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Potential Effects of Groundwater Extractions on Carmel Lagoon

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(Table 6.1 was ommitted in previous version)

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1 Executive summary and discussion

1.1 Executive summary

In 2003, Cal-Am intended to increase pumping rates from the lower Carmel Valley aquifer on a trial basis. The purpose of the present study was to measure possible effects of this pumping on the Carmel Lagoon. Ultimately, groundwater profiles remained approximately the same as in previous years – since the intended pumping increases in one well (40% at Rancho Canada) were largely offset by a requirement to cease pumping in nearby well (San Carlos) (Feeney, monitoring reports to Cal-Am). Therefore, the study addressed current lagoon-groundwater interactions, and potential effects of increased net pumping at some point in the future.

The study focused on summer conditions when the lagoon is closed to the ocean – since winter conditions are clearly governed by free tidal exchange through an open sand bar. The lagoon provides summer rearing habitat for threatened steelhead trout – which in general terms require sufficient volumes of fresh, cool, oxygenated water.

Several questions were addressed:

What controls the ***water level*** *of the lagoon when the sandbar is closed?*

- The lagoon water level is set by the ocean, as a dynamic equilibrium maintained by sub-surface flow back and forth through the sandbar. The level rises with high waves and tides, and falls thereafter. (See Section 6)

What controls the ***volume*** *of the lagoon when the sandbar is closed?*

- For a given water level, the volume of water in the lagoon is set by sedimentation, erosion, and excavation. Each year, sediment is brought into the lagoon both by the River and by ocean wave action. Much of this is eroded away during winter, but there is also a net-long term accumulation of sediment. Backwater habitats are periodically excavated using earth-moving equipment. (See Section 7)

What controls the ***salinity*** *of the lagoon when the sandbar is closed?*

- A relatively fresh layer is normally maintained near the surface of the lagoon. This originates as the residual from the last river flows of spring. Data also suggest that the freshwater layer is maintained by shallow groundwater inputs from the lower Carmel Valley aquifer. The relatively fresh layer fluctuates in thickness during the summer, being apparently dissipated by saltwater ocean inputs through and over the sandbar, and re-established by both local and distant groundwater inputs once the ocean subsides. If groundwater inputs did not exist, it is likely that both evaporation and ocean exchange would eventually eliminate the relatively fresh water. Water levels in monitoring wells above and inland from the lagoon rise in response to abrupt changes in lagoon stage as a result of ocean wave in-wash. This hydraulic backwater effect is confirmation of flow from the lower Carmel Valley aquifer into the lagoon that persists throughout the dry season. Further confirmation is provided by the detection of fresh groundwater immediately beneath the saline sump at the bottom of the lagoon. (See Section 9)

*How would the lagoon be affected by **increased pumping** in the lower Valley?*

- Within limits, increased pumping would not affect the lagoon **level**, but may affect the lagoon **salinity**. Current pumping of approximately 5 cfs in the Rancho Canada area several miles upstream leads to an annual cycle – with pre-winter groundwater depressions extending west to above Rio Road, followed by rapid wintertime recovery. If similar pumping in the Odello area yielded similar depressions, the primary source of summer freshwater flow into the lagoon would be reduced. This is a qualitative assessment, based on quantitative analysis. A quantitative prediction is not yet possible. (See Section 9)

*How would increased dry-season salinity affect **steelhead** habitat in the lagoon?*

- Increased lagoon salinity **may adversely affect** steelhead habitat. Availability of fresh water is a key, limiting factor in lagoons with respect to steelhead rearing habitat. Without fresh water, stratification is enhanced, leading to poor mixing below the surface, low dissolved oxygen, and high temperatures. (The other key limiting factor may be dissolved oxygen crashes in early winter, caused by decomposition of kelp and other organic matter washed into the lagoon, over the sandbar, by high ocean waves.) (See Section 10)

***Were rearing steelhead adversely impacted** by salinity in the 2003 dry season?*

- There is no evidence that steelhead were adversely impacted by excessive salinity while rearing in the Carmel Lagoon during the 2003 dry season. Several thousand juveniles were planted in the lagoon, which was seined some time afterwards to confirm that at least several hundred had successfully grown to about 60-200 mm. It is presumed that many, especially the larger fish, migrated to the ocean some time after the lagoon breached. It is possible that they may have experienced adverse effects just prior to the lagoon breaching due to oxygen levels uniformly below 5 mg/L, most likely caused by decomposition of kelp and other organic matter washing into the lagoon over the sandbar from the ocean.

1.2 Additional notes of interest

- When the sand bar is closed, there is a close correlation between lagoon stage, and the progression of increasing peak wave heights during the season. There is also a close correlation with tide height.
- The magnitude of flow back and forth through the sandbar is of the same order of magnitude (~5 cfs) as current Cal-Am pumping at Rancho Canada.
- Groundwater flow persists throughout the dry season from the lower Carmel Valley aquifer into the lagoon, but the magnitude of this flow is unknown.
- The timing of final sandbar closure in spring may be a strong determinant of the amount of fresh water available to juvenile steelhead for the remainder of the dry season.
- It is likely that there is dry-season flow back and forth between the lagoon and the shallow groundwater immediately adjacent to the lagoon. The adjacent groundwater may act as a temporary storage of fresh water during periods where high ocean waves and tides force the lagoon stage upwards.
- Ocean fluctuations may cause a seasonal mixing and weakening of stratification, by repeatedly altering the surface area of the lagoon.
- Long-term changes in lagoon capacity associated with sedimentation may be significant, and with respect to total summer habitat volume, may exceed any impact of nearby groundwater pumping. The bottom of the south arm is well below sea level, and is gradually filling up with river sediment.
- The lagoon exhibits distinctly separate layers of pronounced physico-chemical dynamics (oxygen cycles etc.). These layers are determined by salinity and stratification, and may be associated with distinctly separate layers of photosynthetic production and respiration, associated with different organisms.

1.3 Future work

Some ideas for future work (not exhaustive):

- Measure groundwater flow from lower Carmel Valley aquifer into Carmel Lagoon.
- Develop a more detailed simulation model with an hourly time step, a mixing sub-model, and ultimately, a production-respiration sub-model.
- Deploy continuous logging salinity meters, and if practical, oxygen meters (in addition to the temperature loggers deployed in the present study)
- Examine causes of dissolved oxygen crashes in more detail
- Describe the key primary produces and consumers, their seasonal dynamics, and environmental envelopes.

2 Introduction

2.1 Overview

On a trial basis in 2003, California-American Water Company (Cal-Am) planned to conduct additional extractions of groundwater from a new well on the Odello East property and at Rancho Canada. These planned extractions may have had effects on senior water rights, seawater intrusion, the riparian environment, and the environment of the Carmel Lagoon (Feeney, 2002). Ultimately, the increases did not take place.

This study addressed current lagoon-groundwater interactions, and potential effects of increased pumping at some point in the future on the environment of Carmel Lagoon.

2.2 Background

Existing data (See Feeney, 2002) shows strong correlation between lagoon stage and groundwater levels in wells within one hundred meters of the lagoon (Beach Parking Lot & Wetlands wells), indicating free lateral groundwater connection extending beyond the lagoon. A few hundred meters away near the Carmel Area Wastewater Discharge plant, groundwater levels are higher, but still correlated, indicating groundwater discharge to the lagoon, and a possible control of lagoon water levels by groundwater.

Lagoon stage (water level) determines the surface area and volume of aquatic habitat for important species such as steelhead trout and their prey. Lagoon volume may also partly determine the concentration of nutrients and pathogens when these are present in significant quantities. Lagoon surface area is important to both bird species and human aesthetics.

The possibility exists for habitat effects, water quality effects, and aesthetic impacts on the Lagoon environment following increased lower Carmel Valley groundwater extractions

3 Study area

The Carmel Lagoon forms the mouth of the Carmel River, near the town of Carmel at the northern end of the Santa Lucia Range along the Central Coast of California.

The context of the Carmel Lagoon within the surrounding geology and hydrology is shown in Figure **3.1**. The cross-section shown in the Figure is intended to illustrate that the Lagoon in summer is a relatively small water body, being the surface expression of a larger aquifer.

The cross-section was drawn based on a range of different data:

- River thalweg elevations from a topographic map drawn as part of a study by Phillip Williams & Associates (PWA)
- Geologic cross-sections, well locations, direction of groundwater flow, and approximate location of saltwater interface from SGD (1989)
- Well data from Feeney (pers. comm.)
- Highway 1 bridge dimensions from field survey
- Lagoon bathymetry from Casagrande & Watson (2003)
- Wave height data from NOAA web site
- Ocean bathymetry from bathymetric image of Monterey Bay (200 x 200 m grid cells)

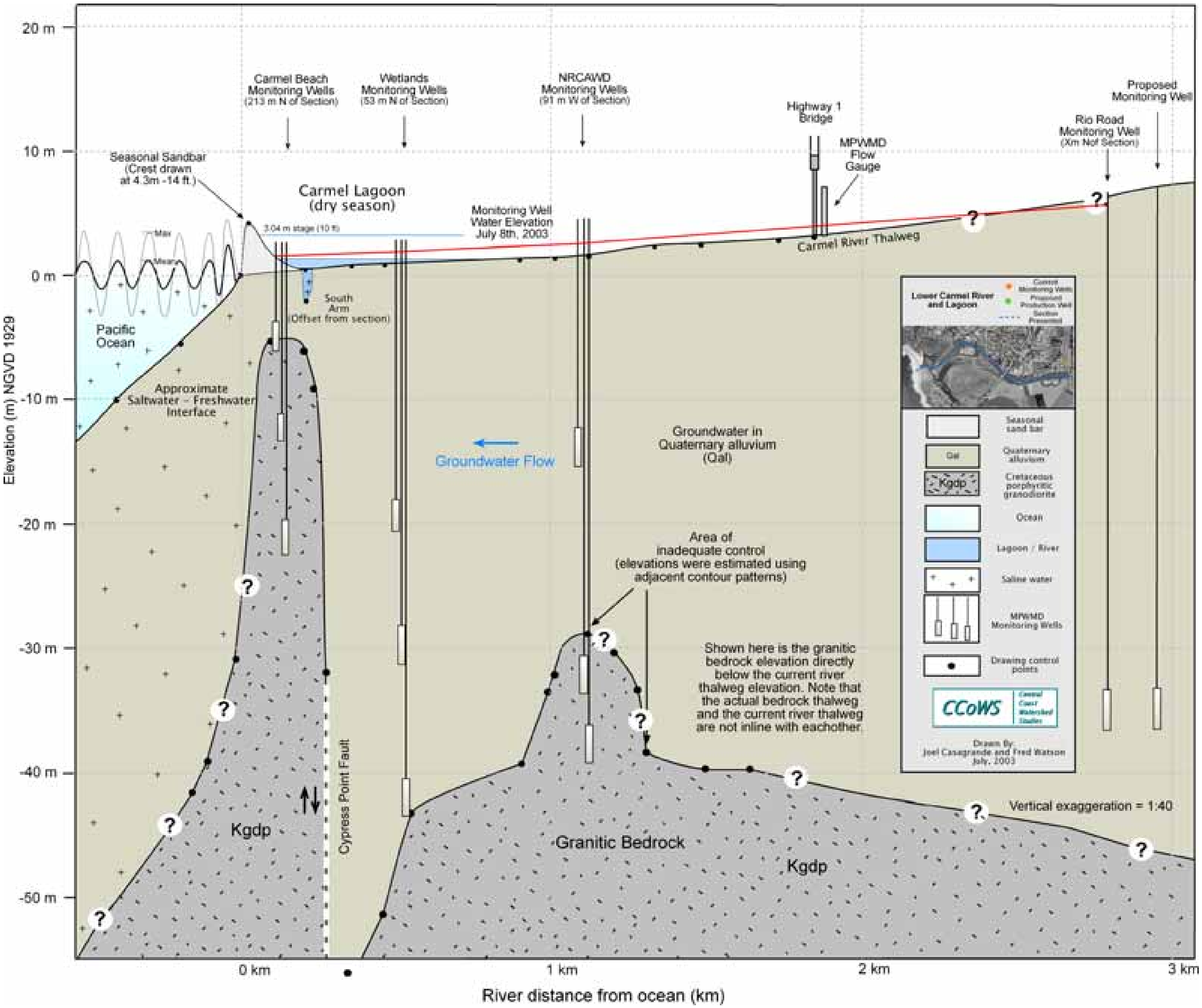

Figure 3.1. Cross-section of the Carmel Lagoon and lower Carmel River during typical summer conditions. See text for description.

4 Existing water balance data

4.1 Lagoon stage

There are two permanent staff plates in the Lagoon, one in the North Arm and one in the South Arm. Both are aligned to the NGVD 1929 vertical datum in feet. Stage is also continuously monitored at the South Arm staff plate by MPWMD on a 15-minute interval. These data have been obtained through mid 2002.

4.2 Lagoon bathymetry

A number of bathymetric or topographic surveys have been conducted on the lagoon:

- Matthews topographic survey – 1997. Excludes south arm
- Odello topographic survey – 1990s
- Ayers – 2001. Topographic (?) survey conducted for Entrix Biological Assessment
- Hagar – 2001. Transects only.
- CCoWS - 2002. Transects only.

The most recent hypsometric curve (relating stage to volume) is the Ayers curve presented by Entrix in their Biological Assessment report (2001?). Lagoon bathymetry changes due to sediment aggradation and degradation, breaching, and manual excavation in the South Arm (late 1990s).

A new hypsometric curve may be constructed as part of the present study using either:

- Detailed topographic survey with total station, or
- Detailed bathymetric survey at high water
- Inversion analysis based on estimate inflow and stage data during a rapidly rising hydrograph
- Extrapolation from existing transect data

4.3 Freshwater surface inflow

The majority of freshwater surface flow input to the lagoon is via the Carmel River, although there are also local sources of runoff from residential areas surrounding the lagoon. The nearest continuous flow gauge to the lagoon is just upstream from the lagoon at Highway 1. This gauge is maintained by MPWMD using USGS techniques. The data have been compiled into a daily record from water year 1993 onwards. 15-minute data are also archived.

The nearest USGS flow-gauging site on the Carmel is at Via Mallorca Road, 4.03 km upstream[1]. Daily data are available for this site since August 1962. Another USGS gauging site is located 18.6 km upstream from Via Mallorca Road at Robles Del Rio.

Differences between the Via Mallorca data and the Highway 1 data are expected due to:

- rating table changes associated with mobile bed sediments
- percolation above groundwater lowered by well-pumping
- differences in watershed area (inputs in the intervening reach include Hatton Canyon, Martin Canyon, and most of the Crossroads area)

Routing of flow between Robles Del Rio and Via Mallorca Road introduces a delay of 2-3 hours in the timing of hydrograph peaks[2]. The subsequent delay between Via Mallorca Road and the Lagoon is thus estimated at about 30-45 minutes, assuming an equal speed of flood-wave progression between the two reaches

Surface inflow is likely to be influenced by groundwater extraction in the lower Valley. This would be manifested through the increased streambed percolation rate that would be expected if the water table were lowered by groundwater extraction. Only some of this influence would be reflected in the Via Mallorca Road gauging record. Further influences are expected in the reach below Via Mallorca Road, especially in relation to extractions near this reach.

4.4 Ocean inflow

Ocean inflow to the Lagoon occurs both when the Lagoon is open to the ocean, and through waves washing over the sand bar when the lagoon is closed. Ocean wave inflow occurs mainly in fall, is correlated with ocean swell height, and is relatively independent of tides (Casagrande et al., 2002). The amounts involved can be very significant, filling the lagoon to capacity in some seasons before any appreciable freshwater inflow occurs. Ocean inflow is thus relatively easy to detect both as increases in the continuous stage record, and discrete increases in Lagoon sump salinity.

4.5 Surface outflow

Surface outflow from the Lagoon occurs only when the Lagoon is open to the ocean after a breach. Post-breach conditions vary from a narrow mostly unidirectional outflow channel, to a relatively wide, open channel with continual interchange of lagoon and ocean waters.

Surface outflow data are only available in the form of historic records of breaching, and estimates based on inference from stage, streamflow, and tidal data.

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[1] Measured from Via Mallorca Road to Wastewater Treatment Plant using TOPO! mapping software and digital USGS 7.5’ topographic maps.

[2] Based on simple graphical analysis of the first large flow of the 2002-3 season.

4.6 Evaporation

Evaporation loss from the lagoon water surface and through transpiration from vegetation is continuous throughout the year. In general, evaporation is highest when there is an abundance of water supply, heat, solar radiation, and wind. The warmest and sunniest periods on the lagoon are in summer, with the caveat that the influence of fog should be analyzed. The windiest periods are generally in the fall, and the largest water supply to a large area is in fall and winter. Evaporation from the free water surface of course also depends on the lagoon surface area at any given time. However, reduced free surface evaporation during times of low surface area may be offset by transpiration in surrounding riparian vegetation with roots connected to the shallow groundwater surrounding the lagoon.

Long-term climate data are available for Monterey Airport, and perhaps for other sites closer to the Lagoon. These can be used to crudely estimate evaporation rates. Additional data will be collected during the present study.

4.7 Groundwater flux

In addition to groundwater influences on streamflow inputs, there may be direct exchange of water between the Lagoon itself and the underlying groundwater. Water levels in nearby monitoring wells (Odello, Mission Ranch, and Beach) are normally slightly higher than the Lagoon stage (Feeney, 2002), implying a slight groundwater input to the Lagoon. Occasionally at high Lagoon stage, the gradient is reversed. There are no direct data on these exchanges, however some estimates may be made based on nearby monitoring well data.

5 Preliminary data exploration

5.1 Streamflow

Simple plots of the flow record at Via Mallorca Road are shown in Figure 5.1. Inter-annual variability is very high, with some years receiving almost no flow. Intra-annual variability is also very high, with flow ceasing in the lower river over 40% of the time.

A comparison between the overlapping periods of the Via Mallorca record and the Highway 1 record reveal (expected) evidence for periods of percolation of low flows (below 1 m^3/s, 35 cfs) into the streambed in the lowermost reaches of the river (Fig. 5.2).

5.2 Stage

Variations in Lagoon stage since mid-1991 are plotted in Figure 5.4. During winter, stages reach high levels and fluctuate daily after breaching through continued tidal exchange and ocean wave inflow. During the dry season, variation is much slower, with each year's dry-season exhibiting distinct rising and falling periods lasting many weeks.

5.3 Losses

Some initial ideas for estimation of lagoon losses are shown in Figure 5.3. This analysis assumes that if the average lagoon stage goes down from the previous day on a day when the daily range is low (i.e. the lagoon is not open to the ocean), then the loss must be due to a combination of evaporation and subsurface fluxes. These losses are typically around 0.03 m/day, or about ten times higher than potential evaporation. Subsurface flow is thus the dominant pathway for loss of water from the lagoon during dry-season conditions – either to the ocean, or to groundwater.

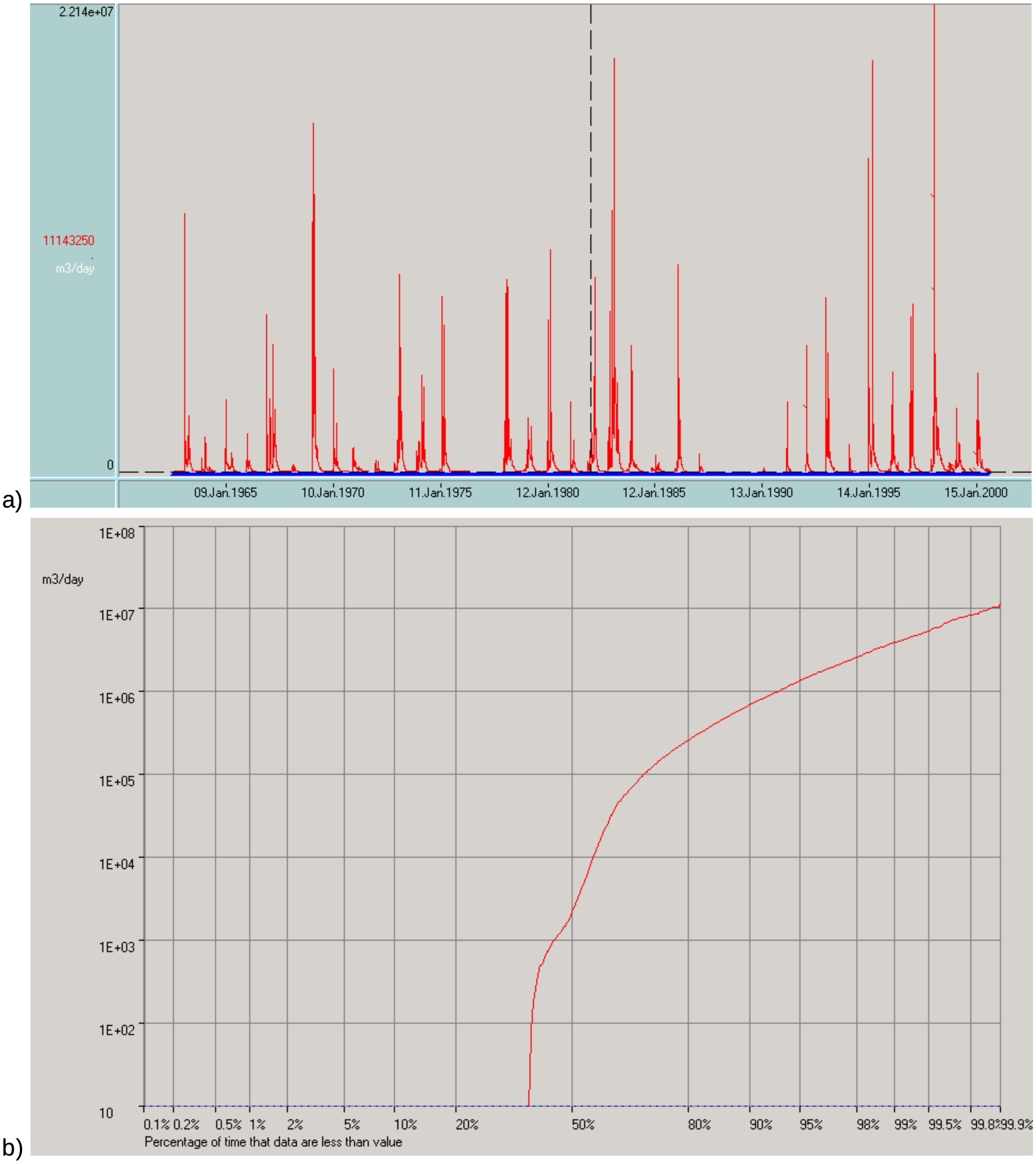


Figure 5.1. USGS flow data - Carmel R at Carmel (Via Mallorca Road): a) hydrograph, b) flow duration curve.

