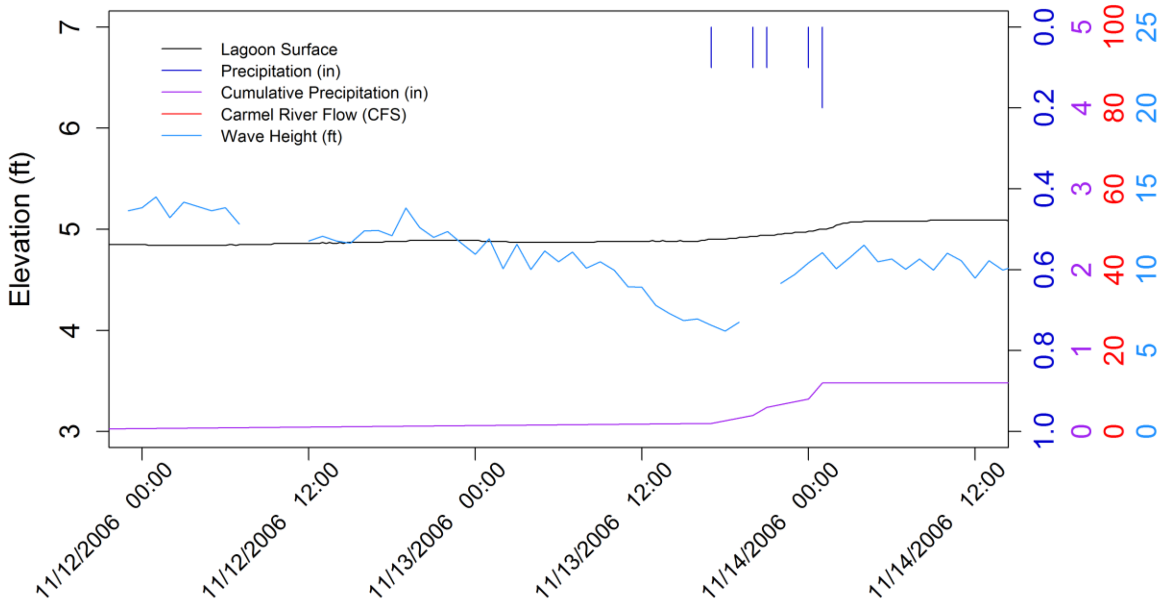

2014
Gage Height (ft)
Precipitation (in)
Flow (cfs)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan

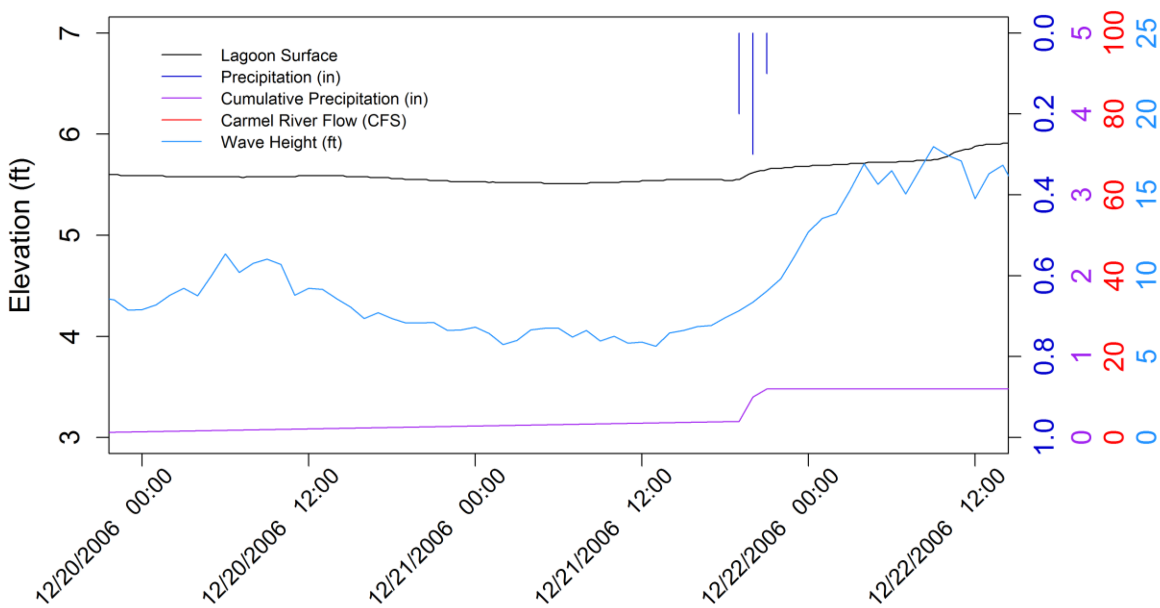

2015
Gage Height (ft)
Precipitation (in)