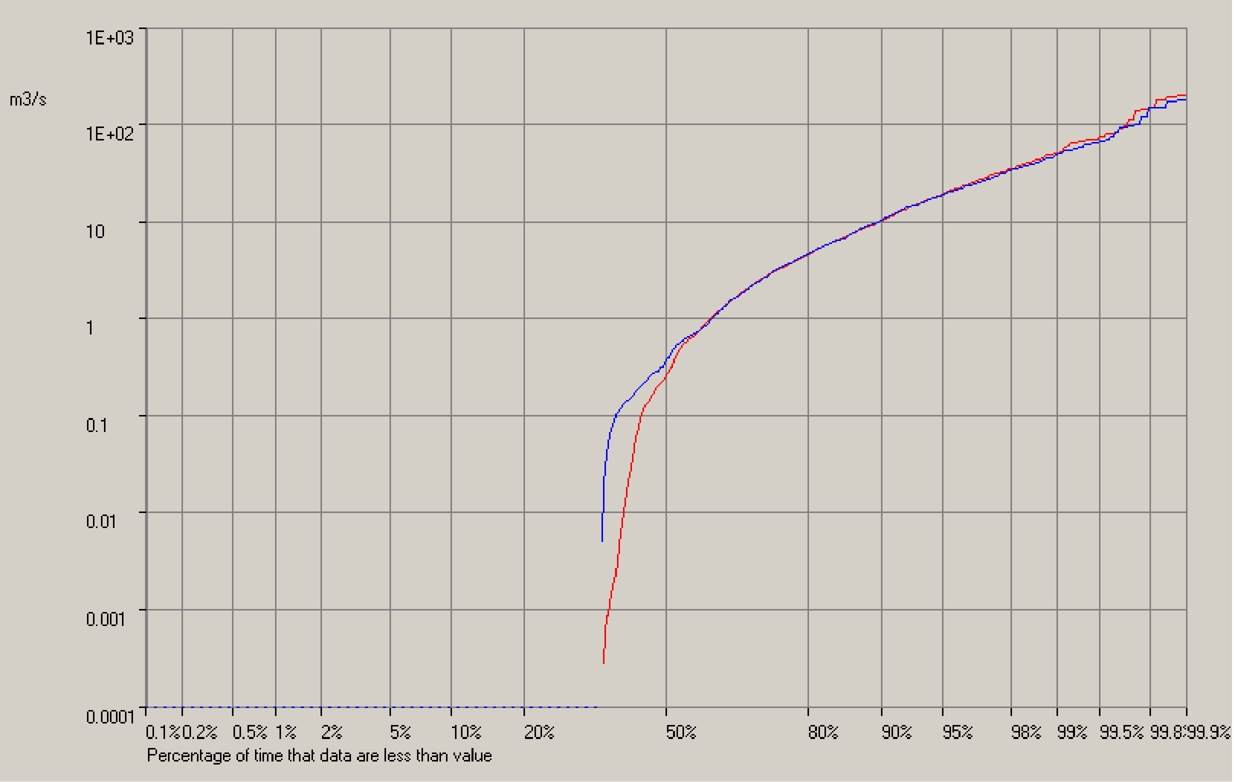


Figure 5.2. Comparison of flow duration curves for Carmel River at Highway 1 (red) and Via Mallorca (blue) (based on data from water years 1993-2001). The low flow differences are attributed to percolation during the tail end of the flow season, when surface flows below 1 m^3/s (35 cfs) reach Via Mallorca, but percolate before reaching Highway 1. The high flow differences are attributed to the increased watershed area at Highway 1 – including runoff from impervious surfaces in the Crossroads area.

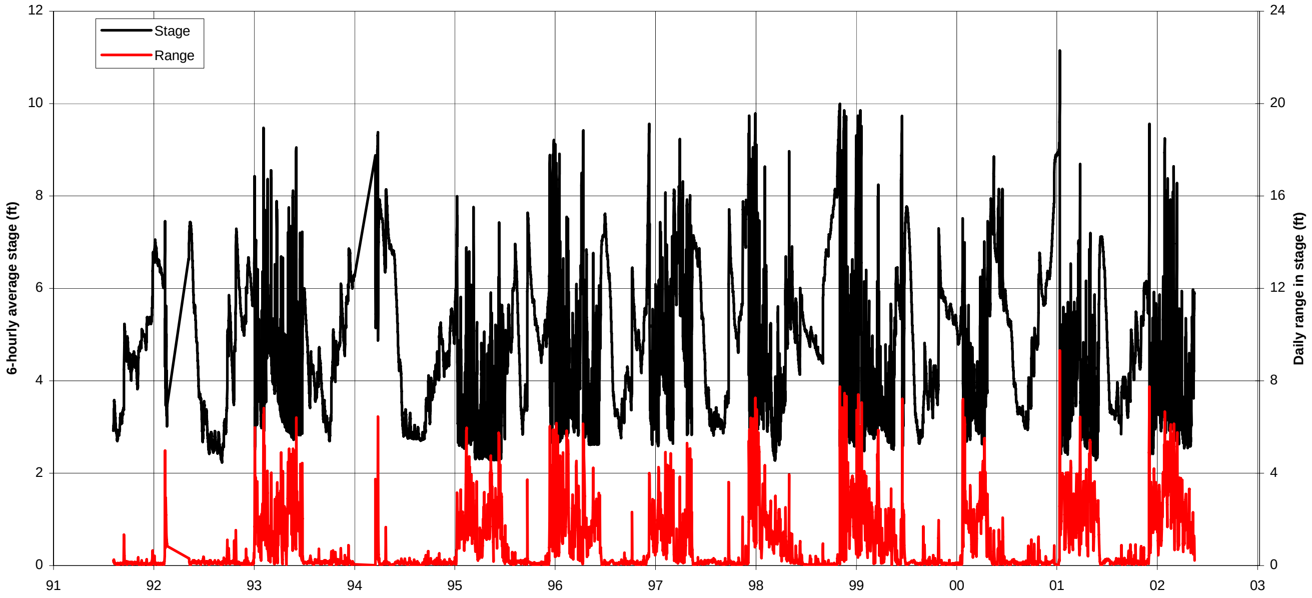


Figure 5.4. 6-hourly stage in Carmel Lagoon, and daily range in stage. Large ranges generally indicate periods where the lagoon is open to ocean tides.

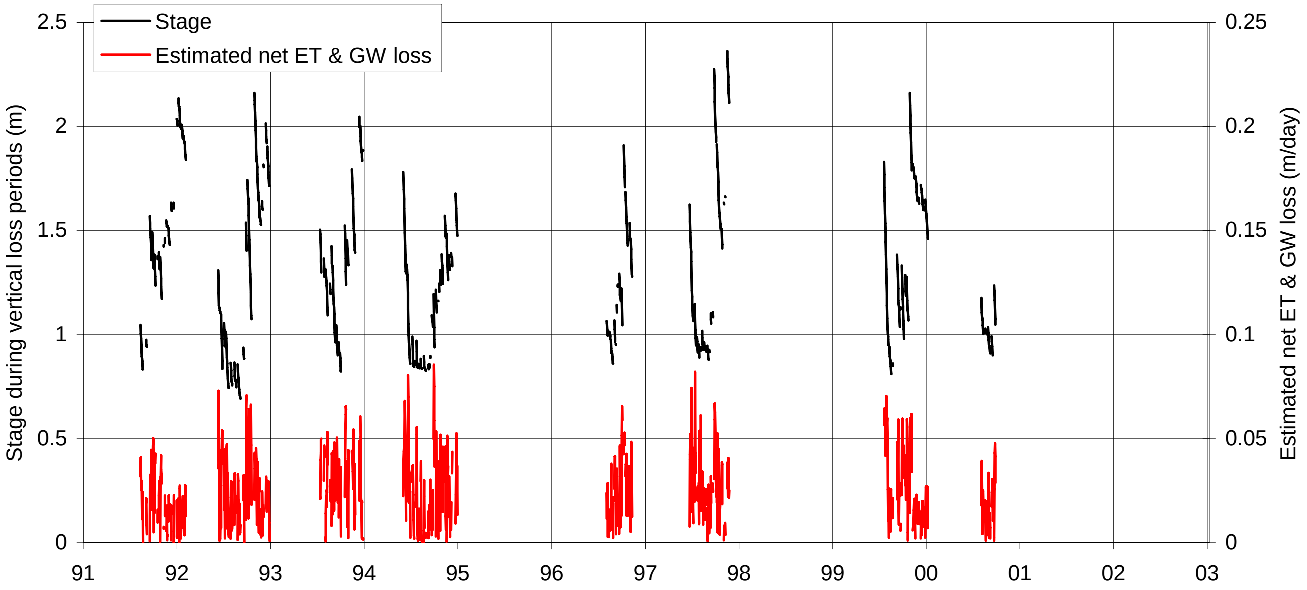


Figure 5.3. Preliminary estimation of net vertical loss from Lagoon water volume - i.e. evaporation minus subsurface inflow. Data shown are all downward changes in lagoon stage when daily range in stage was less than 1 foot, and river flow was zero.

6 Typical water balance

6.1 Introduction

The dominant hydrologic processes of the lagoon vary considerably during the year. About half the time, the lagoon is open to the ocean, and half the time, it is closed by a temporary sandbar. During both phases, inflow may occur from the river, the ocean, or through precipitation. Interaction with groundwater is thought to occur both to and from the lagoon, exchanging with both the ocean and the surrounding freshwater aquifer, depending on the season. The sand bar may breach naturally or it may be breached manually. It is rebuilt by large ocean waves once surface flow subsides sufficiently. Sometimes a rapid cycle of breach-build events occur in succession.

The water balance of the lagoon is not easily conceived in annual or even monthly terms. A daily balance is warranted. The lagoon benefits from excellent data on the primary drivers of the water balance – streamflow and wave height – and on the fluctuations in surface water level.

A daily simulation model was designed and developed within the Tarsier environmental software modeling framework (Watson & Rahman, 2003) as follows.

The model (named Papio) simulates the changes in daily surface water storage of the lagoon by estimating each of the primary fluxes into or out of the lagoon. These include streamflow, open-bar outflow, open-bar inwash, closed-bar overwash, closed-bar throughflow, precipitation, and evaporation. It also simulates daily changes in sand bar elevation based on build-up driven by wave energy, and erosion driven by outflow or manual breaching.

6.2 Spatial structure

The model considers the surface waters of the lagoon as a single ‘bucket’ whose crest elevation is set by the elevation of the sand bar. The bucket is non-linear – its stage-volume relationship is a curve based on a combination of topographic survey and differential flow analysis. The sand bar is characterized solely by its crest elevation. The river is an input, which flows directly into the bucket. The ocean is also a source-sink, and its state is represented by a weighted sum of measured tide level and wave height.

6.3 Variables

6.3.1 State variables

The model has two state variables:

- V_t : the lagoon volume at time t (m^3)
- b_t : the sand bar elevation at time t (m above sea level, NGVD)

6.3.2 Time series input variables

The time series inputs that drive the daily dynamics of the model are:

- $Q_{s,\,t}$: streamflow input (m^3/s)
- h_t: dominant wave height in near-shore waters (m)
- m_t : tide level (m, NGVD)
- $q_{p,t}$: precipitation (m/day)
- B_t : manual breach occurrence (boolean)

6.3.3 Time series output variables

The primary time series outputs simulated by the model include:

- s_t : lagoon stage at time t (m, NGVD)
- $Q_{o,t}$: surface flow output to the ocean (possibly negative) (m^3/s)
- $Q_{b,t}$: subsurface flow through the sandbar (positive toward ocean) (m^3/s)
- $Q_{e,t}$: free-surface evaporation (m^3/s)

6.3.4 Intermediate variables

Some intermediate variables used by the model include:

- $h_{c,t}$ – effective wave height (closed bar) (m, NGVD)
- $h_{o,t}$ – effective wave height (open bar) (m, NGVD)
- $d_{c,t}$ – bar deposition (closed bar) (m/day)

6.3.5 Parameters

Static model parameters include:

- q_e : free-surface evaporation rate (m/day)
- e : sand bar erosivity (m/day/(m^3/s))
- c_m : tide coefficient (-)
- $k_{h,c}$: effective wave height constant (closed bar) (m)
- $k_{h,o}$: effective wave height constant (open bar) (m)
- $c_{h,c}$: effective wave height coefficient (closed bar) (-)
- $c_{h,o}$: effective wave height coefficient (open bar) (-)
- $c_{d,c}$: bar deposition coefficient (closed bar) (m/day/m)
- $c_{d,o}$: bar deposition coefficient (open bar) (m/day/m)
- T: bar transmissivity ($m^3/s/m$)
- c_w : wave overwash coefficient ($m^3/s/m$)
- Q_d : deposition-limiting outflow (m^3/s)

Finally, lookup tables are required that list the lagoon surface area and total volume for incremental stages:

- $A(s)$: lagoon surface area at stage s (m^2)
- $V(s)$: lagoon volume at stage s (m^3)

6.4 Processes

6.4.1 Time step

The model was run on a daily time step (although the equations are structured to run on any time step, Δt (days)).

Execution proceeds sequentially through each modeled process. No numerical solution schemes are used.

6.4.2 Initial fluxes

Execution begins by adding streamflow and precipitation to, and withdrawing evaporation from the lagoon.

$$V_t \quad \uparrow \quad \Delta t\left[Q_{s,t} + (q_{p,t} - q_e)A(s_t)\right]$$

where the notation '↑' denotes that the term on the left is increased by the term on the right.

6.4.3 Dynamic lagoon head

When streamflow is present, this usually leaves the lagoon stage at a somewhat elevated level, which is thought of as reflecting the dynamic head imparted by the river on the lagoon. Subsequent calculations work with this effective lagoon head value in the computation of outflow.

6.4.4 Dynamic wave head

The effect of waves is thought of as a hydraulic head imparted by the waves on the sand bar or the open lagoon waters. Effective wave heights are computed separately for closed and open lagoon conditions:

$$\begin{aligned} h_{c,t} &= k_{h,c} + c_{h,c}h_t + c_{m,c}m_t \\ h_{o,t} &= k_{h,o} + c_{h,o}h_t + c_{m,o}m_t \end{aligned}$$

6.4.5 Through-bar flow

The subsurface transmission of water through the sand bar (in either direction) is determined by the difference in effective head between the lagoon and the ocean, and a transmissivity parameter:

$$\begin{aligned} Q_{b,t} &= (s_t - h_{c,t})\,T \\ V_t &\uparrow -Q_{b,t} \end{aligned}$$

If a manual breach is indicated (B_t), the sand bar elevation is set to sea level:

$$b_t \quad = \quad 0$$

6.4.6 Closed-bar and open-bar modes

Subsequent computations may reflect either closed-bar or open-bar conditions. Closed-bar conditions are indicated if the lagoon stage as at or below the sand bar crest (after computing streamflow inputs, precipitation, evaporation, and through-bar flow; but before computing outflow or overwash):

$$s_t \quad \leq \quad b_t$$

6.4.7 Closed-bar processes: deposition and overwash

If the effective wave height is above a closed bar, the elevation of the bar is raised due to sand pushed up by the waves, and simultaneously, overwash is simulated. Sand deposition on the bar under closed conditions is modeled as being proportional to wave height above the bar, and a coefficient:

$$d_{c,t} = (h_{c,t} - b_t)\, c_{d,c} \qquad 0 \leq c_{d,c} \leq 1$$
$$b_t \uparrow d_{c,t}\ \Delta t$$

Overwash from the ocean into the lagoon is based on a similar formulation, with the upper bound for overwash being set by the ability of the newly raised sand bar elevation to retain the water:

$$Q_{w,t} = \min\left[\left(h_{c,t} - b'_t\right) c_{o,c}, \frac{\left(V\left(b_t\right) - V_t\right)}{86400\ \Delta t} \right]$$
$$V_t \uparrow Q_{w,t}\ 86400\ \Delta t$$

where b'_t is the bar elevation prior to deposition.

6.4.8 Open-bar processes: outflow

The existence of outflow for an open-lagoon is predicted if the lagoon stage is higher than the effective wave height:

$$s_t > h_{o,t}$$

Given this condition, the outflow is set such that the lagoon drains down to a level determined either by waves or the sand bar, whichever is higher:

$$Q_{o,t} = \frac{V_t - V\left(\max\left[h_{o,t}, b_t\right]\right)}{86400\ \Delta t}$$

$$V_t \uparrow -Q_{o,t}$$

This outflow also causes erosion of the sand bar (with effective wave height as a boundary control):

$$e_t = \max\left\{0, \quad \min\left[\frac{b_t - h_{o,t}}{\Delta t}, \quad Q_{o,t}\ e\right]\right\}$$

$$b_t \uparrow -e_t$$

6.4.9 Open-bar processes: inflow

Inflow is predicted when the effective wave height is above the stage of an open lagoon. It is represented as negative outflow, computed so as to equalize zero head difference between lagoon and ocean:

$$Q_{o,t} = -\frac{V\left(h_{o,t}\right) - V_t}{86400\ \Delta t}$$

$$V_t \uparrow -Q_{o,t}$$

6.4.10 Open bar processes: bar deposition

The sand bar of an open lagoon will tend to close under both ocean inflow conditions, and low outflow conditions. Simulation of the overall process is driven by wave height, but linearly reduced to zero as outflow increases from zero to a defined threshold value, Q_d:

$$d_t = h_{o,t}\ c_{d,o}\ \max\left\{0, \quad 1 - \frac{\max\left[0, Q_{o,t}\right]}{Q_d}\right\} \qquad Q_d > 0$$

$$b_t \uparrow d_t\ \Delta t$$

6.5 Calibration

Values for a few of the less-sensitive parameters were specified based on typical data. e.g.:

$$e = 0.003 \quad \text{m/day}$$

The remaining parameters were calibrated against observed stage data using a pattern-search optimization algorithm implemented within the Tarsier framework (Hookes and Jeeves, 1961). This involves specifying a random parameter set, computing an objective function (OF) that measures the goodness of fit between observed and simulated stage, and iteratively changing parameters using an algorithm designed to efficiently converge the parameter values to an optimal set. Local optima are avoided by repeating the process from many random starting points. Confidence in the global optimum is gained when clear unimodal relationships emerge between each parameter and the objective function value. The chosen objective function was based on the Nash-Sutcliffe coefficient of efficiency, with a five times penalty to differences in means of greater than 5%:

$$OF = \frac{\sum (y - y^*)^2}{N} \times \begin{Bmatrix} 1 & 95\% \le \frac{\overline{y^*} - \overline{y}}{\overline{y}} \le 105\% \\ 5 & \text{otherwise} \end{Bmatrix}$$

Lower values of this function indicate superior model performance.

Note also that the model flags its output as ‘missing’ whenever any of the input time series data are missing for some reason. The OF excludes ‘missing’ data, to minimize unfair comparisons. There are a few long periods where the wave height data are missing, as well as shorter periods for the streamflow, tide, precipitation, and observed stage data.

The model was run on various periods of record from several hundred random starting points, progressing through several hundred more model runs in each case to arrive at a local optimum. The total number of model runs thus exceeded 40,000.

The results indicate that most of the model parameters have well-defined values. This is illustrated in Figure 6.1, which plots OF against the sand bar transmissivity parameter for a large number model runs during which the values of other parameters also varied.

In turn, well-defined parameter values are indicative of a well-formed model. Poorly defined parameters, with flat OF response, are indicative of poorly represented or irrelevant processes. This is the case for the overwash parameters, whose poorly defined values might be clarified in future using a sub-daily application of the model.

6.6 Simulation results

An approximate global optimum parameter set was determined based on model runs over the full period of record (water years 1993-2001). This is summarized in Table 6.1. Some plots of simulated versus observed stage are shown in Figure 6.2.