Flow (cfs)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan

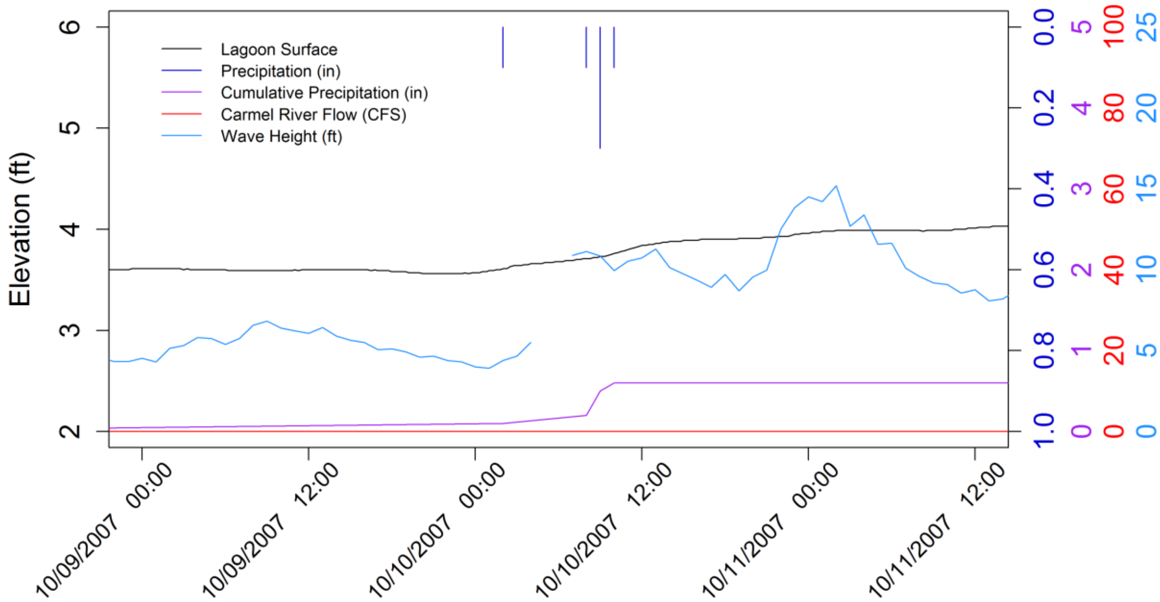
11 Appendix B: Storm Event Plots

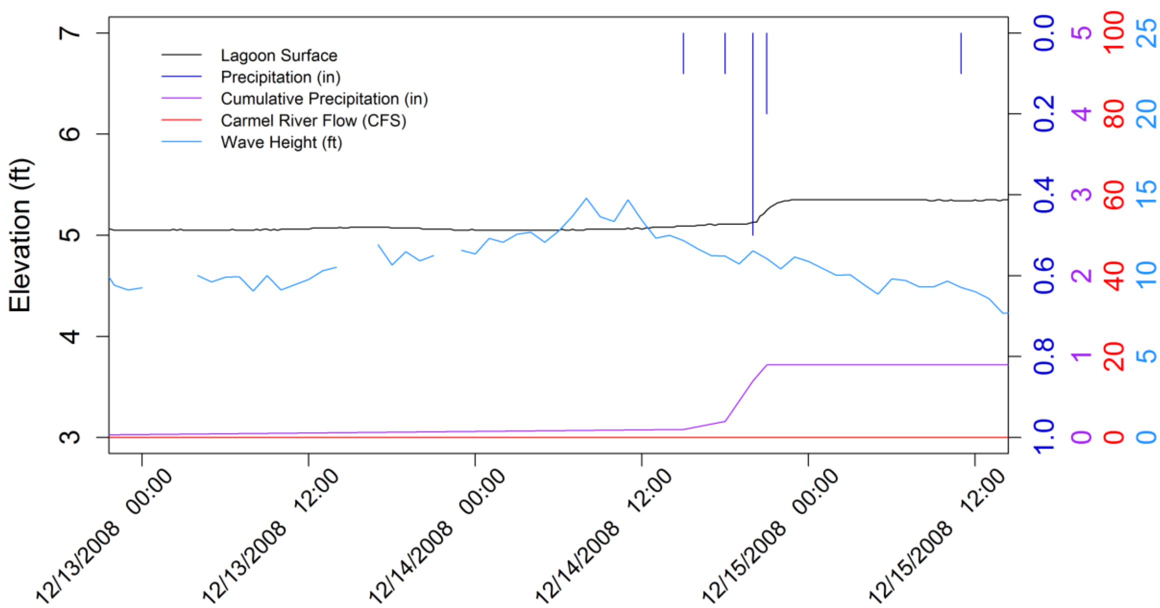


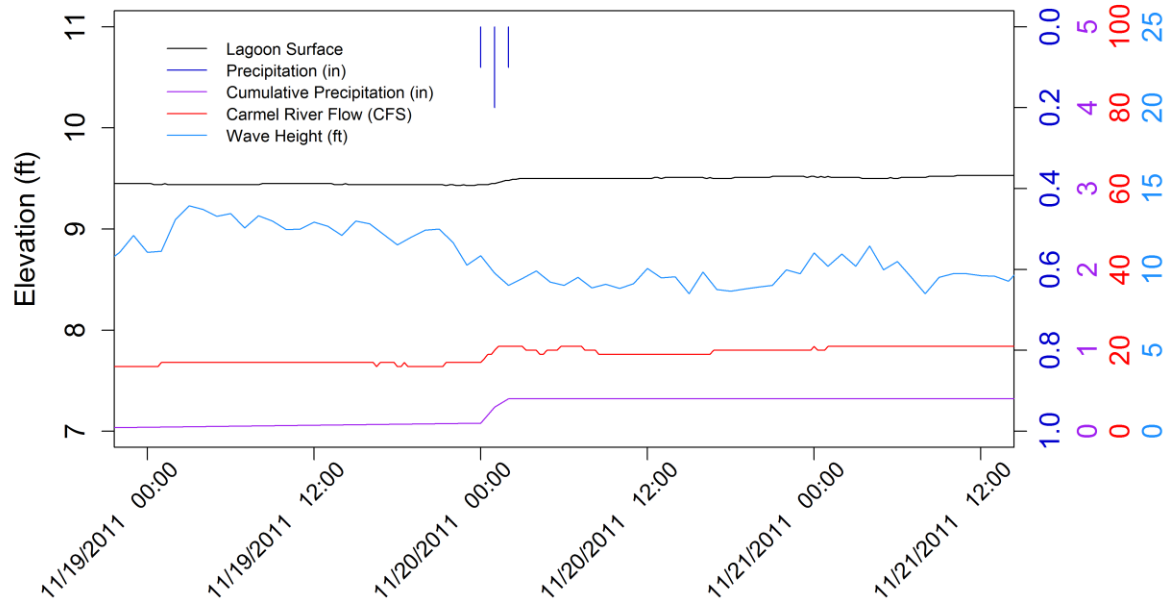


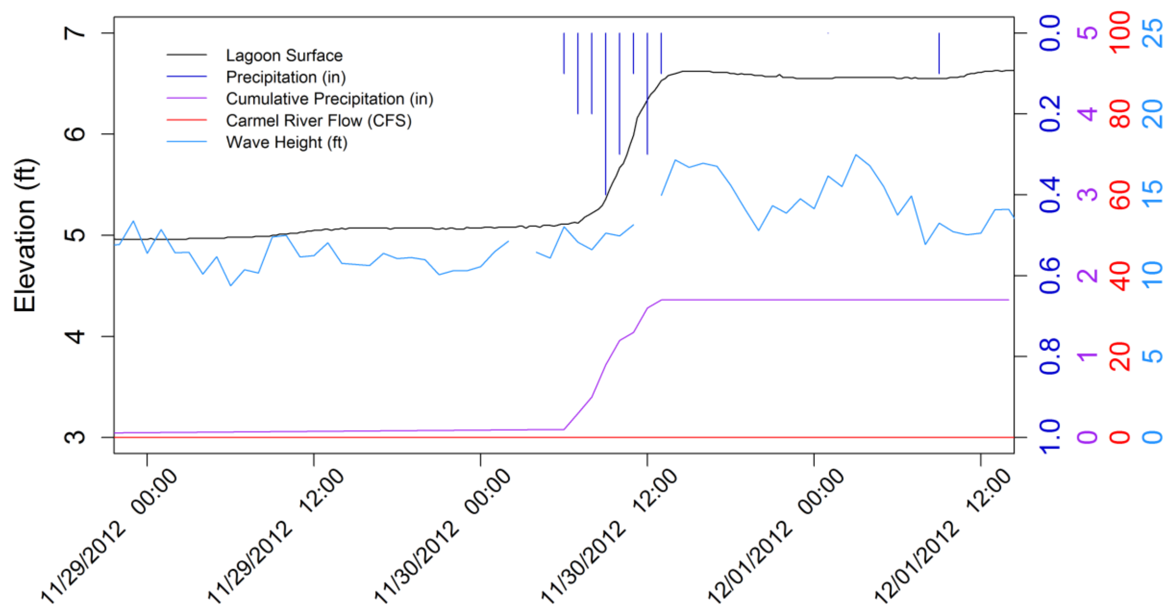

Lagoon Surface
Precipitation (in)
Cumulative Precipitation (in)
Carmel River Flow (CFS)
Wave Height (ft)
Elevation (ft)
11/12/2006 00:00
11/12/2006 12:00
11/13/2006 00:00
11/13/2006 12:00
11/14/2006 00:00
11/14/2006 12:00