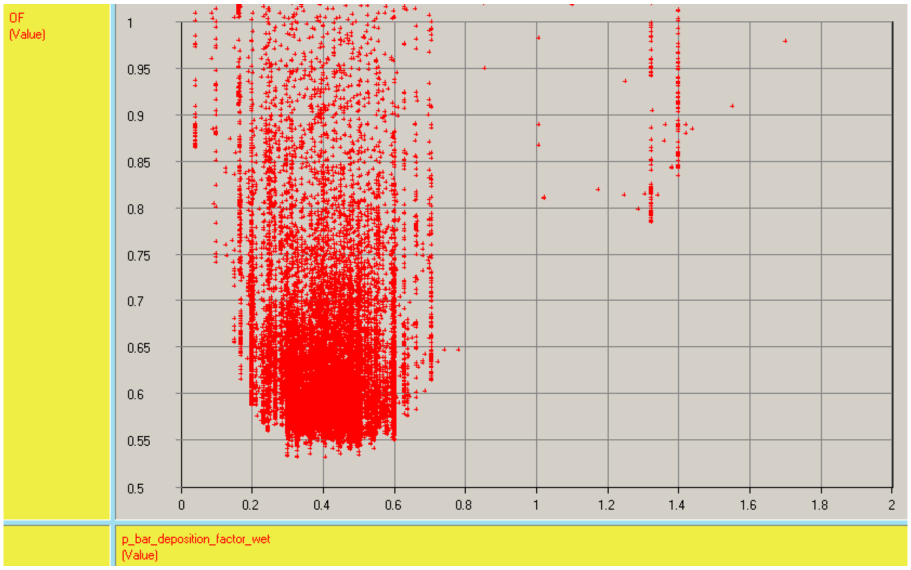


Figure 6.1. Example results of parameter optimization process. Objective function (OF) plotted against open-lagoon bar-deposition coefficient. The plot reveals that the optimal parameter value is most likely to be about 0.4, because this is the region of lowest OF values.

Table 6.1. Calibrated parameter values.

Parameter	Calibrated value
q_e	0.003 m/day
e	1.93032 m/day/(m^3/s)
c_m	0.16
$k_{h,c}$	0.75998 m
$k_{h,o}$	0.706717 m
$c_{h,c}$	0.350793
$c_{h,o}$	0.223515
$c_{d,c}$	8.610920 m/day/m
$c_{d,o}$	0.339155 m/day/m
T	0.350169 m^3/s/m
c_w	5.749596 m^3/s/m
Q_d	2.698309 m^3/s

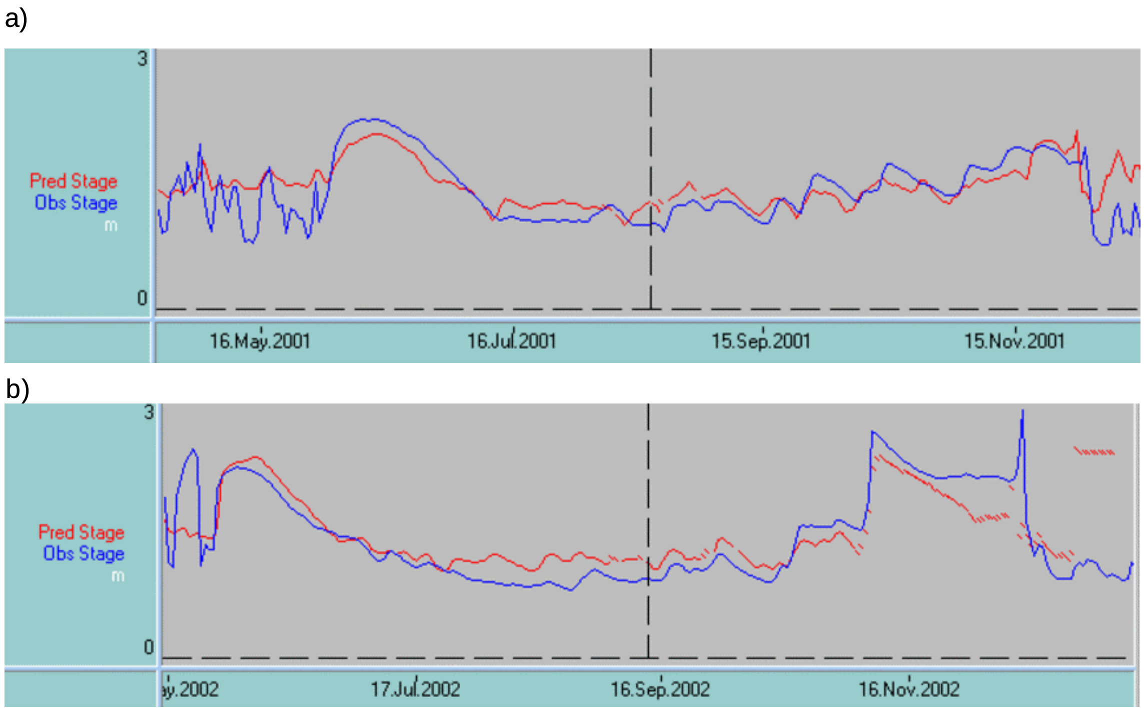


Figure 6.2 Simulated versus observed lagoon stage for closed-bar periods in: a) 2001 and b) 2002.

The results indicate that the model is able to reproduce the fundamental dry-season dynamics of the lagoon, including:

- late winter closure of the lagoon, and subsequent gradual rising stage while low streamflow persists
- through-bar draining of high lagoon stages to the ocean in the early dry season
- week-scale fluctuations in summer stage driven by ocean wave height and back and forth flow through the sand bar
- Discrete jumps in stage and sand bar elevation due to high wave overwash
- Persistence of manual breaches
- Some natural breaches

Stage dynamics are poorly predicted during high streamflow conditions, due to un-simulated sub-daily variance.

6.7 Discussion

The model yields insight into the general magnitude of the components of the Carmel Lagoon's water balance. Simulations during the 2001 water year are discussed.

The maximum mean daily inflow during the 2000-1 winter was in the region of 50 m^3/s, occurring on March 3rd (49 m^3/s at Hwy 1, and 55 m^3/s at Via Mallorca). Inflow gradually subsided until flow ceased around 30th June 2001. The lagoon stage fluctuated over a 1-meter amplitude during the inflow period, with the stage apparently controlled by ocean waves and tides more than the magnitude of streamflow input (a hydraulic backwater effect).

By May 30th, inflow had subsided below 0.6 m3/s, at which time sand deposition by ocean waves began to exceed sand erosion by outflow. The sand bar elevation rose from about 1 meter (3.4 feet) to 2.2 meters (7.1 feet) by June 9th, about 10 days later. The inflow magnitudes remained high enough for the lagoon stage to keep pace with the sand bar aggradation, with excess flow probably spilling over the crest as net outward surface flow.

By June 9th, the inflow had subsided to about 0.2 m^3/s. From this time onwards, all remaining inflow was equaled and exceeded by subsurface outflow through the sand bar in the region of 0.15 m^3/s (5 cfs). Surface outflow was not required in order to compensate for surface inflow, so surface outflow ceased and the lagoon closed. The stage then gradually fell from its spring high point, below the elevation of the sand bar, which remained relatively stable through to the following fall.

By mid-July, the stage had declined from over 2 meters down to a dynamic equilibrium with a mean stage of about 1 meter. During the remaining summer months the lagoon went through week-long rising periods, driven by subsurface inflows through the sand bar of 0.05 to 0.15 m^3/s (2 to 5 cfs); and week-long falling periods at a slightly lower rate of about 0.03 to 0.1 m^3/s (1 to 4 cfs). These periods were primarily driven by fluctuations in ocean wave height, and to a lesser extent, tide height. The lagoon stage did not apparently reach the bar elevation at any time, except on one possible occasion when waves may have raised the bar elevation and contributed a matching over-bar inflow to the lagoon.

Aside from these fluctuations, there was a general trend toward increasing stage throughout the summer months. This may simply be due to a rising trend in wave height. It may also be due to a wave-pumping effect, where the transmission response to head is non-linear and favors subsurface inflow over subsurface outflow. Closer inspection is warranted here.

By late November, the lagoon remained closed with a stage fluctuating just below 2 meters (6 feet). The winter of 2001-2 arrived on the December 3rd 2001 following a storm generating a mean daily flow of 8 m^3/s. Some minor flows arrived in the preceding days, gradually building up the lagoon stage. The lagoon was manually breached as the stage reached a maximum level of 3.25 meters (10.65 feet). The stage fell rapidly to below 1 meter, and thereafter entered a winter period of high inflow, high outflow, and wave driven stage fluctuations between about 1 meter and 2 meters.

These dynamics are typical of many of the years included in the simulation.

7 Lagoon volume

7.1 Empirical stage-capacity relationships

The stage-volume curve for a lagoon is typically determined through topographic or bathymetric survey. It can also be determined by analysis of the rate at which stage increases for given streamflow inputs when the lagoon is closed. We term the resulting relationship a stage-capacity relationship, because it directly quantifies the capacity of the lagoon system to store water both above the surface, and in the pore spaces of shallow soil and sand.

The analysis used sub-hourly streamflow data from Highway 1, and sub-hourly stage data from August 1991 through May 2002. The data were first aggregated into hourly averages. Then, the following statistics were computed for stage at the daily level:

- mean
- minimum
- maximum
- first value of day
- last value of day
- monotonically rising throughout day?

Days were selected for further analysis only if they were the middle day in a period of continually rising stage at least 3 days long. These periods are highly likely to exclusively reflect closed bar conditions with continuous streamflow input. They occur just before breach events, and just after closure events.

For each selected day, the effective surface area of the lagoon (m^2) was computed as the inflow (m^3/day) divided by the change in stage (m/day). The term 'effective' is used to account for additional 'surface' water capacity contributed by shallow soil porosity. A plot of this area versus stage is a stage-area relationship. Integrating with respect to stage yields a stage-capacity relationship.

The result is shown in Figure 7.1, where each sequence of rising stages is plotted separately. The Matthews 1997 curve based on topographic survey of part of the lagoon is shown for comparison. The overall magnitude of the computed effective surface areas matches the Matthews data. Exceptions are explained as follows.

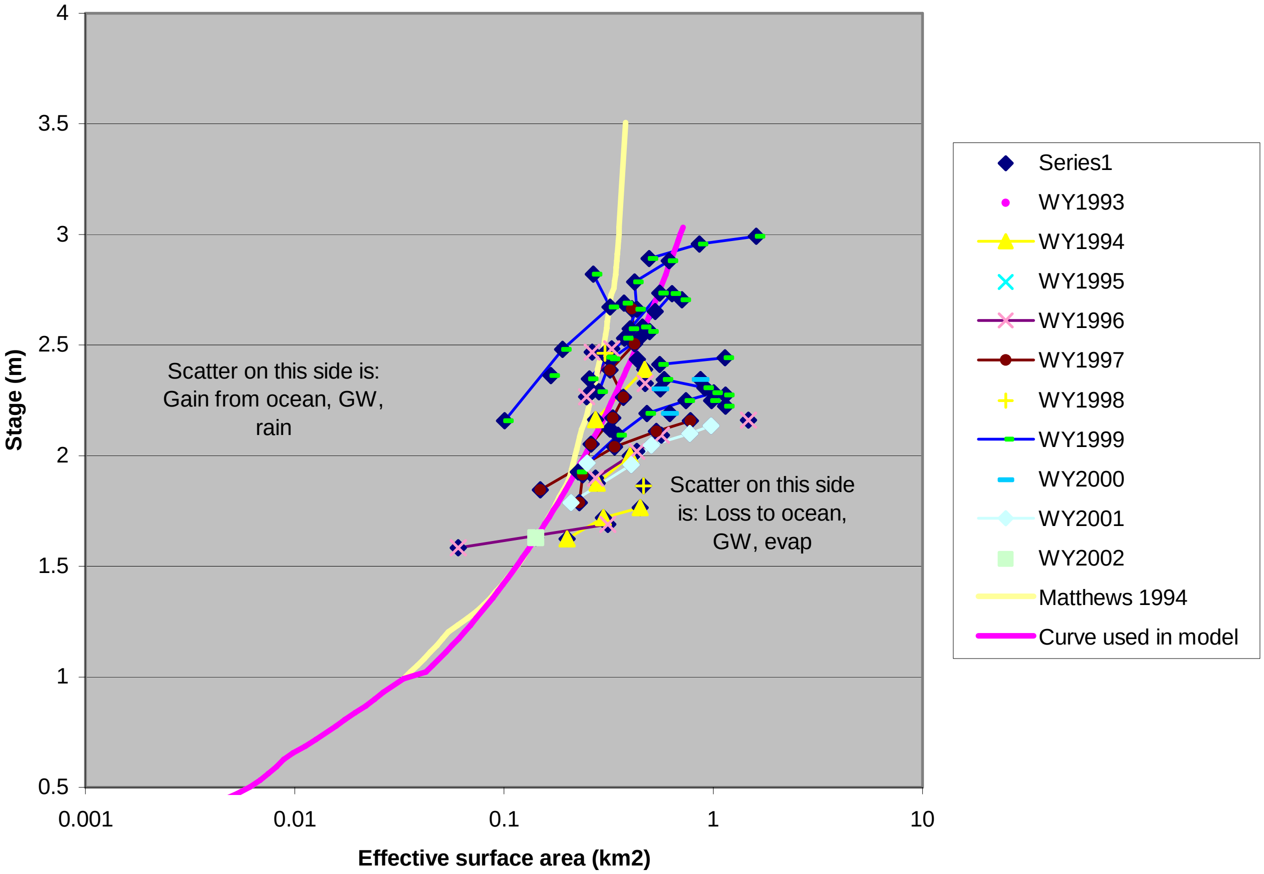


Figure 7.1. Lagoon stage-capacity relationships estimated by differential analysis of stage data and inflow data during quiescent periods.

The rising-stage curves are biased toward large surface areas than the Matthews data. This is both because the Matthews data excluded most of the southern lagoon area, and because topographic survey excludes shallow soil storage capacity. The same factors account for the lower slopes of the rising-stage curves than the Matthews curve, with the addition of a further explanation. The smallest inflows represented may be offset by subsurface outflow through the sand bar of a similar magnitude. This has the effect of lowering the slope of the stage-area curve, especially for the relatively few cases where the streamflow input was low enough to be potentially equaled or exceeded by the sand bar throughflow.

A final source of variance in the analysis is the actual change over time of the storage capacity of the lagoon. The study period includes very severe storm events in 1995 and 1998, as well as the excavation of the South Arm. In addition, the large amount of data included from 1999 suggests that the storage capacity changes within a flow season. Specifically, it appears that the first rising stage of the season fills soil pore spaces from a completely empty state. After the stage falls again, the drainage of shallow groundwater may lag behind the stage to a sufficient degree that some residual capacity remains filled prior to the onset of subsequent rising-stage events.

To analyze these changes, we assumed that each data point in Figure 7.1 lay on a simple stage-area curve of the form:

$$s = a + b \log(A)$$

where *a* and *b* are the coefficients of a log-linear relationship.

Under this formulation, the mean slope of the rising-stage curves in Figure 7.1 is approximately constant with a value *b* = 0.5. Differences between curves are then characterized solely by changes in *a*:

$$a = s - b \log(A)$$

The value of *a* was computed for every day included in the analysis, and plotted against time in Figure 7.2. Long-term, increasing values of *a* indicate aggradation of lagoon sediments (e.g prior to 1999). Decreasing values indicate scour or excavation (e.g. post 1999). Short-term increases within a single winter may indicate that residual shallow groundwater storage reduces the storage capacity to each subsequent lagoon filling event.

The curve used in the simulation model was a hybrid of the raw Matthews data for low stages, augmented by a mathematical curve fitted to bisect the rising-stage data for high stages:

$$Vol = \begin{Bmatrix} Vol_{Matthews} & h < 1\,\mathrm{m} \\ 0.04 \times h^{2.6} & h \geq 1\,\mathrm{m} \end{Bmatrix} \quad \mathrm{m}^3$$

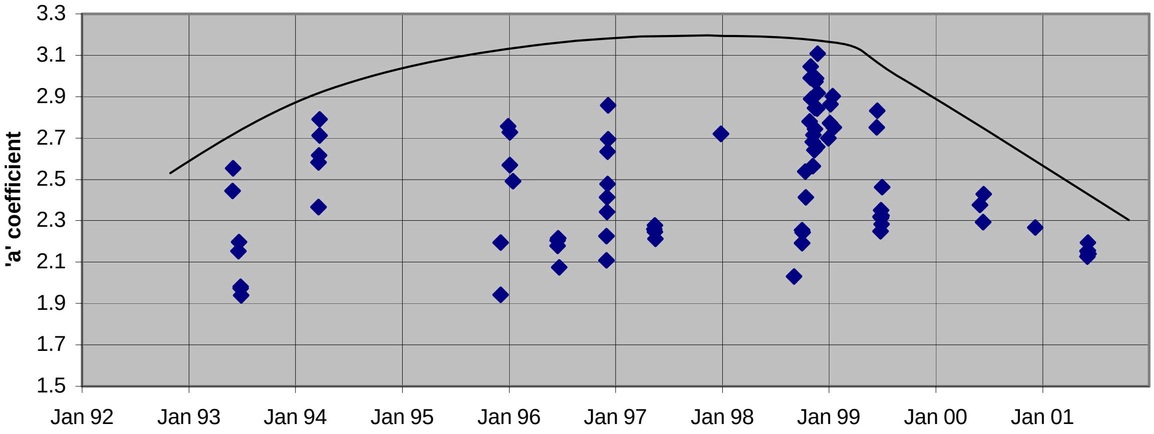


Figure 7.2. Evidence for change over time in lagoon storage capacity.

8 Lagoon hydrology: 2003

The four figures on the following two pages describe time series of river discharge, lagoon stage, ocean wave height, and precipitation in the watershed.

8.1 River discharge

The river discharge in 2003 was typical for a relatively dry year. Flow declined from winter storm peaks throughout spring, finally drying up on July 29th. The first flow of the following winter came late, on December 30, 2003. Thus, for 5 months, there was effectively no surface water input to the lagoon from its watershed – other than direct, local inputs associated with traces of rainfall in summer, and some minor storms in November.

8.2 Lagoon stage

The lagoon stage also followed a typical pattern. After some temporary closures in June, the sandbar closed for the summer in early July. River flow proceeded to fill the lagoon to about 1.6 m NGVD as waves maintained and increased the sandbar. Flow through the sandbar was sufficient to disperse the declining river flow, as a result and the stage declined to a summer low-point of below 0.4 m NGVD by early August. The stage then fluctuated every week or two throughout the summer due to through-bar flow driven by tides and waves. Marked increases occurred in October and December during particularly high ocean wave events. Inflow from the river rapidly filled the lagoon just before the new year, when it was manually breached.

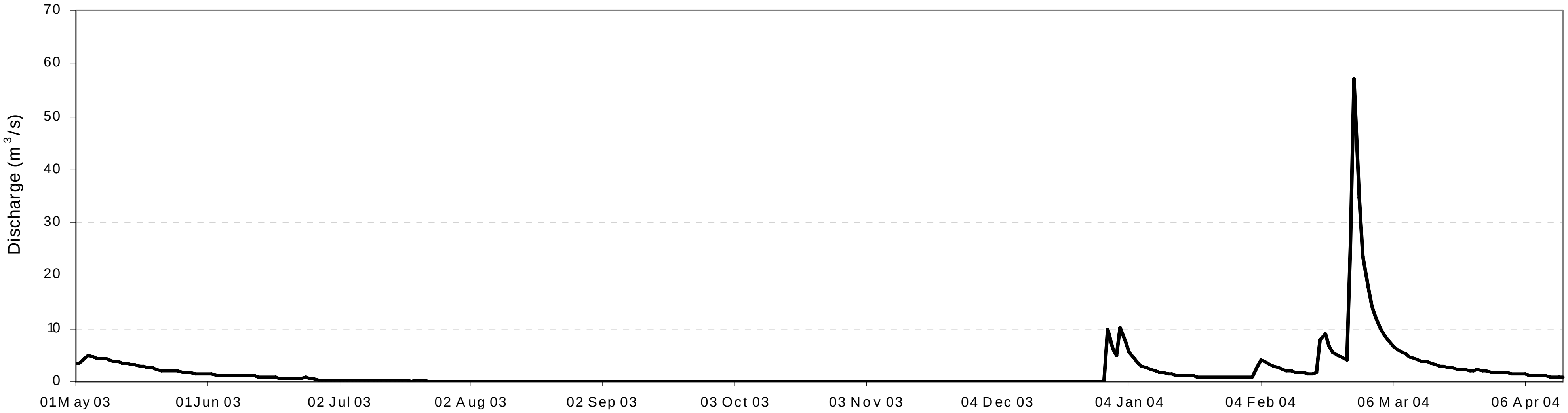


Figure 8.1. Discharge in the Carmel River at USGS Gage 11143250 Carmel River nr Carmel.

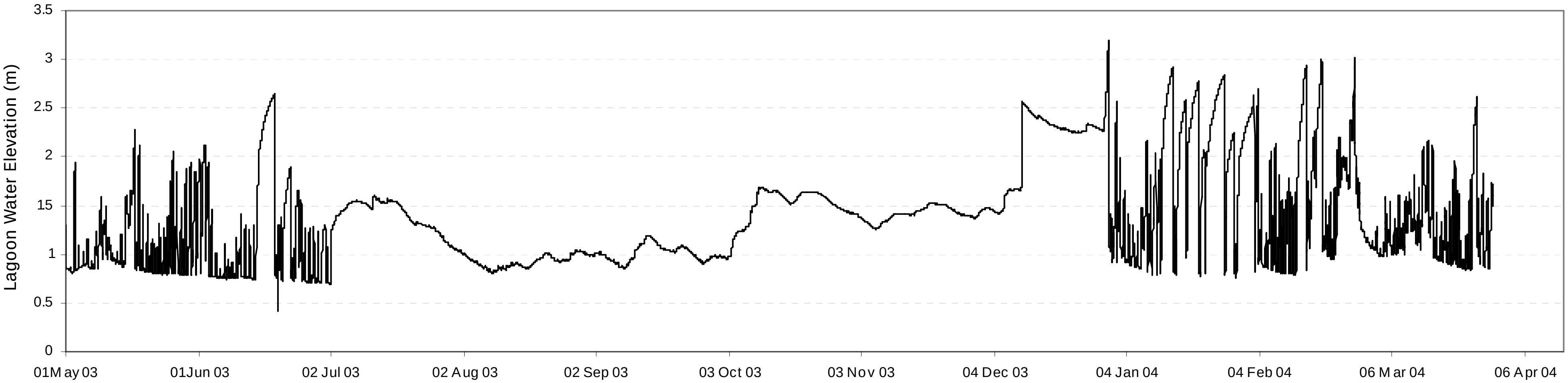


Figure 8.2. Carmel Lagoon water elevation. Data Source: Monterey Peninsula Water Management District

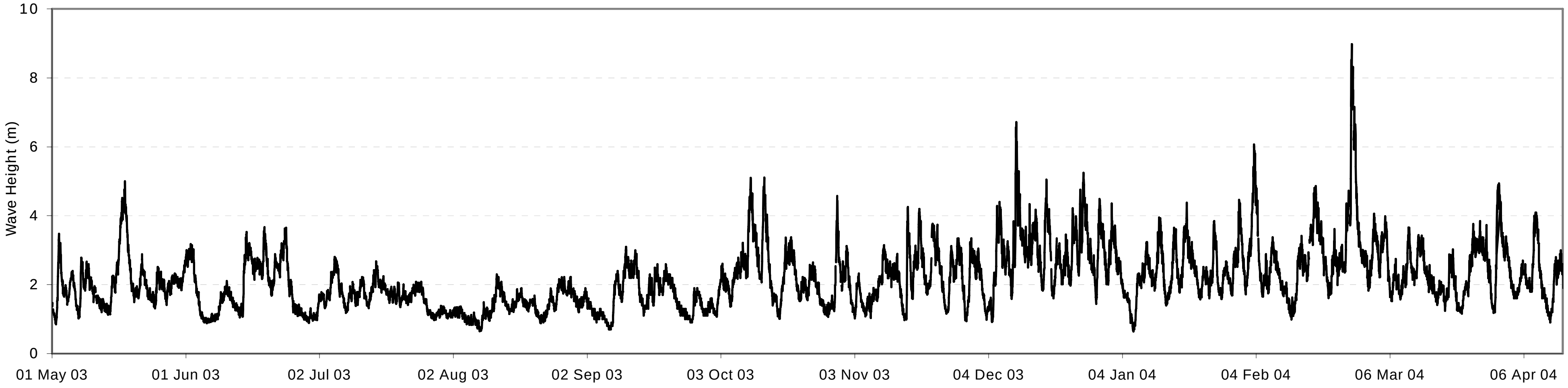


Figure 8.3 Hourly significant wave height for Monterey Bay. Data source: NOAA.

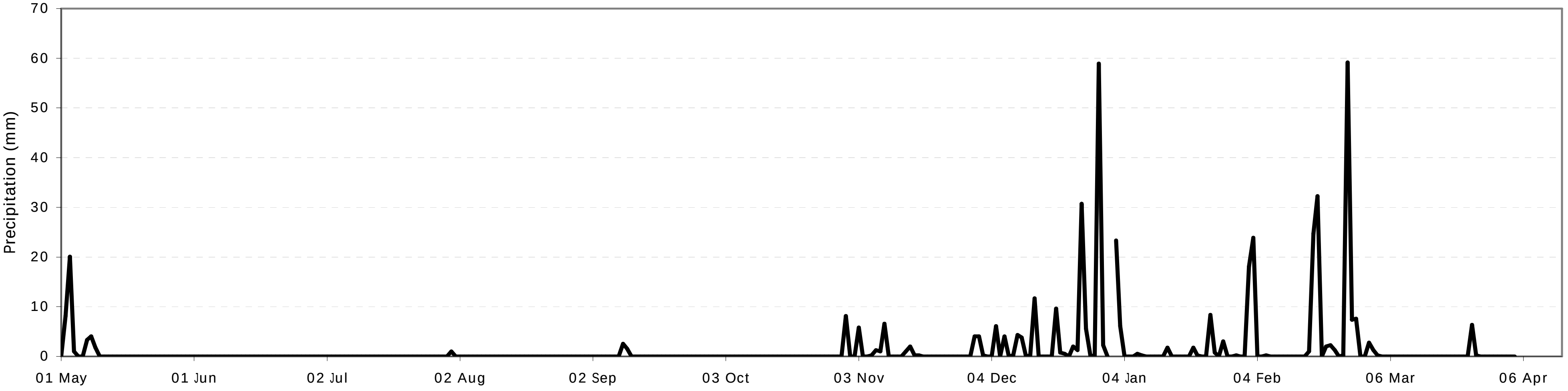


Figure 8.4 Daily precipitation, Carmel Valley. Data Source: Hastings Ranch Natural History Reservation.

9 Lagoon salinity: 2003

Three aspects of lagoon salinity were examined. Firstly, the seasonal development of the salinity profile during 2003 was described. Secondly, a flow of groundwater into the lagoon was demonstrated. And thirdly, a lagoon-groundwater hydraulic connection was shown to extent as far inland as the Rio Road monitoring well, near the site of proposed future increased groundwater pumping.

9.1 Seasonal development of the salinity profile

A YSI 556 multi-probe sensor was used to manually record salinity at 0.5 m depth increments below the CAWD outflow pipe on various dates during the 2003 dry season. The readings were color-coded and plotted as crosses (+) on the figure below. Isohalines were drawn in manually.

Just prior to final lagoon closure in late July, a 2.5 m thick seawater (33 ppt) layer existed below sea level (0 m NGVD) in the lagoon, while the surface was nearly fresh (around 2 ppt). From that point onwards, the seawater layer thinned and became limited to the deepest half meter by late September. In its place, the broadly brackish zone expanded from being 1 m thick in July to about 2.5 m thick in September.

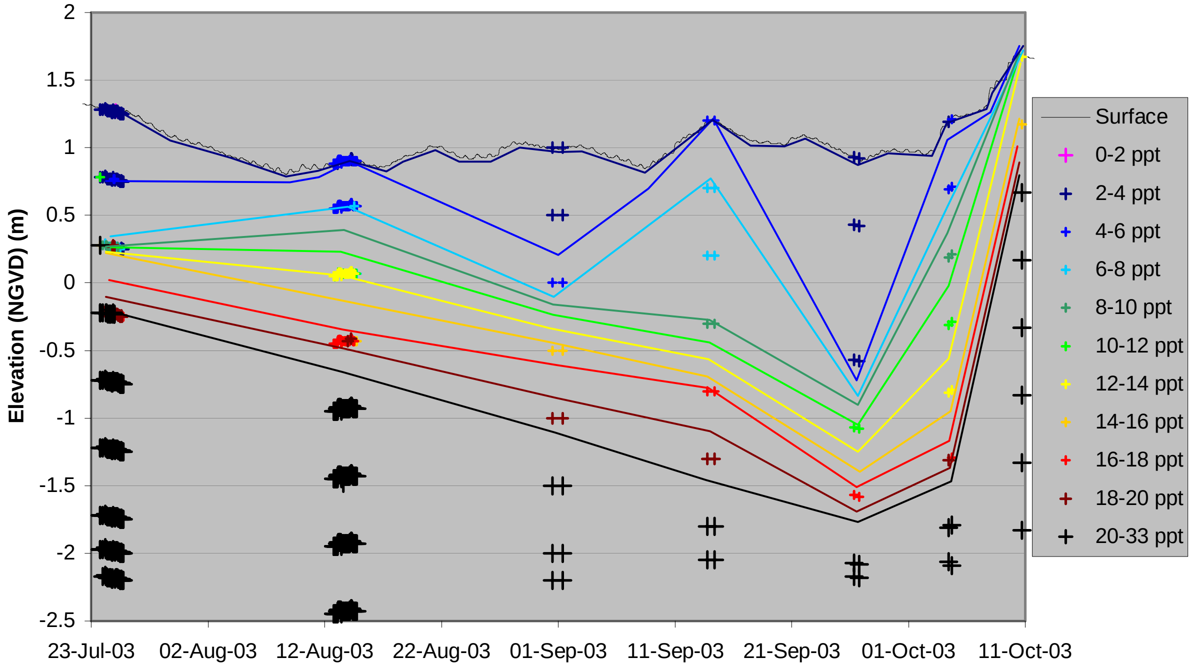


Figure 9.1. Development of the Carmel Lagoon salinity profile throughout the 2003 dry season.

Despite this general increase in freshness, the surface itself did not remain fresh. High waves in mid-September forced enough seawater through and over the sandbar to raise the stage about 0.5 m and bring the upper 1.5 m to 5-8 ppt. This wave pressure then relaxed and by late September, the upper 1.5 m had rapidly freshened to 2-4 ppt. Bigger waves returned in early October, bringing the surface to 13 ppt, and in November to 18 ppt, after an intervening relaxation to 6 ppt.

Surface and bottom salinity patterns are plotted in more detail below. The effect of waves increasing stage and salinity in unison during the dry season is clear.

It is unclear whether the total freshwater volume of the lagoon increased or decreased during the dry season. It is possible that the season-long trend is simply one of gradual mixing and de-stratification, with no net input of freshwater. It is also possible that the periods of surface freshening can only be explained by an ongoing freshwater source, such as groundwater. The freshwater balance is non-linear with respect to the elevation of isohalines. For example, there is 6 times more volume between 0.5 m and 1 m as there is between 0 m and 0.5 m NGVD. We transformed the isohalines into volumes using the stage-volume curve, but found that imprecision in both the curve and the salinity data were such that a stable freshwater balance could not be constructed in this way.

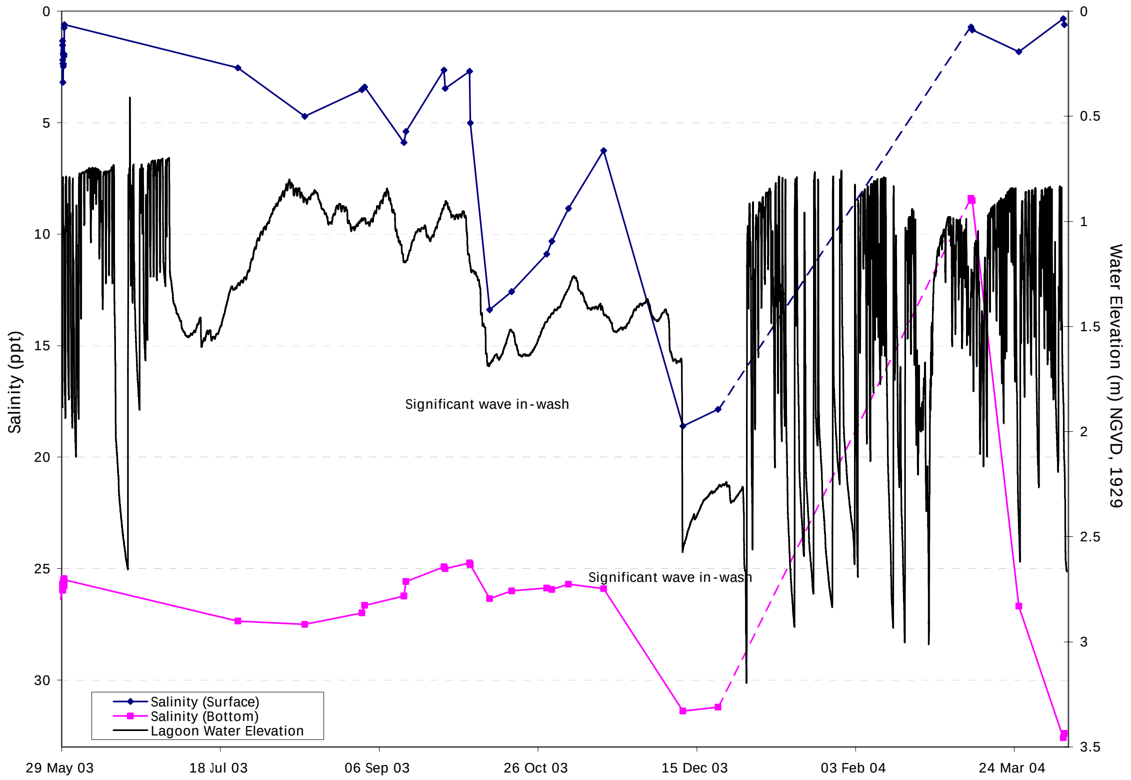


Figure 9.2 Surface and bottom salinity change with lagoon stage.

9.2 Measurement of shallow groundwater salinity beneath lagoon

The groundwater monitoring wells in the vicinity of the lagoon reveal generally fresh groundwater at all depths (Feeney, 2004). Some salinity is occasionally detected at the Beach well near the surface, and at the Beach and Wetlands wells just above bedrock during drought (M. Feeney, pers. comm.). The bottom of the lagoon, on the other hand, is usually very saline. There must therefore be a reverse halocline beneath the lagoon. Further, the location of this halocline would be determined by the direction of groundwater flow into or out of the deepest parts of the lagoon.

Field measurements of the salinity profile in the sediments below the bottom of the lagoon were made using a drive-point piezometer. This is simply a steel rod pushed or hammered into the lagoon bottom. The 30 cm of the tip of the rod is screened with a stainless steel mesh. We sealed a conductivity meter inside the screened portion.

The results in the Figure below reveal that fresher water lies within a meter of the

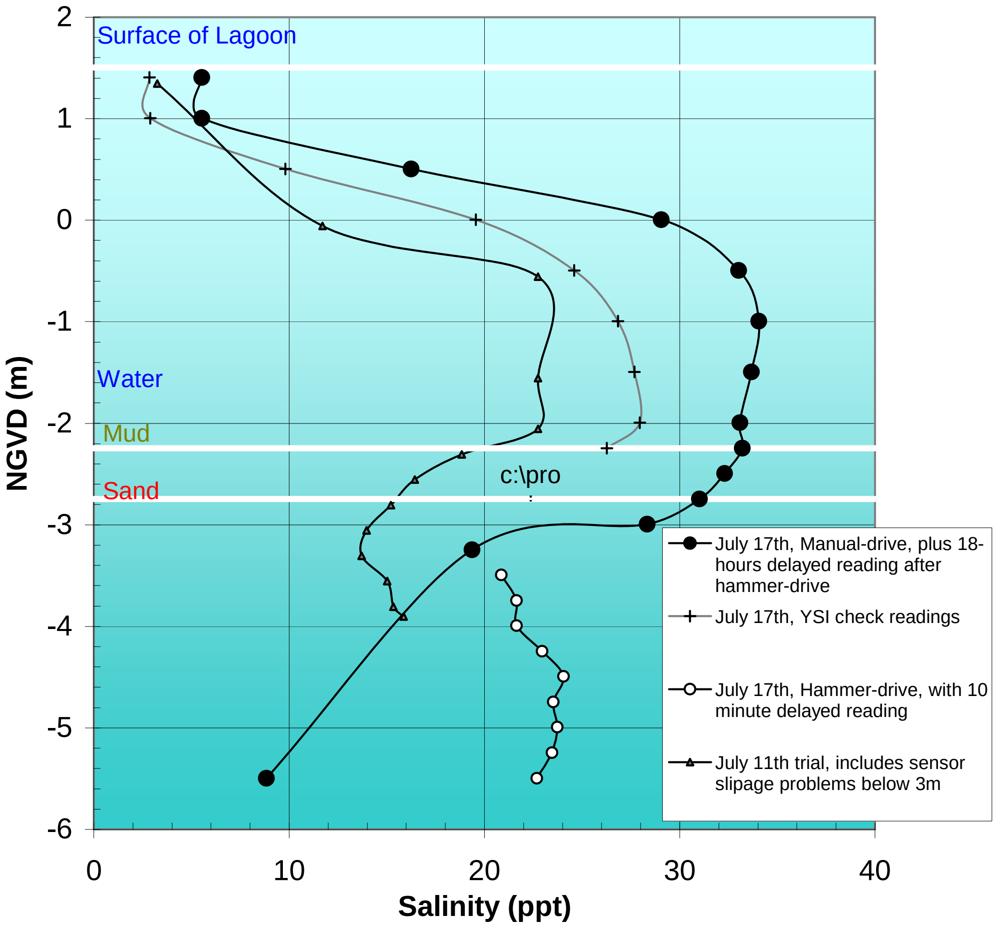


Figure 9.3. Salinity profiles in sediments beneath the lagoon.

bottom of the lagoon. This indicates minimal diffusion of salt away from the lagoon, which can only be due to groundwater flow under positive pressure into the lagoon.

Note that any leakage of lagoon water down into the well made by the sensor would result in increased salinity, since the bottom of the lagoon is comprised of seawater. When the piezometer was driven by hand, no such leakage occurred – all deep readings were fresher than those above. Under hammer drive, leakage clearly occurred, since salinity increased as soon as the hammer was used. This could be eliminated by waiting several hours after hammering for any leakage to be dissipated by the surrounding groundwater.

The conclusion is thus that groundwater flows into the lagoon at depth during mid-summer.

9.3 Detection of hydraulic backwater effects

The spatial extent of groundwater influencing the lagoon was determined by examining the system in reverse – i.e. by examining the response of distant groundwater monitoring wells to a rapid perturbation in lagoon stage.

The figure below overlays lagoon stage with monitoring well data (from Feeney, 2004, pers. comm.) and effective ocean wave height. The latter was calculated hourly using the equation and parameters from the water balance model, with a 6-hour lag for wave height data, and a 4-hour lag for tide data. These lags were determined by optimizing the correlation between effective wave height and the water level in the Beach monitoring well.

A distinct wave over-wash event in November 2002 is shown. The Beach well very clearly responded to both tidal variation and the large wave event lasting about a day. The lagoon stage rose rapidly over a few hours in response to two major increments in wave height. The Wetlands well rose at the same rapid rate, but to a lesser extent. The NRCAWD well rose more slowly, over about a day. The response of the Rio Rd well was very slight, and probably marks the inland limit of detectability for this type of disturbance of the hydraulic gradient surrounding the lagoon.

The response to the wave event is shown in section view in the figure below. Note the increase in water level of the most inland well (Rio Rd), despite the fact that its water level is higher than any water level closer to the ocean. This is a backwater effect that can only occur when there is a flow past this well toward the ocean. The increase in downstream water levels forced by the ocean caused a reduction in the hydraulic gradient at Rio Rd, forcing the water level there to rise.

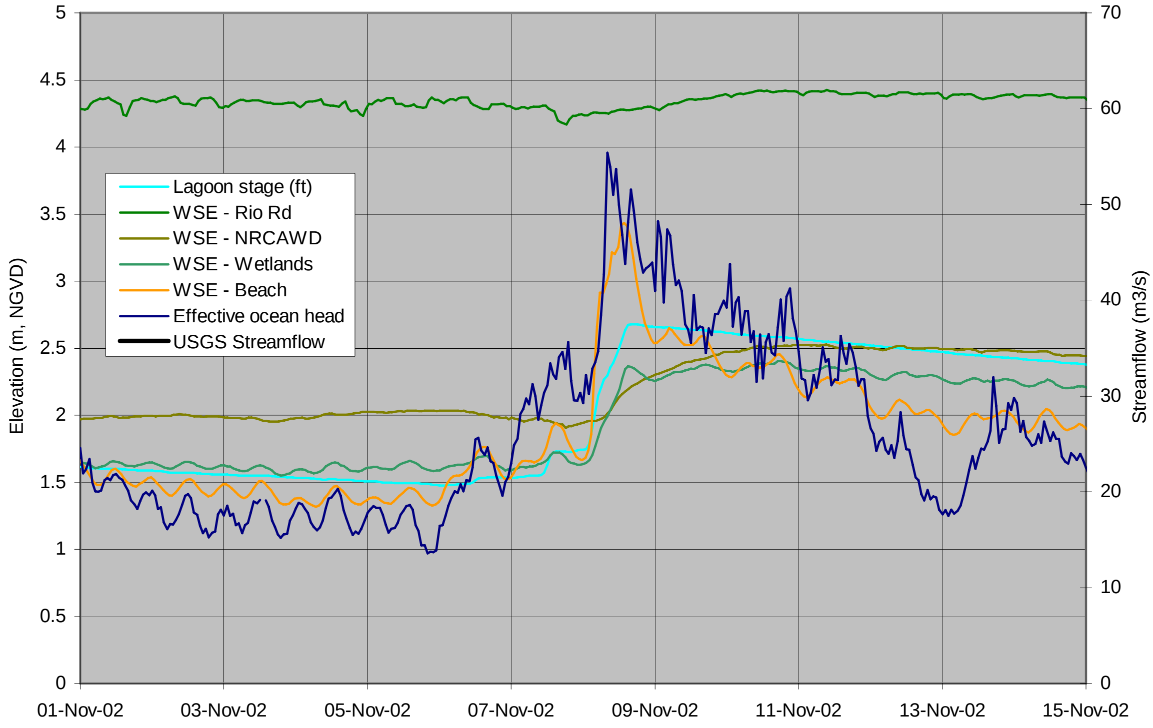


Figure 9.5. Response of lagoon, and groundwater levels to a large increase in ocean wave height.