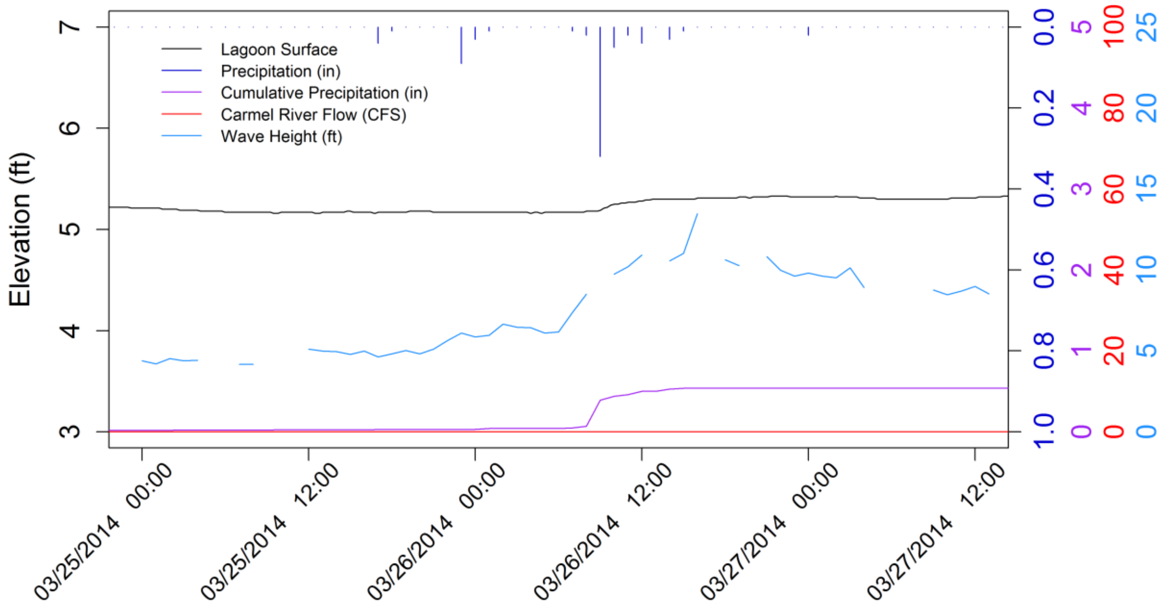

Lagoon Surface
Precipitation (in)
Cumulative Precipitation (in)
Carmel River Flow (CFS)
Wave Height (ft)
Elevation (ft)
12/20/2006 00:00
12/20/2006 12:00
12/21/2006 00:00
12/21/2006 12:00
12/22/2006 00:00
12/22/2006 12:00

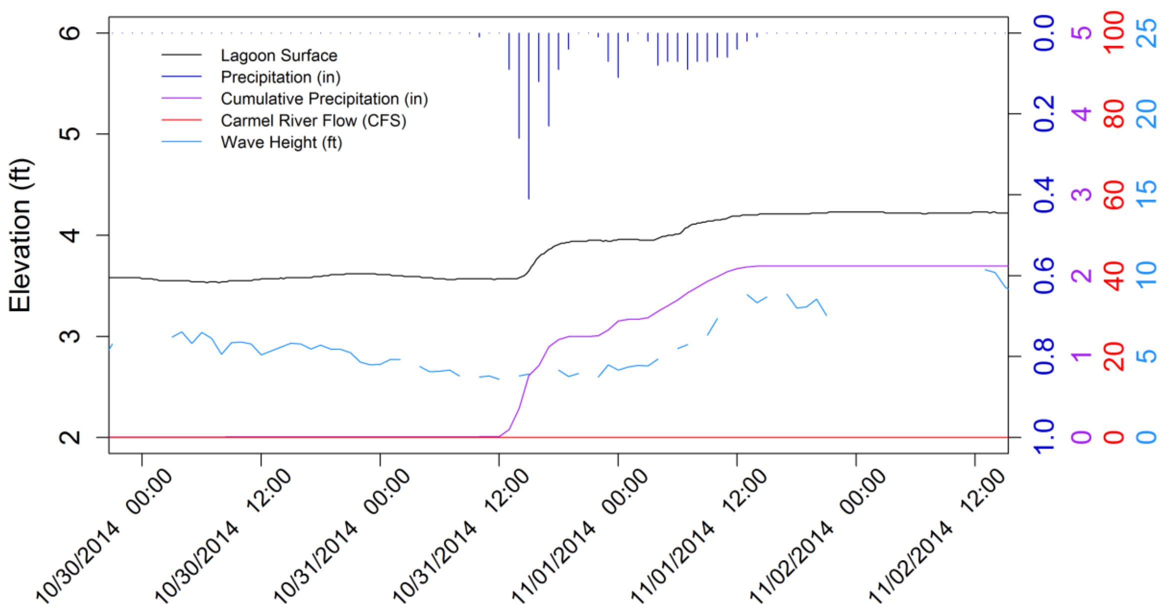

Elevation (ft)
Lagoon Surface
Precipitation (in)
Cumulative Precipitation (in)
Carmel River Flow (CFS)
Wave Height (ft)
10/09/2007 00:00
10/09/2007 12:00
10/10/2007 00:00
10/10/2007 12:00
10/11/2007 00:00
10/11/2007 12:00