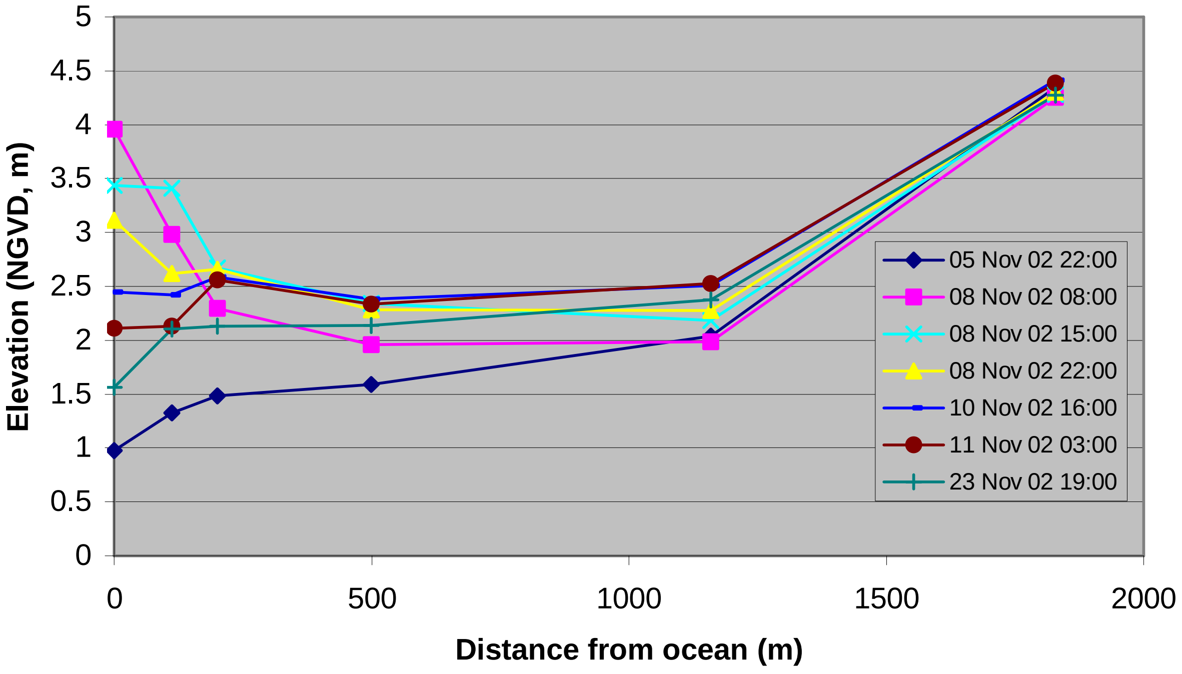


Figure 9.4. Cross-section of ocean, lagoon, and groundwater water levels near Carmel Lagoon – in response to a large ocean wave event.

The implication of this observation is the inverse situation. If groundwater pumping caused a reduction of water levels within about 1750 m of the ocean, this would reduce the existing flow through the lower Carmel Valley aquifer into the lagoon. Note however, that the absolute magnitude of this flow remains unknown, and so too therefore does the magnitude of its influence on the salinity of the lagoon.

10 Detailed water quality monitoring narrative

10.1 Introduction

This section attempts to establish a reference framework for summer physical water quality conditions in the lagoon, against which future conditions may be compared. The pretext is that rearing habitat for juvenile steelhead may reach its least optimal condition in later summer/ early autumn due to:

- low volume
- high salinity
- high temperature
- low daily dissolved oxygen minima

Field monitoring was based around the measurement of salinity, temperature, and dissolved oxygen in vertical profiles with 0.5 m intervals. Most measurements were taken from the CAWD outflow pipe, with some ancillary profiles taken near the sandbar from time to time. Measurements were taken every few weeks, more often in late summer, when lagoon water quality is most stressed, and less often in winter, when lagoon water quality is unrelated to groundwater interactions. On three occasions, intensive 24-hour or 48-hour campaigns were undertaken, with hourly profiles taken around the clock. On one occasion, nutrient and chlorophyll samples were taken and analyzed. In addition, a vertical chain of temperature loggers was installed between May 2003 and April 2004. Data are presented separately from an initial period in May-June 2003, and then for a longer deployment from July 2003 onwards.

The following sections describe these activities in detail, and explain the results. An overall timeline of profile surveys is given in Table 10.1.

Table 10.1 Summary of water quality monitoring activities.

Date/Time	Data Type										Location	Notes
	T	DO	S	pH	De	Z_{sd}	NO3	NH3	PO4	CHL-a		
28 May 03 15:30	X	X	X		X						South Arm-Pipe	Sand bar Open, river water coming in
29 May 03 5:30-19:30	X	X	X		X						South Arm-Pipe	Sand bar Open, river water coming in
23-25 Jul 2003	X	X	X	X	X	X					South Arm – Pipe	Sand bar closed, no river flow
12 - 14 Aug 2003	X	X	X	X	X	X	X	X	X	X	South Arm – Pipe	Sand bar closed, no river flow
31 Aug 03 11:45	X	X	X	X	X	X					1. South Arm-Pipe 2. Granite Outcrops 3. Bar	Sand bar closed, no river flow, aerator in south arm running
01 Sep 03 9:00	X	X	X	X	X						1. South Arm-Pipe 2. Granite Outcrops 3. Bar	Sand bar closed, no river flow, aerator in south arm running
13 Sep 03 18:45	X	X	X	X	X						South Arm – Pipe	Sand bar closed, no river flow, two aerators running in south arm
14 Sep 03 9:05	X	X	X	X	X						South Arm - Pipe	Sand bar closed, no river flow, aerators not running in south arm
26 Sep 03 8:39	X	X	X	X	X						South Arm - Pipe	Sand bar closed, no river flow, aerators not running in south arm
26 Sep 03 18:12	X	X	X	X	X						South Arm - Pipe	Sand bar closed, no river flow, aerators running in south arm
04 Oct 03 10:15	X	X	X	X	X						South Arm - Pipe	Sand bar closed, no river flow, aerators not running in south arm
04 Oct 03 16:42	X	X	X	X	X						1. South Arm-Pipe 2. Granite Outcrops	Sand bar closed, no river flow, aerators not running in south arm
10 Oct 03 17:34	X	X	X	X	X						1. South Arm-Pipe 2. Granite Outcrops	Sand bar closed, no river flow, aerators running
17 Oct 03 16:50	X	X	X	X	X						1. South Arm-Pipe 2. Granite Outcrops	Sand bar closed, no river flow, aerators running
28 Oct 03 17:14	X	X	X	X	X						1. South Arm-Pipe 2. Granite Outcrops	Sand bar closed, no river flow, aerators running
30 Oct 03 8:13	X	X	X	X	X						1. South Arm-Pipe 2. Granite Outcrops	Sand bar closed, no river flow, aerators running

Table 10.2 Continued.

Date/Time	Data Type										Location	Notes
	T	DO	S	pH	De	Z_{sd}	NO3	NH3	PO4	CHL -a		
04 Nov 03 14:10	X	X	X	X	X						1. South Arm-Pipe 2. Granite Outcrops	Sand bar closed, no river flow, aerators running
15 Nov 03 15:45	X	X	X	X	X						1. South Arm-Pipe 2. Granite Outcrops	Sand bar closed, no river flow, aerators running
22 Nov 03 12:05	X	X	X	X	X						Granite Outcrops	Sand bar closed, no river flow, aerators running
02 Dec 03 9:04	X	X	X	X	X						Granite Outcrops	Sand bar closed, no river flow, aerators running
10 Dec 03 14:03	X	X	X	X	X						South Arm-Pipe	Sand bar closed, no river flow, aerators running
21 Dec 03 16:02	X	X	X	X	X	X					South Arm-Pipe	Sand bar closed, no river flow, aerators running
10 Mar 04 8:20	X	X	X	X	X						1. South Arm –Pipe 2. Granite Outcrops	Sand bar opened, River flow ~180 cfs
10 Mar 04 17:25	X	X	X	X	X						1. South Arm –Pipe 2. Granite Outcrops	Sand bar opened, River flow ~180 cfs
25 Mar 04 9:35	X	X	X	X	X						1. South Arm –Pipe 2. Granite Outcrops	Sand bar closed, River flow ~90 cfs
08 Apr 04 9:32	X	X	X	X	X						1. South Arm –Pipe 2. Granite Outcrops	Sand bar closed, River flow ~65 cfs
08 Apr 04 17:05	X	X	X	X	X	X					South Arm-Pipe	Sand bar closed, River flow ~65 cfs
15 Apr 04 9:20	X	X	X	X	X	X					1. South Arm –Pipe 2. Granite Outcrops	Sand bar closed, River flow ~32 cfs

Date Types

T = Temperature
DO = Dissolved Oxygen
S = Salinity
Z_{SD} = Secchi Depth
De = Depth
ph = pH
NO3 = Nitrate – N
NH3 = Ammonia - N
PO4 = Orthophosphate
CHL-a = Chlorophyll – a

10.2 Late spring

10.2.1 May - June 2003

Late spring dynamics are summarized by a month-long series of continuous temperature profile data in Figure 10.1. On May 29, the River was still flowing and the surface layers of the lagoon were fresh. The lagoon was partly open, and experiencing tidal fluctuations in stage. These fluctuations were larger prior to June 3rd, due to larger waves during this time, and yielded large lunar swings in water quality associated with whole-lagoon turbulence. During more quiescent periods, prolonged heating occurred. Heating at depth is a solar effect, enhanced by stratification, which isolates deeper layers from atmospheric cooling. Surface heating also occurred, in layers quite distinct from the depth-heated layers. The sand bar temporarily closed on June 15, due to larger waves and subsiding river flows. At this time, the lagoon was initially cooled by the transition to a fresher, river-fed state. It then re-stratified and heated in separate layers - only to return to a turbulent dynamic after a breach on June 18th.

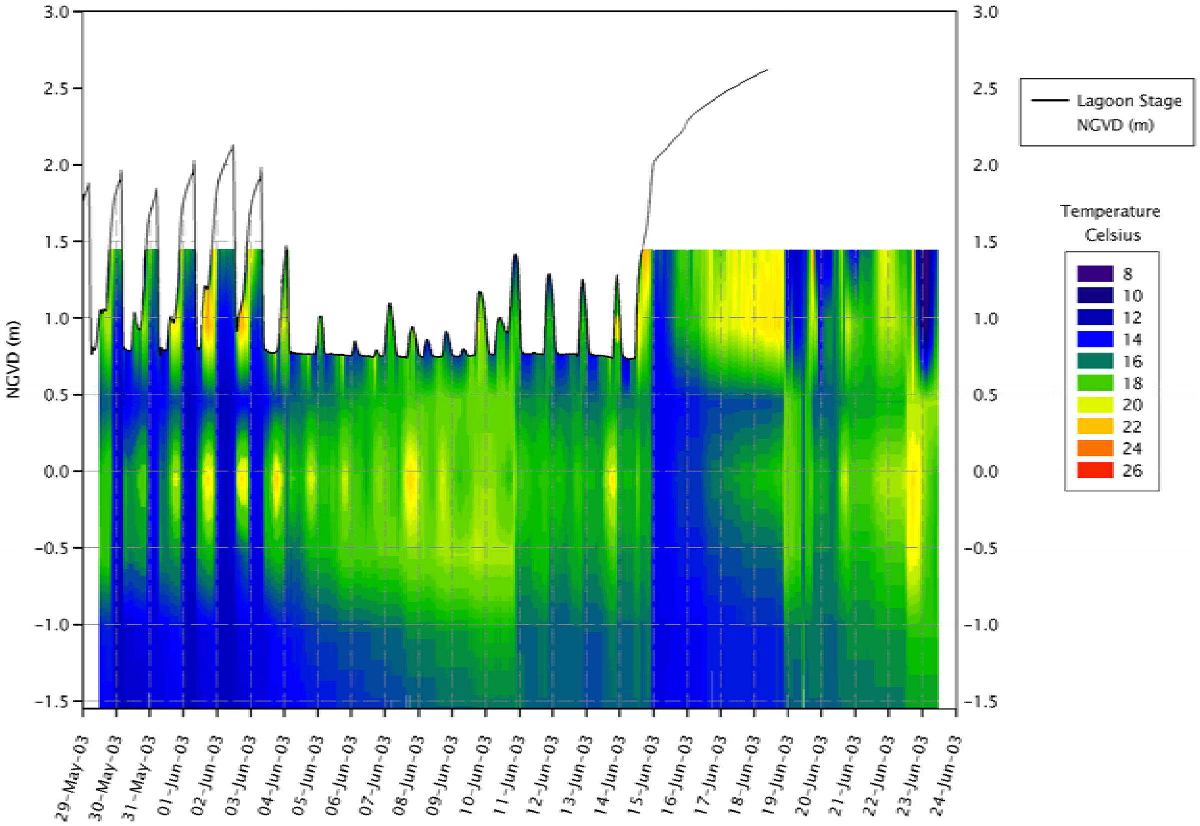


Figure 10.1. Temperature profile dynamics during May-Jun 2003.

10.2.2 28-29 May 2003

Some more detail on spring conditions was revealed by hourly manual measurements of salinity, temperature, and oxygen conducted over a 24-hour period on 28-29 May 2003 (Figs

10.2 - 10.4). The first measurement was collected on May 28th at 15:30. Local weather was warm, clear and calm. Streamflow at the Carmel River at the USGS Via Mallorca gage was minimal, 1.59 m^3/s (58 cfs) (Fig 10.2).

In general, the water quality in the lagoon was dominated by the presence of a strong halocline due to reduced mixing as stream flows receded (Figs. 10.3, 10.4 & 10.4). At the time of measurement, the lagoon was experiencing tidal fluctuations in stage on a lunar cycle, associated with semi-closures and semi-breaches under declining river flow (Fig 10.2). Due to cool overcast weather conditions, afternoon heating effects were small. Maximum heating occurred later than expected, peaking at about 18:00 or 19:00 – an unexplained observation.

Oxygen cycling was highest at the top of the saline layer (i.e. between 0 and 0.5 m NGVD), probably due to photosynthesis by algae that prefer these conditions to the freshwater above (although note that super-saturation – typical of photosynthetically produced dissolved oxygen in this lagoon (see Casagrande & Watson, 2003) – was not observed). Between 5:00 and 6:00 AM dissolved oxygen concentrations reduced quickly. This may be attributed to the re-suspension of accumulated decomposing organic matter in the lagoon as the lagoon drained during a semi-breach.

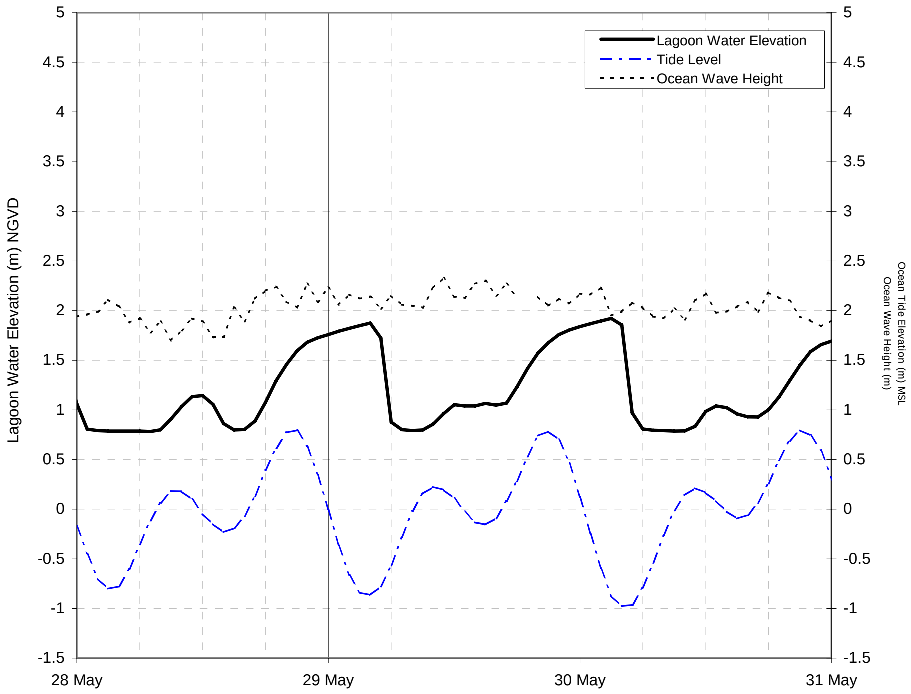
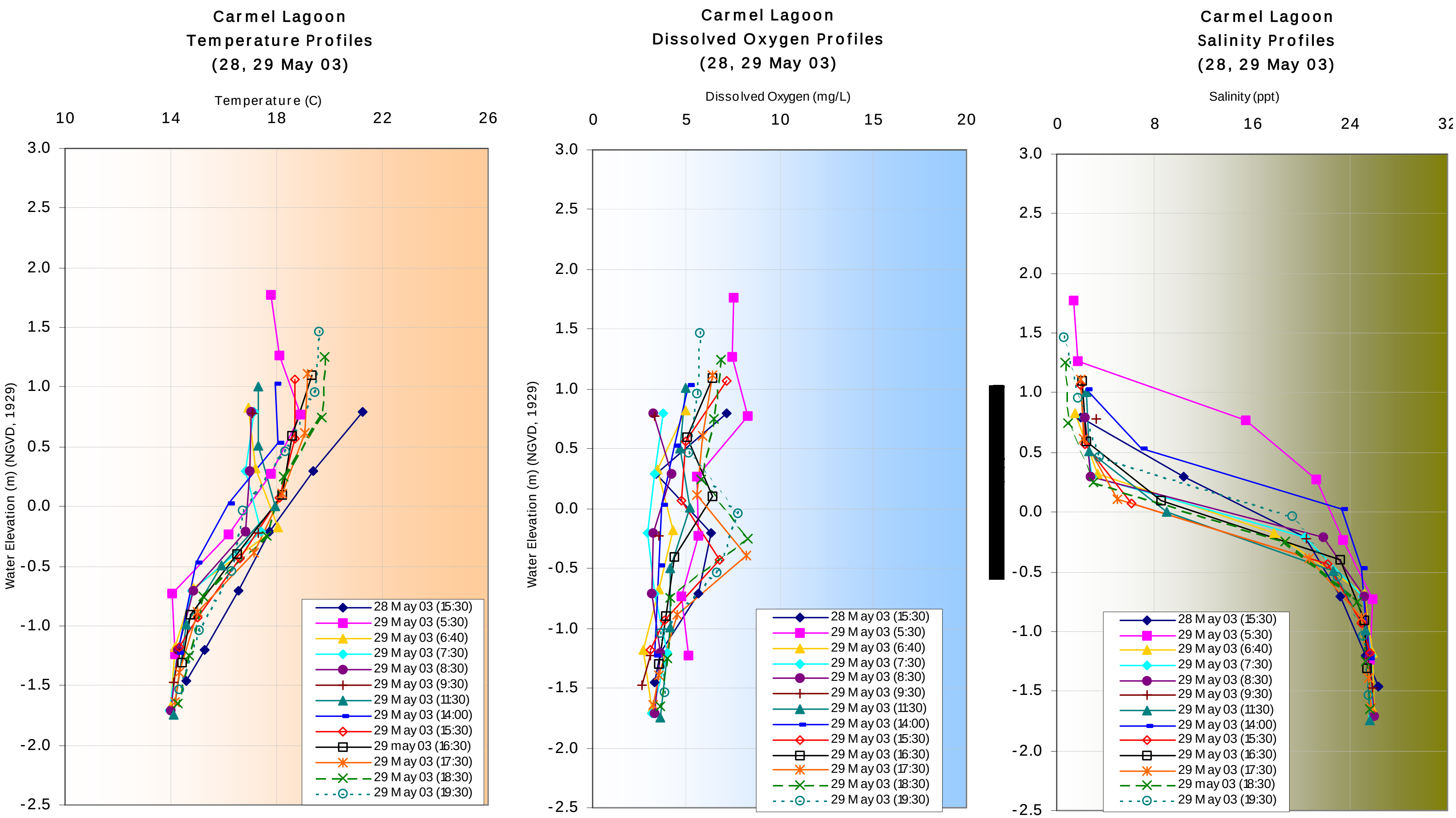


Figure 10.2 Carmel Lagoon water elevation and ocean tide elevation for the 28th and 29th of May 2003. Water elevation data is from Monterey Peninsula Water Management District (MPWMD) and tide data is from NOAA Station 9413450 Monterey Bay, Monterey Harbor.


Carmel Lagoon
Temperature Profiles
(28, 29 May 03)

Carmel Lagoon
Dissolved Oxygen Profiles
(28, 29 May 03)

Carmel Lagoon
Salinity Profiles
(28, 29 May 03)

[redacted]

Figure 10.3 Temperature, oxygen, and salinity profiles collected in the South Arm.

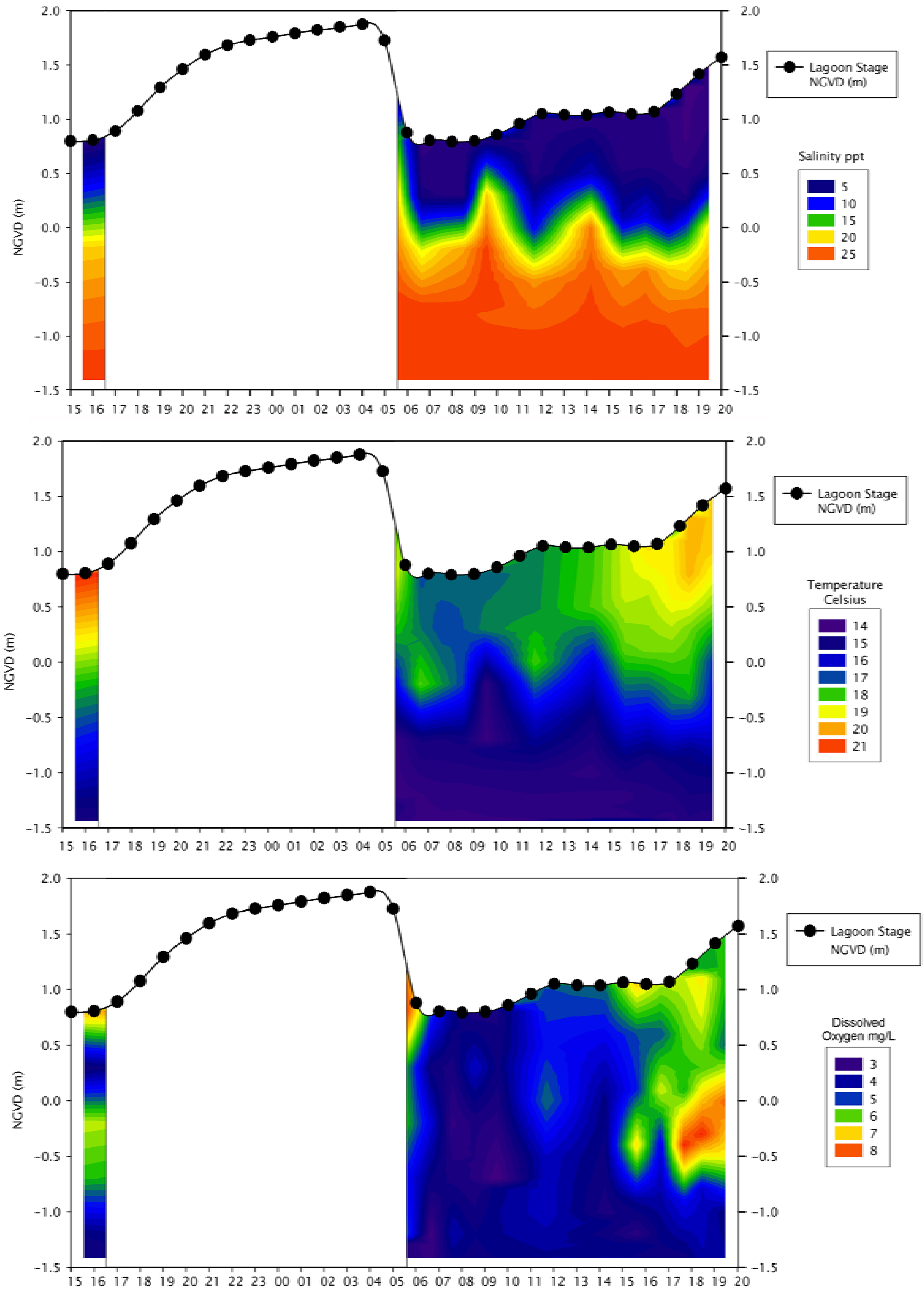


Figure 10.4. Short term dynamics of profiles of salinity, temperature, and dissolved oxygen 28-29 May 2003.

10.3 Summer

Following the temporary closure in June, the lagoon closed for the season at the start of July – heralding summer conditions.

10.3.1 Long-term temperature profile development

The complete summer and winter dynamics of stage, salinity, and temperature are shown in Figure 10.5. This provides an overview before more detailed data are presented later in this Section. The lagoon was most heavily stratified at the onset of summer in July. Pronounced heating occurred at the top of the saline layer, which was isolated from atmospheric cooling by about a meter of relatively fresh water. In the following months, the lagoon gradually became less stratified, leading to more gradual increases in salinity and temperature with depth. Diurnal fluctuations in temperature were confined to the upper meter in July, but were extending down to two meters deep in October. The reason for this weakening of stratification is unclear. It could be driven by periodic influxes of ocean water during high wave periods. It could be due to addition of fresh groundwater. It could be due to stronger wind-forced mixing in fall. Ocean inputs certainly explain periodic increases in surface salinity (see previous Section), but they do not appear to explain all periods of weakening temperature stratification.

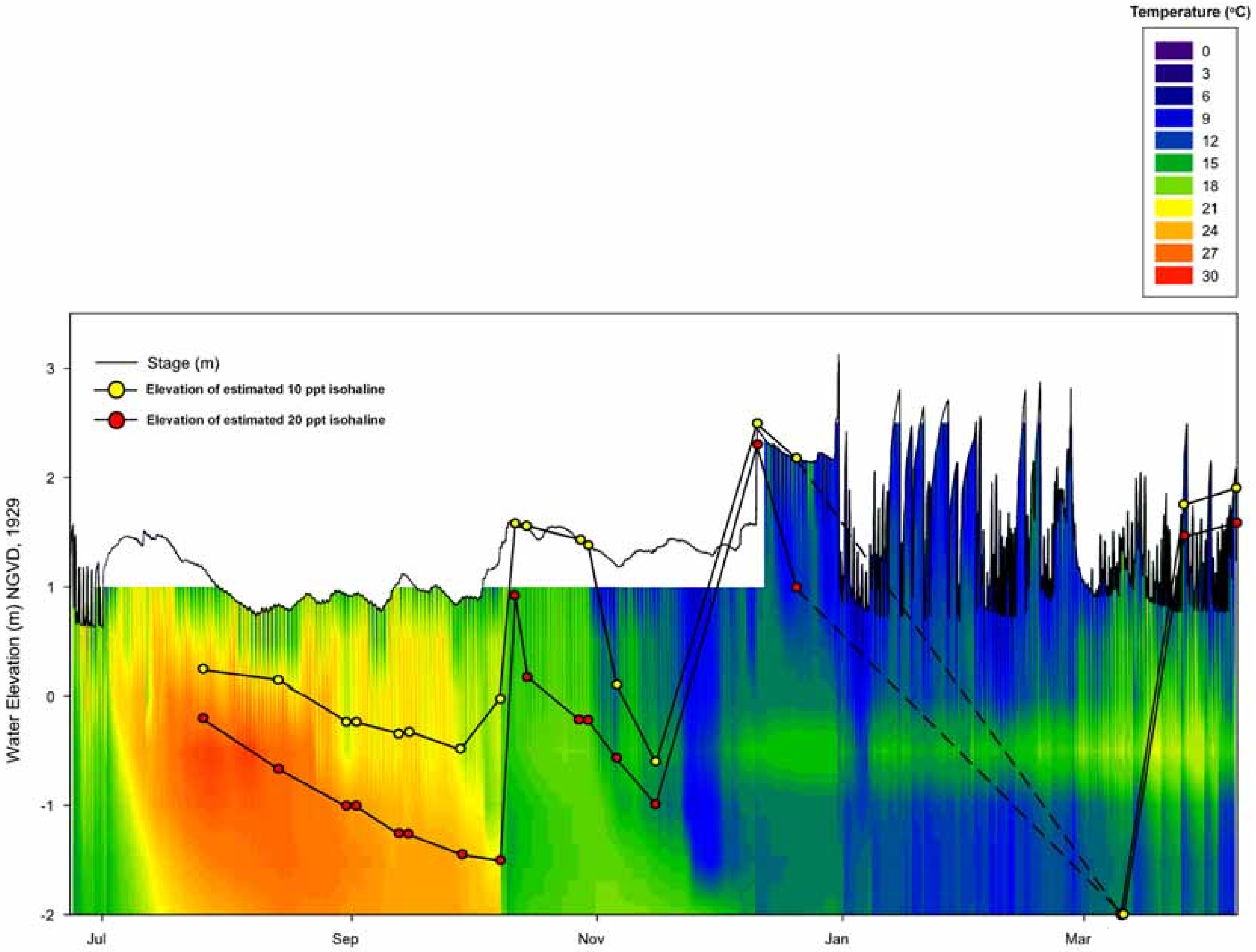


Figure 10.5. Lagoon temperature profile dynamics between June 23, 2003 and April 7, 2004.

10.3.2 July 23rd to 25th 2003

Twice during the summer months, the Carmel Lagoon was monitored hourly over 48-hour periods: July 23-25 and August 12-14. These campaigns were designed to accurately document the diurnal change in the lagoon water quality conditions, with an emphasis on dissolved oxygen cycles. The first of the two campaigns (July 23-25) occurred on consecutive overcast and cool days. For comparison, the second campaign was conducted during a series of warm and clear days.

Water quality monitoring began on July 23rd at 18:00. Streamflow in the Lower Carmel River (Via Mallorca Road) had stopped a week earlier. Weather conditions at this time were overcast, cool and there was a slight breeze. This was also the dominant weather pattern throughout much of the campaign. The water elevation in the lagoon was 1.28 m (4.20 ft.) and the sandbar was closed. Figure 10.6 shows both lagoon and tide elevation data. Figure 10.7 summarizes the water quality conditions during the 48-hour period.

The lagoon was heavily stratified and quiescent. Dissolved oxygen varied diurnally over about 5 mg/L in the upper 1.5 m, indicating a clear photosynthesis and respiration cycle – probably due to algae and zooplankton. This did not occur in the deepest 1.5 m – most likely because these layers are very dark – an observation we confirmed with secchi[3] observations and by snorkeling. The darkness may be due to a combination of shading by algae above, and dead organic matter that remains buoyant in the denser water. The upper part of the saline layer, at about 0 m NGVD is also warmer. There is probably a positive feedback at this depth comprising: heat, algal production, increased turbidity, increased solar absorption, more heat. The surface layer does not experience this because of its exposure to night-time atmospheric cooling. This system as a whole is ultimately caused by density stratification due to fresh river water overlying saline ocean water, which is trapped at depth by its own density – a fundamental property of lagoons in general. Wind velocities (presented with the salinity profiles), were moderate in the afternoon, but had little affect on breaking up the stratified conditions. Lagoons with greater freshwater inputs are less stratified – they are mixed more by wind, and thus stay cooler and less prone to oxygen crashes.

In summary, the lagoon was stratified and stable with little or no mixing and oxygen cycling was low due to overcast and cool weather conditions.

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[3] Secchi depths are the depths at which a black and white disk can only just be seen from the surface, and are overlaid on the oxygen and temperature Figures. Cole (1994) states that generally secchi depth measurements (Z_{SD}) are at the level where 21% of the surface light remains, and at 2.7-3 times the Z_{SD} is the 1% surface light level, or the end of the euphotic zone. The minimum light requirement for photosynthesis to occur is approximately 1% of the surface light. At 1% of the surface light, only phytoplankton can sustain photosynthetic activity, whereas rooted aquatic plants usually require 20% of the visible light. This obviously varies throughout the aquatic realm.

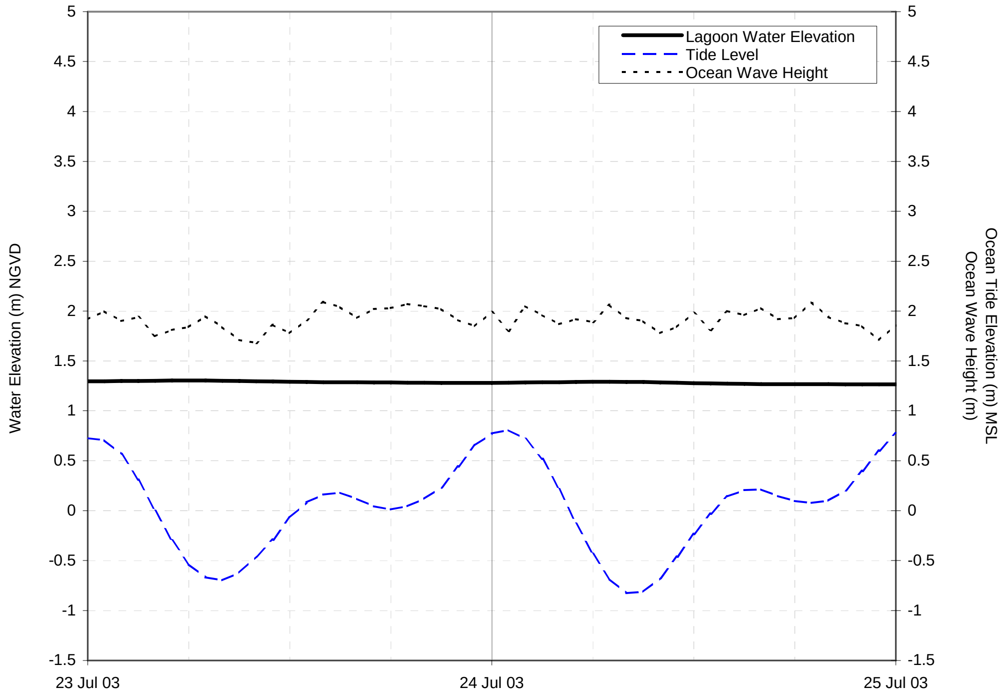


Figure 10.6 Carmel Lagoon water elevation and ocean tide elevation for July 23rd through the 25th, 2003.

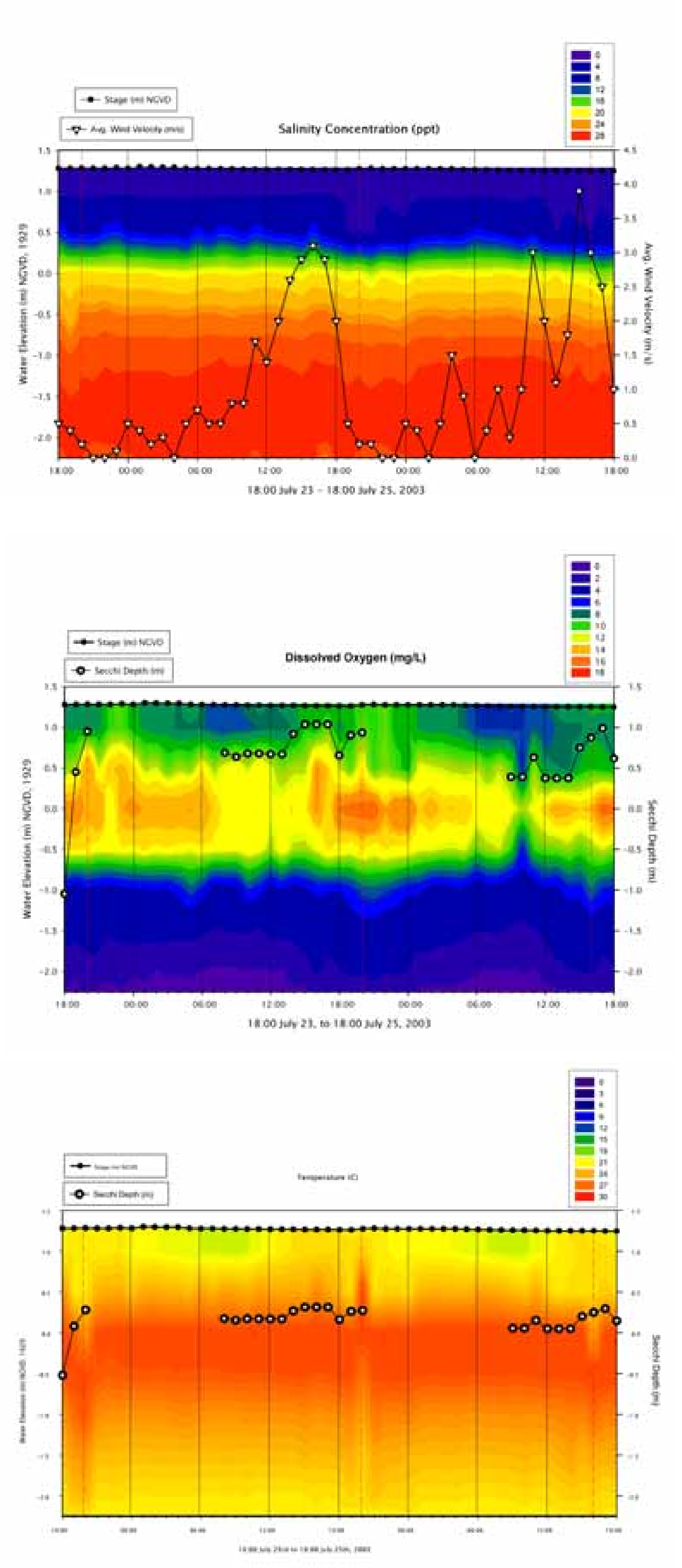


Figure 10.7 Depth-time isopleths of salinity, dissolved oxygen concentrations, and temperature in the Carmel Lagoon in the Carmel Lagoon July 23rd-25th, 2003.

10.3.3 August 12th to 14th 2003

A second 48-hour monitoring campaign was conducted during a series of warm and clear days in the middle of August (Figs 10.8 & 10.9). Water elevation in the lagoon had dropped, from 1.28 m (4.19 ft.) in late July, to 0.90 m (2.95 ft.), due to sandbar seepage. The sandbar was closed and there was no evidence of any recent wave overwash.

As observed in the late July campaign, the water elevation in the lagoon did not fluctuate significantly. In general, the water quality in the Carmel Lagoon was similar to conditions observed in late July (Figs. 10.7 & 10.9), except that the diurnal temperature and oxygen cycles were more pronounced due to the clearer weather. The water column was markedly stratified, although slightly less so than previously. Oxygen cycling was spread over a larger depth, and the temperature and salinity gradients were less marked. The lagoon was highly photosynthetic in the upper half, and warm throughout, especially the middle layers. Diurnal cooling only occurred in the upper 80 cm.

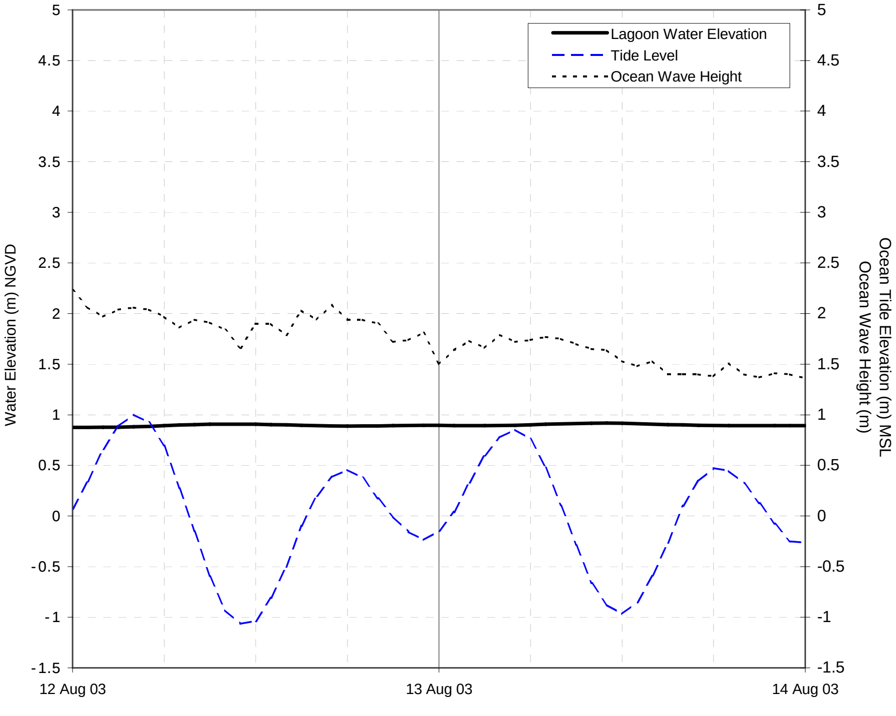


Figure 10.8 Carmel Lagoon water elevation and ocean tide elevation for August 12-14, 2003.