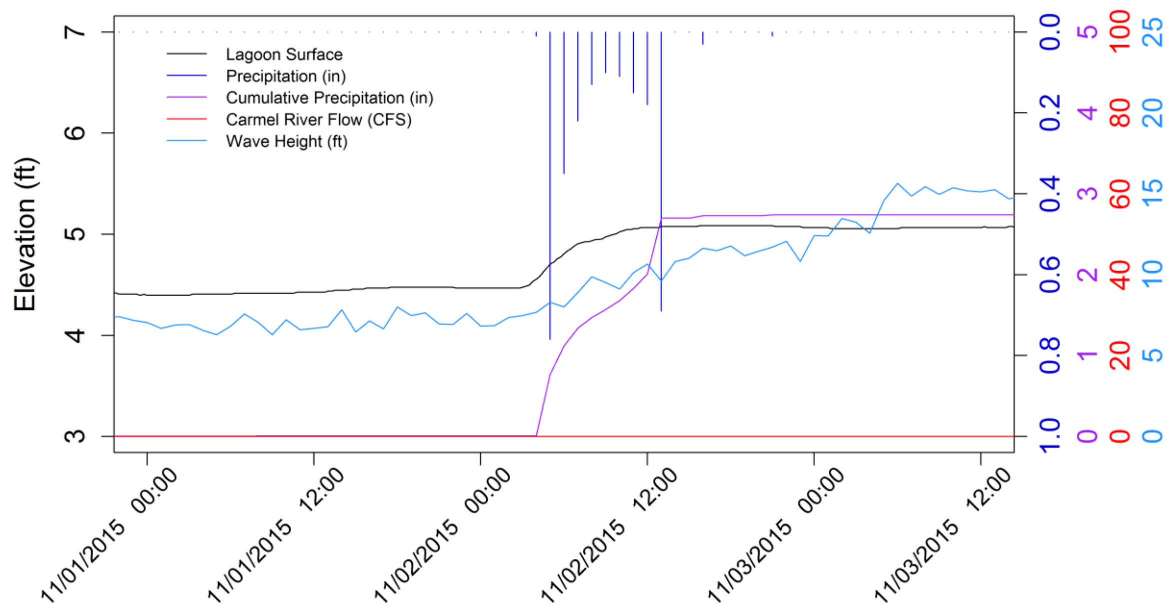

Elevation (ft)
Lagoon Surface
Precipitation (in)
Cumulative Precipitation (in)
Carmel River Flow (CFS)
Wave Height (ft)
12/13/2008 00:00
12/13/2008 12:00
12/14/2008 00:00
12/14/2008 12:00
12/15/2008 00:00
12/15/2008 12:00

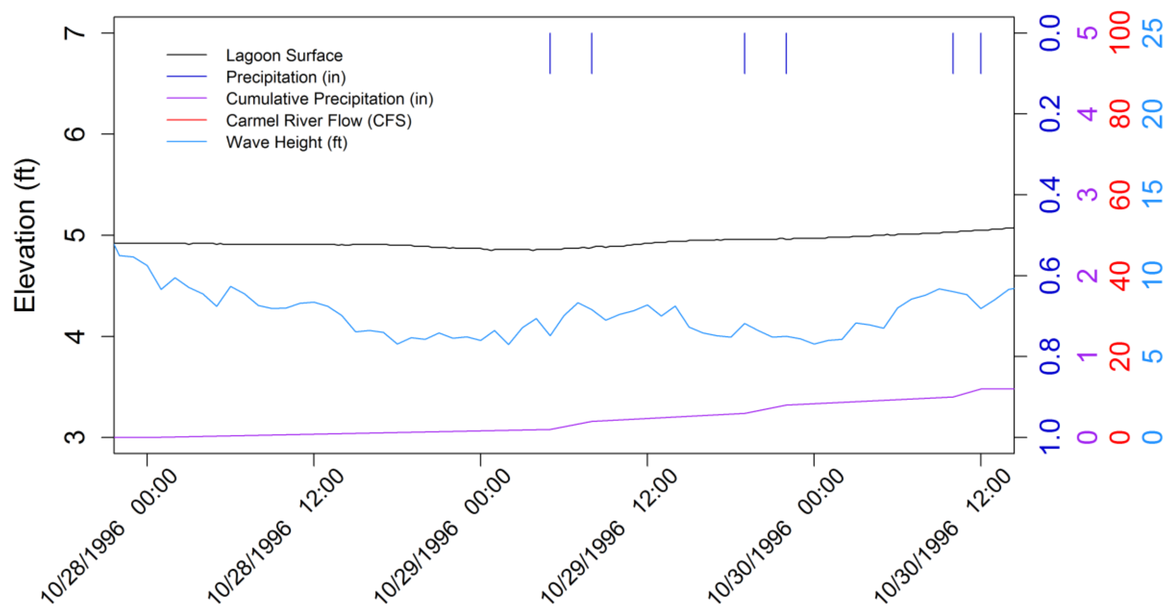

Lagoon Surface
Precipitation (in)
Cumulative Precipitation (in)
Carmel River Flow (CFS)
Wave Height (ft)
Elevation (ft)
11/19/2011 00:00
11/19/2011 12:00
11/20/2011 00:00
11/20/2011 12:00
11/21/2011 00:00
11/21/2011 12:00

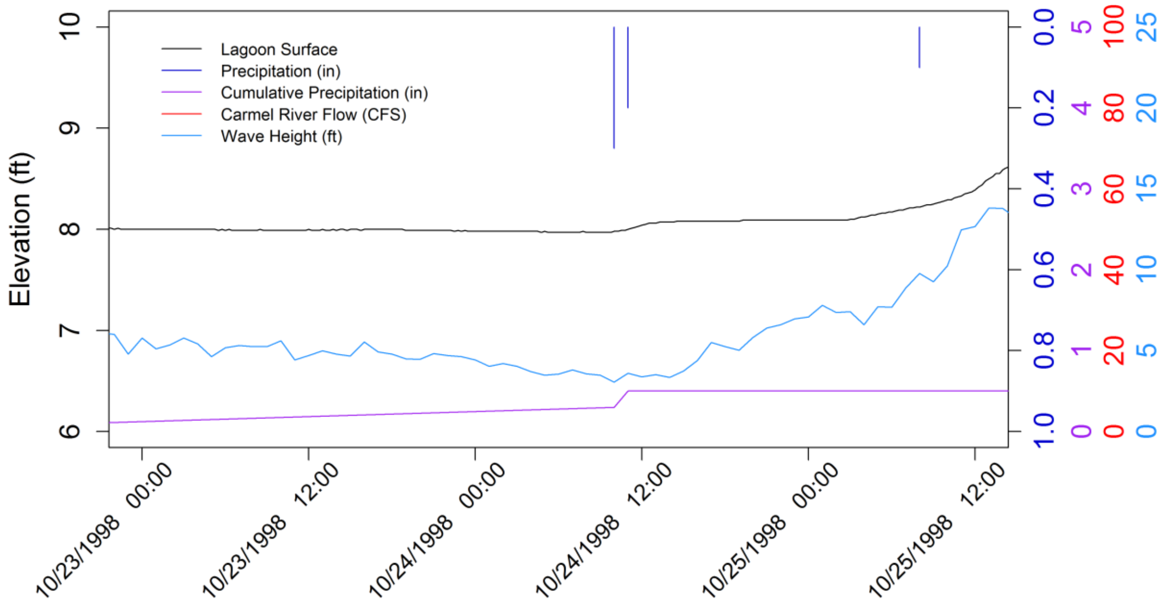

Lagoon Surface
Precipitation (in)
Cumulative Precipitation (in)
Carmel River Flow (CFS)
Wave Height (ft)
Elevation (ft)
11/29/2012 00:00
11/29/2012 12:00
11/30/2012 00:00
11/30/2012 12:00
12/01/2012 00:00
12/01/2012 12:00