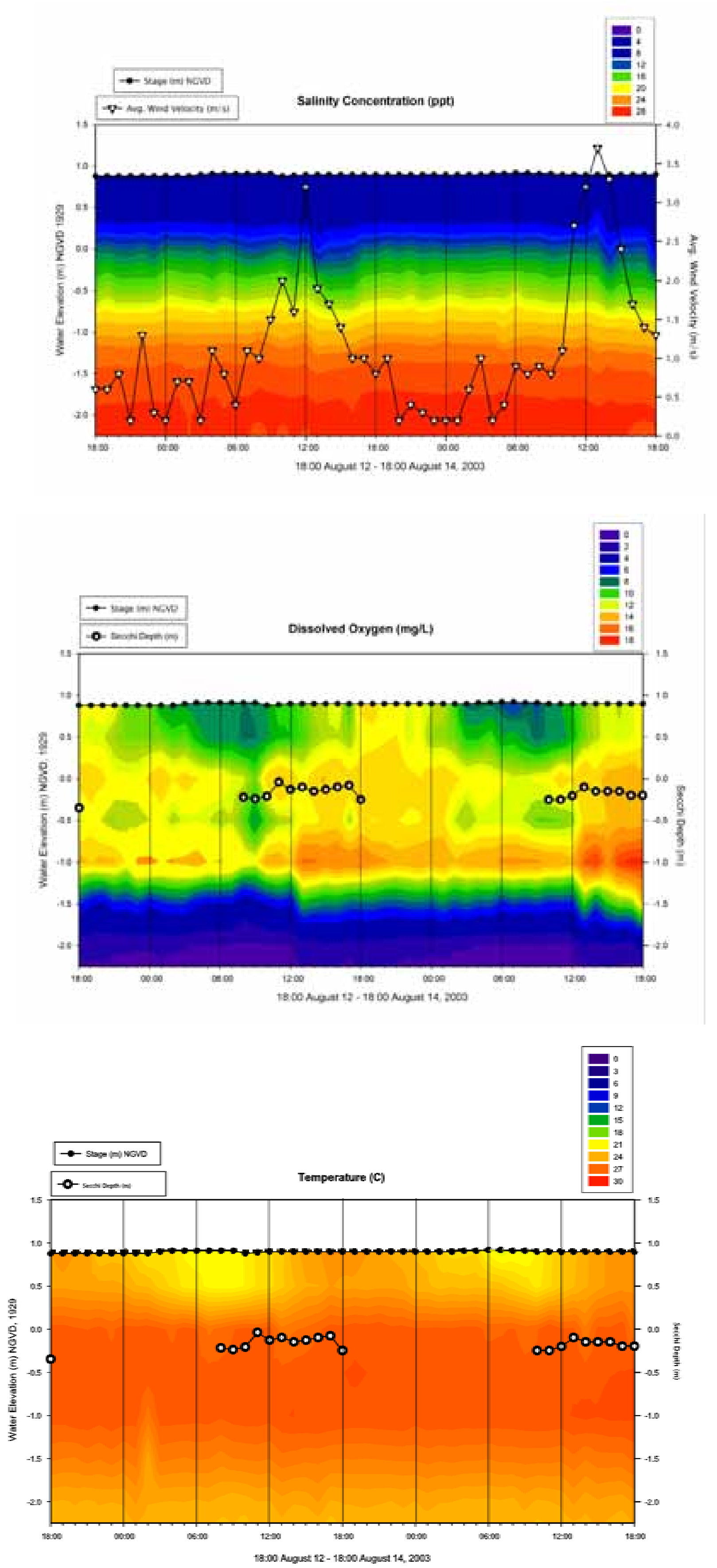


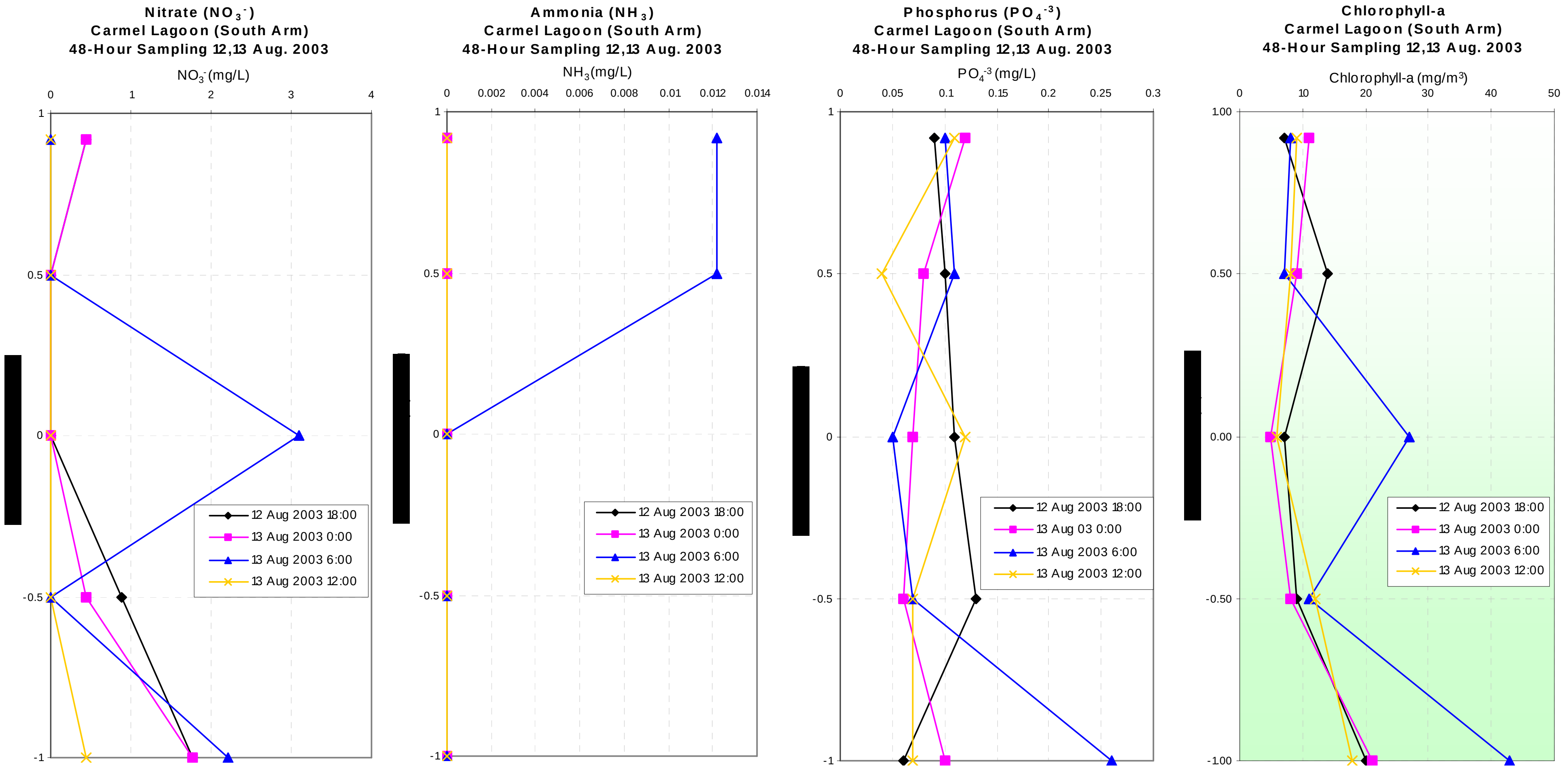
Figure 10.9 Depth-time isopleths of salinity, dissolved oxygen concentrations, and temperature in the Carmel Lagoon August 12th-14th, 2003.

During the August 48-hour campaign, nutrient (nitrate, ammonia, phosphate) and chlorophyll-a samples were collected at the same evenly spaced water elevations as the temperature, dissolved oxygen and salinity data, with the exception of the –1.0, -1.5 and lagoon bottom elevations (Table 10.3 & Fig. 10.10). The data do not display clear patterns that are easily interpretable. The following observations are made. In marine plankton, there is a relatively constant ratio of nitrogen to phosphorus of 16:1, known as the Redfield Ratio (Wetzel, 2001). The ratio is usually higher in freshwater ecosystems, sometimes reaching > 30:1. Low ratios indicate that nitrogen limits growth more than phosphorus, and vice versa. The Redfield ratio in the lagoon data is low enough that nitrogen is more limiting to algal growth than phosphorus in most samples. Accordingly, nitrate varies more than phosphorus both vertically, and throughout the 24-hour sampling period. As expected, variance in nutrients and chlorophyll is highest in the layers of greatest dissolved oxygen cycling, at 0 m and –1 m NGVD. The data suggest that oxygen cycles would be less pronounced if there was less nitrate in the lagoon on this particular day.

Table 10.3 Nutrients values collected during the August 48-hour campaign.

Date/Time	Elevation	NO_3-N	NH_3-N	PO_4-P	Ratio (N:P)
12 Aug 03 18:00	0.92	0.44	-	0.09	4.88
	0.5	-	-	0.1	-
	0	-	-	0.11	-
	-0.5	0.88	-	0.13	6.76
	-1	1.77	-	0.06	29.5
13 Aug 03 00:00	0.92	0.44	-	0.12	3.67
	0.5	-	-	0.08	-
	0	0	-	0.07	-
	-0.5	0.44	-	0.06	7.33
	-1	1.77	-	0.1	17.7
13 Aug 03 6:00	0.92	-	0.012	0.1	0.12
	0.5	-	0.012	0.11	0.11
	0	3.09	-	0.05	61.8
	-0.5	0	0	0.07	-
	-1	2.21	-	0.26	8.5
13 Aug 03 12:00	0.92	0	-	0.11	-
	0.5	-	-	0.04	-
	0	-	-	0.12	-
	-0.5	-	-	0.07	-
	-1	0.44	-	0.07	6.28

- Non-detect.


Nitrate (NO_3^-)
Carmel Lagoon (South Arm)
48-Hour Sampling 12,13 Aug. 2003

Ammonia (NH_3)
Carmel Lagoon (South Arm)
48-Hour Sampling 12,13 Aug. 2003

Phosphorus (PO_4^{-3})
Carmel Lagoon (South Arm)
48-Hour Sampling 12,13 Aug. 2003

Chlorophyll-a
Carmel Lagoon (South Arm)
48-Hour Sampling 12,13 Aug. 2003

Figure 10.10 Nutrient and chlorophyll-a profiles measured during the August 48-hour campaign. Note that the data were collected only in the upper 2 meters of the water column.

10.4 Late Summer/Early Autumn

In each of the past two years, ocean waves began spilling over the sandbar in greater frequency between the months of the August and November (Casagrande et al., 2002; Casagrande and Watson, 2003; HES, 2003). Water quality data collected following these events suggested that the dissolved oxygen concentrations have declined sharply as a result (Casagrande et al., 2002; Casagrande and Watson, 2003; HES, 2003). Other studies have suggested that kelp decomposition and the annual decomposition of macro-algae already present in the lagoon, lead to such reductions in dissolved oxygen (Smith, 1990). It is possible that, on an annual basis, these large over wash events are the limiting factor to the survival of fish in the Carmel Lagoon.

In an effort to detect and assess this phenomenon a consistent monitoring plan of weekly or bi-weekly water quality profiles were collected. In addition to water quality, a photo collection from a cross-sectional view of the sandbar was also taken to access both the sandbar dimensions and the occurrence of ocean wave overwash into the lagoon-See Appendix A for a complete set of photos.

10.4.1 August 31st – September 1st 2003

A water quality profile was collected in the South Arm on the 31st of August at 11:45. In addition, a second profile was collected at the granite outcrops near the sandbar in the main body of the lagoon (Figs 10.11 - 10.13). The water elevation in the lagoon was 1.0 m (3.28 ft.) and the secchi depth was 1.20 m. Recent weather conditions were cool, overcast, and slightly breezy.

An aeration machine had been installed in the South Arm of the lagoon and was running during this time. The aerator was installed by members of the Carmel River Watershed Council (CRWC) to protect rescued steelhead, which were placed in the lagoon, from low dissolved oxygen levels.

The lagoon was stratified below 0 m NGVD. Temperatures had cooled down slightly since mid-August. Still, the warmest and most oxygenated waters were found at the saltwater/freshwater interface. Oxygen concentrations did not appear to be affected, positively or negatively, by the aerator. Below the halocline, oxygen concentrations deteriorated rapidly, as expected for a heavily stratified system (Smith, 1991; Casagrande et al., 2002; Casagrande et al., 2003). Conditions near the sandbar were similar to the upper meter of the South Arm profile.

On September 1st at 9:00, another profile measured from the pipe in the South Arm. The aeration machine was still running, and weather conditions were still overcast and cool. The water quality showed little change from the previous afternoon.

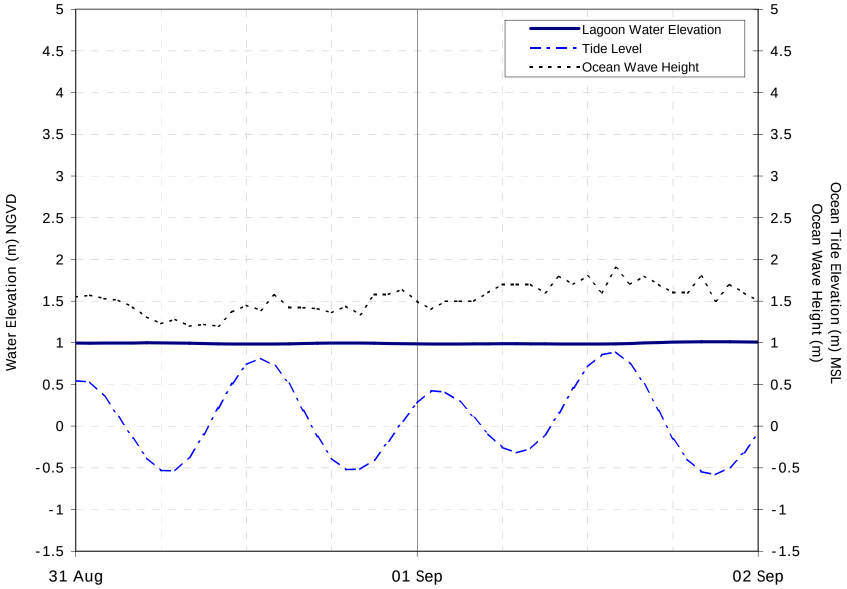


Figure 10.11 Carmel Lagoon water elevation and ocean tide elevation: Aug. 31 – Sep. 2, 2003.

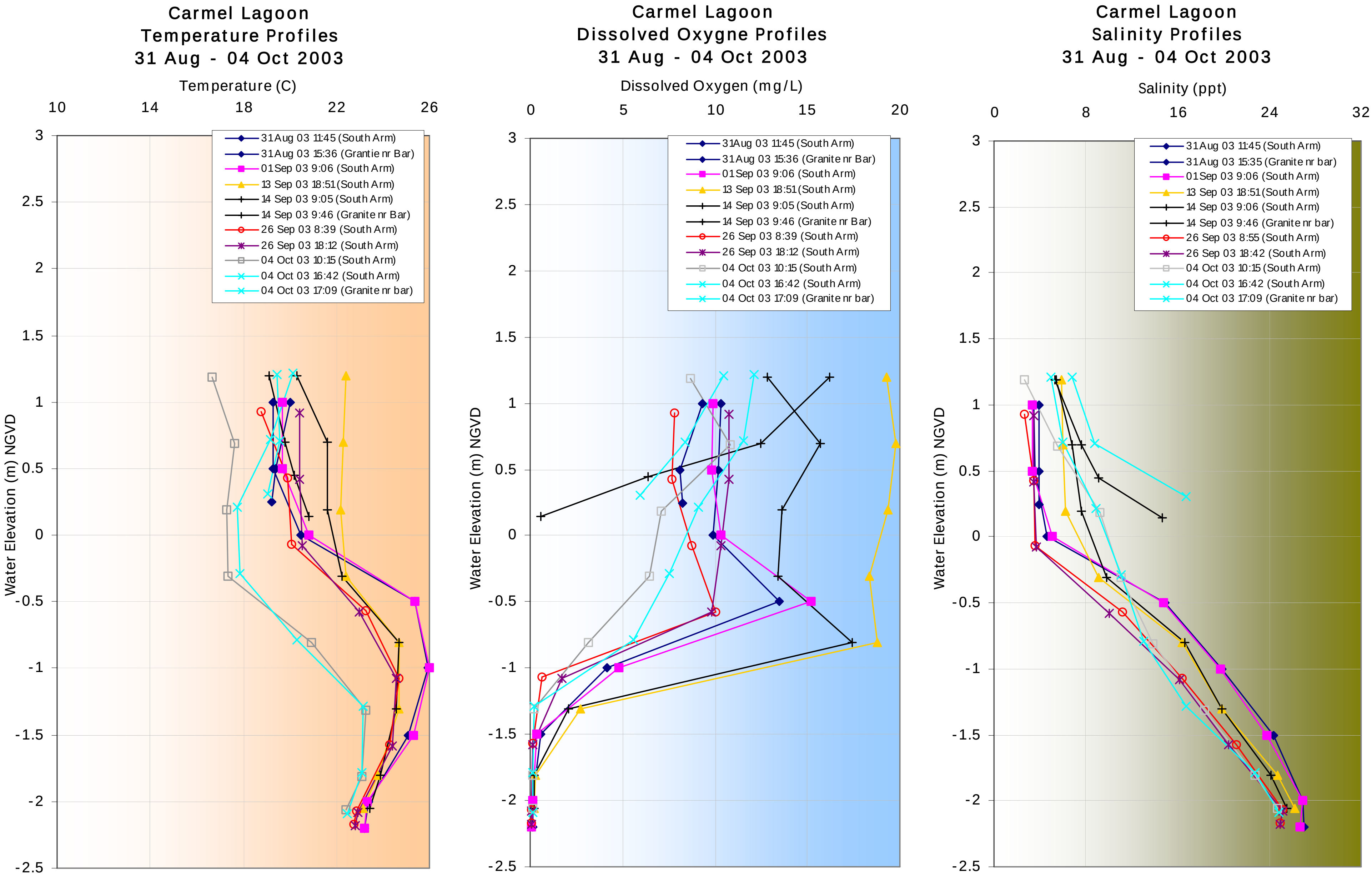


Figure 10.12 Temperature, oxygen, and salinity profiles collected at the pipe in the South Arm and at the granite rock outcrops near the sandbar as noted in the legends.

Figure 10.13 The first of two aeration machines installed in the South Arm of the Carmel Lagoon during the fall. Photo: Joel Casagrande, 01 Sep 03

Figure 10.14 The second of two aeration machines installed in the South Arm of the Carmel Lagoon. Photo: Joel Casagrande, 14 Sep 03.

10.4.2 September 13th & 14th 2003

The lagoon was revisited two weeks later on September 13th and 14th. On the 13th at 18:50, the lagoon elevation was 1.2 m (3.9 ft.). The three days preceding this were warm and clear. A second aeration machine was now running in the South Arm (Fig 10.14). Due to the warm and clear weather, dissolved oxygen concentrations increased significantly at all depths except for the bottom. Temperatures also increased in the upper 1.5 m but had cooled slightly at depth. Also, salinity levels increased slightly at the surface, likely indicating inputs from the ocean.

The following morning the aerators were not running and the sky was overcast. Water elevation in the lagoon was still 1.20 m (3.92 ft.). Cooler nighttime air temperatures had cooled the upper meter of the water column. There was a significant decrease in dissolved oxygen concentrations in the upper two meters, due to significant diurnal respiration.

A second profile was also collected at the granite outcrop near the sandbar. There was abundant evidence of recent ocean wave overwash into the lagoon (Figs. 10.17 & 10.16). In addition, there was a greater abundance of salt water in the lagoon, especially near the bar, when compared to the profile measured on August 31st. Kelp, brought in from wave overwash, had accumulated on the beach and more importantly, on the bottom of the lagoon. An oxygen profile measured directly on top of the kelp had significantly lower oxygen levels compared to same elevations in the South Arm where kelp was absent.

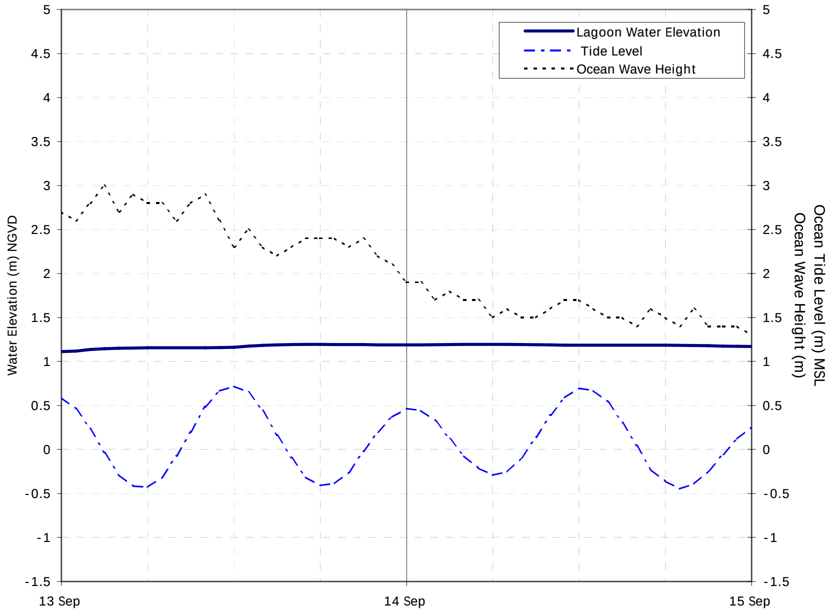


Figure 10.15 Carmel Lagoon water elevation and ocean tide elevation for Sept. 13-15, 2003.