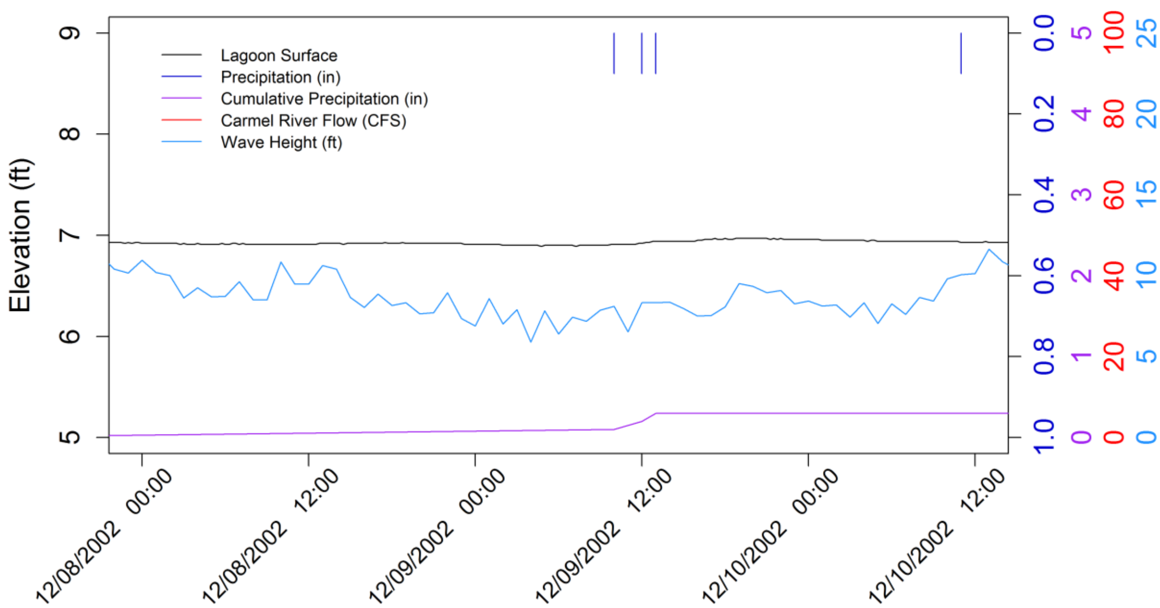

Lagoon Surface
Precipitation (in)
Cumulative Precipitation (in)
Carmel River Flow (CFS)
Wave Height (ft)
Elevation (ft)
03/25/2014 00:00
03/25/2014 12:00
03/26/2014 00:00
03/26/2014 12:00
03/27/2014 00:00
03/27/2014 12:00


Lagoon Surface
Precipitation (in)
Cumulative Precipitation (in)
Carmel River Flow (CFS)
Wave Height (ft)
Elevation (ft)
10/30/2014 00:00
10/30/2014 12:00
10/31/2014 00:00
10/31/2014 12:00
11/01/2014 00:00
11/01/2014 12:00
11/02/2014 00:00
11/02/2014 12:00


Elevation (ft)
Lagoon Surface
Precipitation (in)
Cumulative Precipitation (in)
Carmel River Flow (CFS)
Wave Height (ft)
11/01/2015 00:00
11/01/2015 12:00
11/02/2015 00:00
11/02/2015 12:00
11/03/2015 00:00
11/03/2015 12:00


Elevation (ft)
Lagoon Surface
Precipitation (in)
Cumulative Precipitation (in)
Carmel River Flow (CFS)
Wave Height (ft)
10/28/1996 00:00
10/28/1996 12:00
10/29/1996 00:00
10/29/1996 12:00
10/30/1996 00:00
10/30/1996 12:00

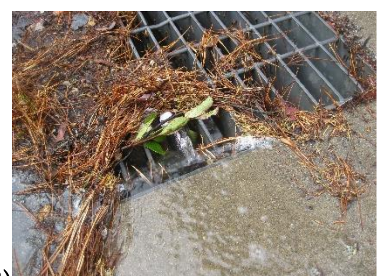

Elevation (ft)
Lagoon Surface
Precipitation (in)
Cumulative Precipitation (in)
Carmel River Flow (CFS)
Wave Height (ft)
10/23/1998 00:00
10/23/1998 12:00
10/24/1998 00:00
10/24/1998 12:00
10/25/1998 00:00
10/25/1998 12:00


Elevation (ft)
Lagoon Surface
Precipitation (in)
Cumulative Precipitation (in)
Carmel River Flow (CFS)
Wave Height (ft)
12/08/2002 00:00
12/08/2002 12:00
12/09/2002 00:00
12/09/2002 12:00
12/10/2002 00:00
12/10/2002 12:00

12 Appendix C: Outfall Photos

ID	*Photos*	Structure	Description
1	A) 	Storm outfall 16” corrugated steel.	Runoff from Odello East property flows through the south bank levee and drains into the Carmel river main stem. Photo (A) on south side of levee bank. E: 597193, N: 4043810
2	A)  B) 	Road drain	Hwy 1, across from Palo Corona Regional Park. Road drain ~20 yards north of Ribera Rd. E: 596886, N: 4043350

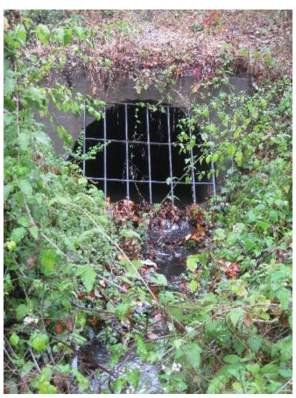
3	A)  B) 	Road drain	Mariposa Dr., road end. Photos of the road end dry (A) and during rain event (B) on 10/16/2016. E: 596608, N: 4043430
4	A)  B)  C) 	Storm drain	Ribera Rd, through private property An inlet located on the north side of Ribera Rd (A–B), exits through a ~12 steel pipe behind residences (C). E: 596714, N: 4043280

5	A)  B)  C) 	Storm outfall and surface drain. 16” corrugated steel.	Calle La Cruz, behind Ribera Rd. residences. Surface runoff flows down the hill onto unpaved road and into lagoon (A), or through a storm drain ~5ft to the east (B – C). E: 596260, N: 4043760
6	A)  B)  C) 	Storm drain and outfall	Calle La Cruz, near CAWD pipe. Runoff drains into inlets at the bottom of Calle La Cruz (A-B) and flow to an outfall east of CAWD transfer pipe (C). Outfall structure was overgrown with poison oak on 10/4/2016. No photo of actual outfall taken. E: 596186, N: 4043820

7	A)  B) 	Road drain	Camino Real, road end. Photos taken prior to rain in fall 2016 (A) and during storm event (B, 10/16/2016). E: 596003, N: 4044520
8	A)  B)  C)  D)  E) 	Road drain	River Park Pl., road end. Photos taken prior to rain in fall 2016 (A) and during storm event (B – E, 10/16/2016). E: 596083, N: 4044520

9	A)  B)  C)  D)  E)  F) 	Road drain	Monte Verde St., road end. Photos taken prior to rain in fall 2016 (A) and during storm event (B – F, 10/16/2016). E: 596167, N: 4044520
11	A)  B)  C) 	Storm outfall. 16” metal pipe. 36” corrugated plastic tube. 12” PVC pipe.	Riverside Way. A 16” metal pipe drains (A) runoff into stacked rocks located inside a 36” corrugated plastic tube with rectangular outlets (B). A 12” PVC pipe is located downstream ~5 ft (C). E: 596851, N: 4044400

12	A)  B)  C) 	Storm outfall 12” flap gate 16” concrete inlet 16” concrete outfall to retention pond.	Mission Fields Rd., downstream of 13. Runoff drains into the retention pond via a 16” concrete outfall (A), exits the pond (13-A) through a 16” concrete outlet (B) and connects to a 12” flap gate ~20m from the river (C). E: 596998, N: 4044300
13	A) 	Retention pond	Mission Fields Rd., upstream of 12. A retention basin leads into outlet 12 (A) E: 597091, N: 4044260

14	A)  B)  C)  D) 	Storm outfall (2) 12" flap gates. 36" central flap gate.	Hwy 1, behind Safeway. 3 outfalls drain surface runoff from Safeway parking lot at Hwy 1 bridge. Pre-rain, the outfall was dry (A). Subsequent to a storm event, runoff connected the outfall to the river (B-D, 10/16/2016). E: 597396, N: 4043970
15	A)  B)  C) 	Storm outfall 56" concrete with metal barrier.	Hatton Canyon, off Rio Rd. Outfall was moist but not connected to the river pre-rain; Outfall is ~10m from river (A). During rain event, runoff was flowing at approximately <1 cfs and connected to Carmel River (B-C, 10/16/2016). E: 597826, N: 4043910

16	A)  B)  C) 	Storm outfall 44" concrete with metal barrier.	Carmel Rancho Outfall, on Rio Rd. Outfall was moist but not connected during pre-rain reconnaissance; Outfall is ~15m from river (A). During rain event runoff was flowing at approximately <1 cfs and connected to Carmel River (B-C, 10/16/2016). E: 598095, N: 4043960
17	Not found in 2016 reconnaissance trip.	Storm Outfall	Val Verde Dr., Road end.
	A)  B) 	CAWD pipe crossing encased in concrete.	CAWD concrete barrier, downstream of outfall 11. During reconnaissance trip, barrier was above the water's surface (A). The barrier was submerged in ~0.5 ft of water on 10/16/2016 subsequent to rain (B). E: 596803 N: 4044415

	A)  B) 		Carmel River, downstream of Hwy 1 bridge. During field reconnaissance, the river was dry with intermittent pools of water ~500m below Hwy 1 bridge (A, 9/30/2016). Subsequent to rain, river was connected below the bridge to the lagoon (B, 10/16/2016).
	A)  B) 		Beginning of RNC reach. Photos of the River Not Connected reach (A). RNC reach began at Rancho Cañada golf course pedestrian bridge. Downstream of this location for ~500m there were intermittent dry patches pre-rain (B, 10/04/2016).

13 Appendix D: Water Quality Model Derivation

The following equations were used to derive a model to augment salinity profiles with surface runoff where M is quasi-mass (m.g/kg), T is thickness of the freshwater layer (m), S is salinity (g/kg), and subscripts are: 0 (initial lagoon layer), 1 (final lagoon layer), and A (augmentation from runoff).

1. $M_0 = S_0 \times T_0$
2. $M_1 = S_1 \times T_1, \; S_1 = \frac{M_1}{T_1}$
3. $T_1 = T_0 + T_A$
4. $M_1 = M_0 \times M_A, \text{ where } M_A = 0$, thus $M_1 = M_0$

To solve for S_1, we start with Equation 2:

$$S_1 = \frac{M_1}{T_1}$$

then we make a substitution using Equation 4:

$$S_1 = \frac{M_0}{T_1}$$

then we make a substitution using Equation 1:

$$S_1 = \frac{S_0 \times T_0}{T_1}$$

then we make a substitution using Equation 3:

$$S_1 = \frac{S_0 \times T_0}{T_0 + T_A}$$