Figure 10.16 An accumulation of decaying kelp on the bottom of the Carmel Lagoon near the granite outcrops. Photo: Joel Casagrande 14 Sep 03.

Figure 10.17 Evidence of recent kelp litter due to ocean wave overwash into the Carmel Lagoon. The kelp observed on the beach was fresh and still wet. Also, the sand in the center of the picture had evidence in the form of deposition into the lagoon. Photo: Joel Casagrande, 14 Sep 03.

10.4.3 September 26th 2003

On September 26th, water quality was measured on two different occasions, 8:30 and 18:40 (Fig 10.18). During the morning monitoring, the aerators were not running and the water elevation was 0.92 m (3.04 ft.). The sky was overcast and there was a slight breeze.

Water quality measurements collected on this data showed little change from profiles collected approximately two weeks prior. Both profiles were collected in the south arm of the lagoon. The morning profile indicated that the lagoon was warm, especially at depth, with moderate dissolved oxygen concentrations, and stratified with respect to salinity (Fig 10.12). Small diurnal changes in both oxygen concentration and temperature were detected in the upper meter of the water column. This is supported by the afternoon profile, which had only slightly higher temperatures and dissolved oxygen concentrations in the upper meter of the lagoon.

10.4.4 October 4th, 2003

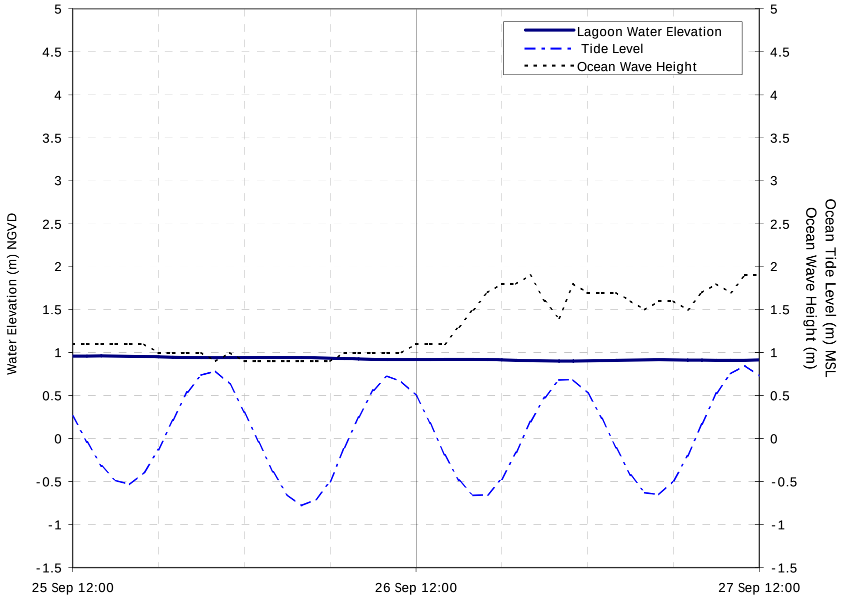


Figure 10.18 Carmel Lagoon water elevation and ocean tide elevation for Sept. 25-27, 2003.

The following week the lagoon was visited on October 4th at 10:15 and 16:42. Weather conditions were clear and breeze in the morning followed by a clear, warm and calm afternoon. The aerators were not running during the morning but had turned on by the afternoon.

The morning lagoon water elevation was 1.2 m (3.9 ft) and by the end of the day had rose to 1.21 m (3.92 ft) (Fig 10.19). This represented an increase of 1 m in 9 days with no incoming river flow. Ocean waves had recently overtopped the sandbar creating a small sand delta leading into the lagoon (Figs. 8.3, 10.20 & 10.21). The newly formed delta would continue to grow throughout the following months – See Appendix A.

In addition to the new delta, kelp was in greater abundance in the lagoon. However, this had little effect on the dissolved oxygen concentrations. Waves were continuing to add oxygenated ocean water to the lagoon and it is likely that the new kelp had not been in the lagoon long enough to catalyze any significant oxygen consumption.

Salinity increased at all depths with the exception of the surface layer (Fig 10.12). Overall temperatures were slightly cooler, due to cooler incoming ocean waters.

Near the sandbar, conditions were slightly cooler, less oxygenated and saltier than in the south arm.

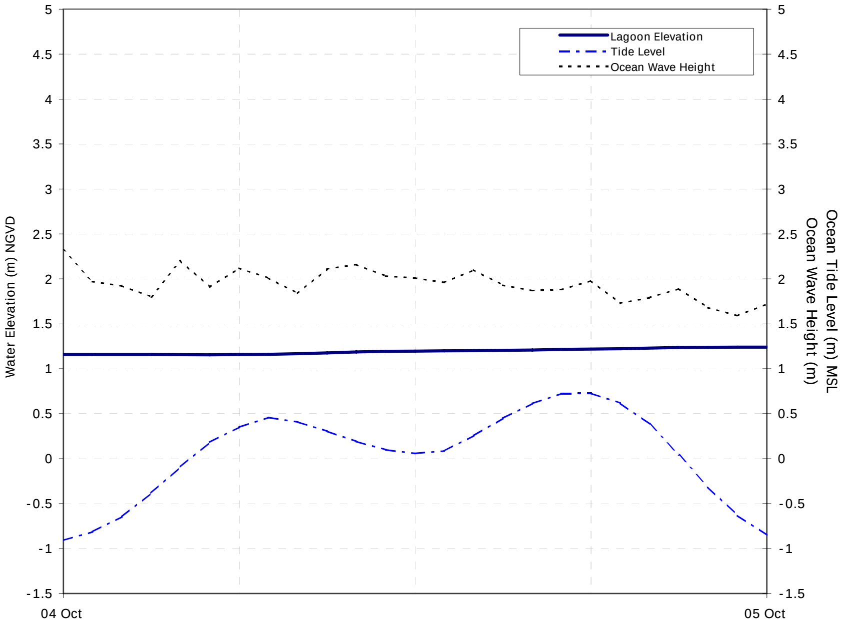


Figure 10.19 Carmel Lagoon water elevation and ocean tide elevation for October 4th, 2003.

Figure 10.20 Ocean wave overwash into the Carmel Lagoon during high surf. Photo: Joel Casagrande, 04 Oct 03

Figure 10.21 Sandbar "delta" moving inland as more ocean waves deposit sand and seawater into the lagoon. Photo: Joel Casagrande 04 Oct 03

10.5 Autumn

In the following months, ocean waves continued to overtop the sandbar, delivering cooler, saltier, water along with organic debris and sand. These conditions, along with shorter daylight hours, were beginning to create adverse conditions in the lagoon for steelhead rearing.

10.5.1 October 10, 2003

On October 10, evening water quality conditions were measured in both the south arm and near the sandbar. Recent weather conditions were clear, calm and warm. Lagoon water elevation was 1.7 m (5.3 ft). On the evening of October 9th, ocean waves over-topped the sandbar resulting in higher water elevations (Figs. 8.3, 10.22, & 10.23). Also, kelp was significantly more abundant throughout the lagoon (Fig 10.24). Large pieces of fresh kelp were found in the South Arm of the lagoon near the wastewater pipe.

Due to the recent ocean overwash, surface salt concentrations were slightly higher near the bar than in the South Arm. Conversely, surface oxygen levels were slightly lower at the bar than in the South Arm.

Overall, lagoon water temperatures were cooler at all depths compared to the previously collected profiles; also a result of cooler incoming ocean water (Fig 10.25).

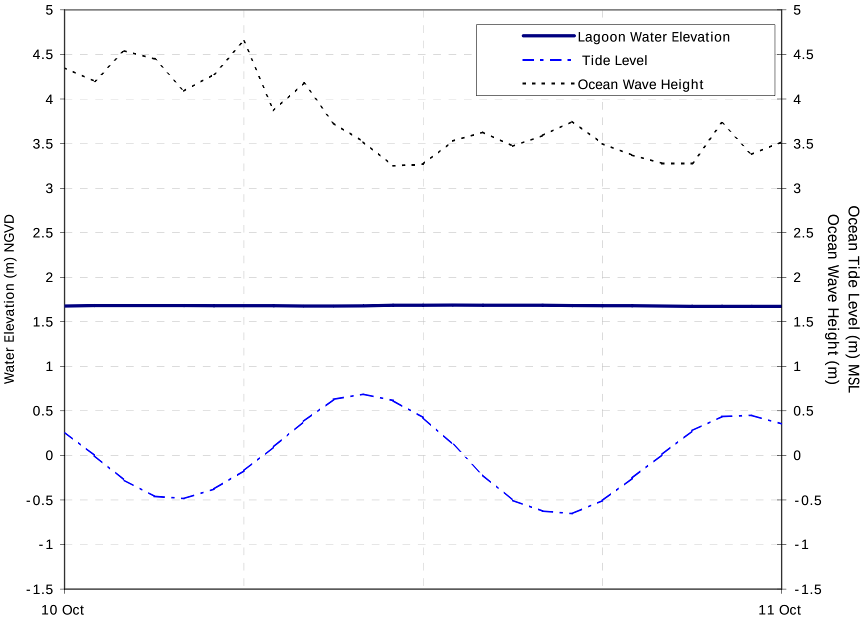


Figure 10.22 Carmel Lagoon water elevation and ocean tide elevation for October 10th, 2003.

Figure 10.23 The sandbar delta at the Carmel Lagoon on October 10, 2003. Photo: Joel Casagrande, October 10, 2003.

Figure 10.24 Decaying kelp floating at the surface near the sandbar. Photo: Joel Casagrande, October 10, 2003.

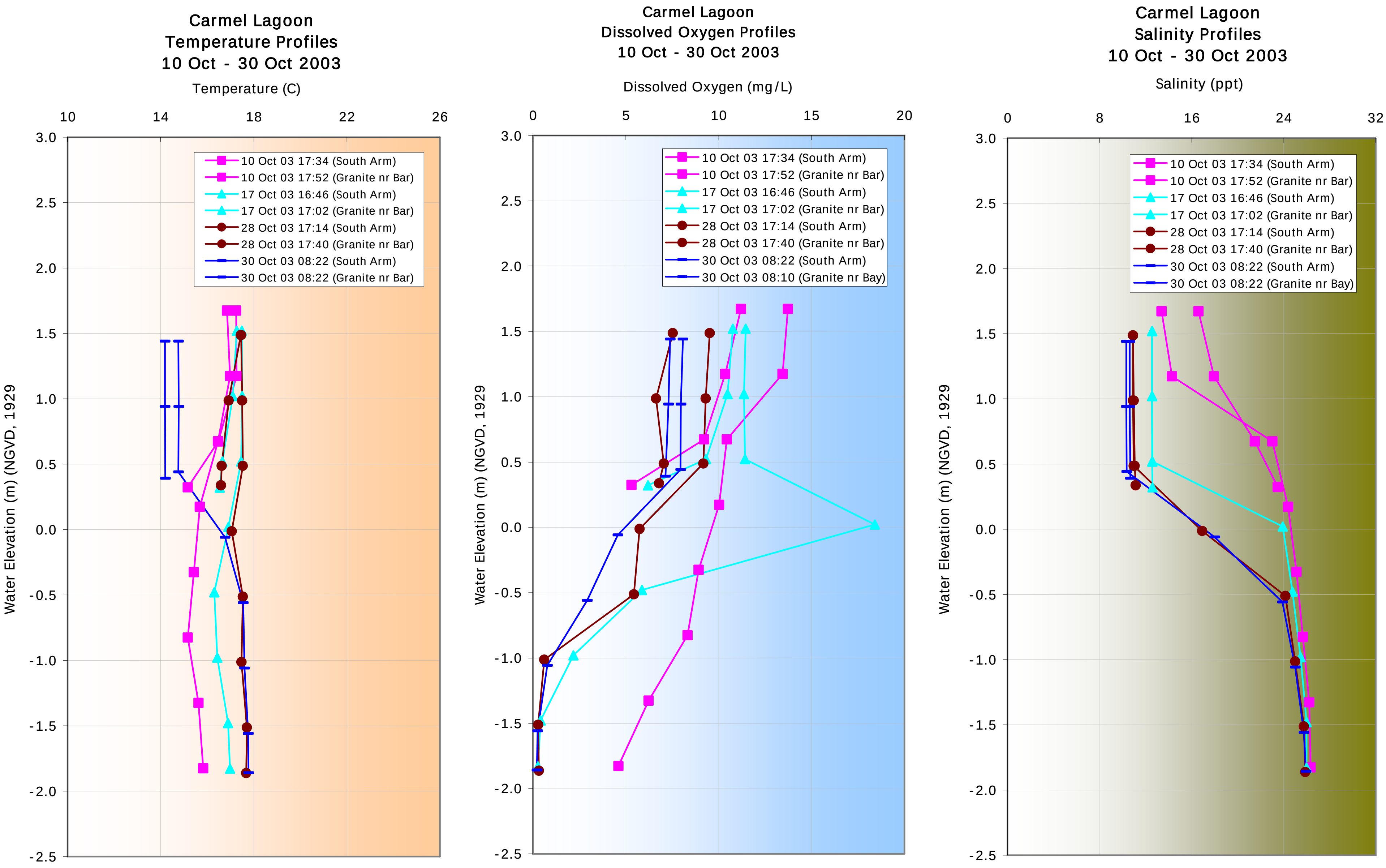


Figure 10.25 Temperature, oxygen, and salinity profiles collected at the pipe in the South Arm and at the granite rock outcrops near the sandbar as noted in the legends.

10.5.2 October 17, 2003

On the evening of October 17th, water quality measurements were collected in both the South Arm and near the sandbar of the lagoon (Figs. 10.26 & 10.25). Water elevation in the lagoon was 1.5 m (4.98 ft). There was no evidence of recent large wave inputs, although a few small waves did spill onto the sandbar near the lagoon water edge (Fig 10.28). During the day, weather conditions were clear, warm and calm, however, the fog had moved in just prior to monitoring.

Temperatures, especially at depth, increased only slightly. Dissolved oxygen concentrations increased slightly near the sandbar, while surface concentrations reduced in the South Arm. At 1.5 meters depth there was a sharp increase in oxygen concentrations followed by a sharp reduction to eventually anoxic levels (Fig 10.25).

The upper meters of the water column were slightly fresher throughout the lagoon with respect to the previous monitoring event (Fig 10.25). This observation is typical of the response of the lagoon after a high wave event (Oct 8-10) has subsided. It is also apparent in the time series presented in Section 9. Surface salinity increases for about a week during a wave event, and then decreases afterwards, but does not completely return to the prior state.

One hypothesis is that ocean inputs displace a certain amount of fresher surface water into shallow groundwater adjacent to the lagoon surface, where it is only partial mixed with the ocean water. Then, once the ocean waves recede, and the lagoon stage drops, the temporary shallow groundwater reservoir drains back into the lagoon resuming its previous place at the surface. This process may be reinforced to some degree by continuous groundwater flow from further inland.

Another hypothesis is that the relatively fresh layer remains on the surface, but that as the lagoon stage rises with ocean inputs, and the surface area expands, the thickness of the fresh layer is reduced to almost undetected levels. The process would then reverse as the ocean recedes, but only after the increased surface area has allowed greater mixing of the freshwater layer. It follows that continual pumping of the lagoon stage by the ocean throughout the season could induce the mixing that would explain the seasonal weakening of stratification.

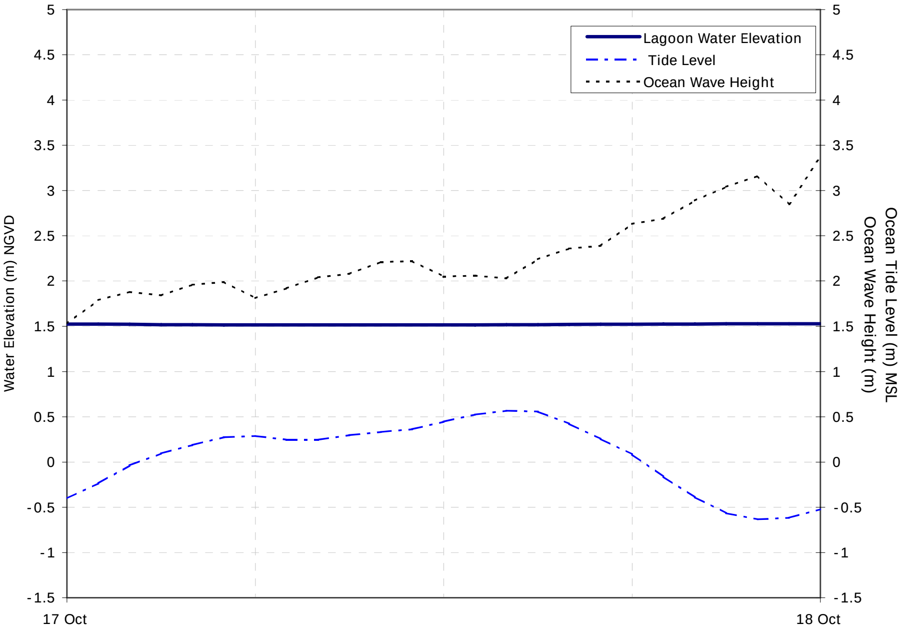


Figure 10.26 Carmel Lagoon water elevation and ocean tide elevation for October 17th, 2003.

Figure 10.27 The sandbar delta at the Carmel Lagoon on Oct. 10, 2003. Photo: Joel Casagrande.

Figure 10.28 A small wave spilling over the crest of the sandbar. During this monitoring event, no waves were observed entering the lagoon directly. Photo: Joel Casagrande, October 17, 2003.

10.5.3 October 28, 2003

The lagoon was revisited on the 28th of October. Evening profiles were collected near the sandbar and in the South Arm (Fig 10.25). The previous four days, air temperatures had been extremely warm with little or no wind. Note that this was the first data collection after the change from Daylight Savings Time. The lagoon water elevation was 1.5 m (4.9 ft), and had not changed much since the previous data collection.

Water temperatures remained the same as the previous sampling event – See Figure 10.25. However, dissolved oxygen concentrations and salinity levels both decreased in both the South Arm and near the sandbar.

The reduction in dissolved oxygen levels from those measured on the 17th was due either to reduced surface mixing, reduced photosynthesis, increased respiration, or a combination of these factors. Reduced mixing would be supported by the calm antecedent winds, but denied by the weakening stratification of the lagoon. Reduced photosynthesis is likely, given the transition toward cooler, darker winter conditions - the October 17th data clearly included an afternoon photosynthetic peak of 18 mg/L dissolved oxygen at 0 m NGVD that was completely absent from the late October data. Increased respiration is also likely, given the opportunity for kelp and algal decomposition, and the observation that oxygen levels were reduced to some extent at all depths, not just the photosynthetic depths.

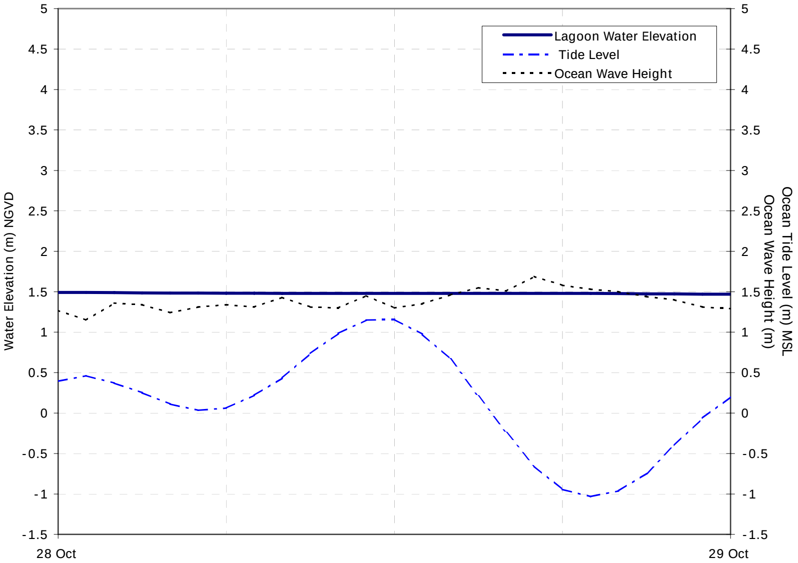


Figure 10.29 Carmel Lagoon water elevation and ocean tide elevation for October 28th, 2003.

10.5.4 October 30, 2003

Following the monitoring conducted on the 28th of October, a morning profile was collected on October 30th to assess the water quality conditions following an extended series of warm days. However, the 29th and the morning of the 30th were both cold and breezy. Morning water quality conditions were measured in the South Arm and near the sandbar. Figure 10.30 indicates that the water quality monitoring was conducted at the tail end of a significant wave event, although there was no evidence of recent wave overwash (i.e. kelp debris and or smoothing of the sandbar). Our inference drawn from modeling experience described in

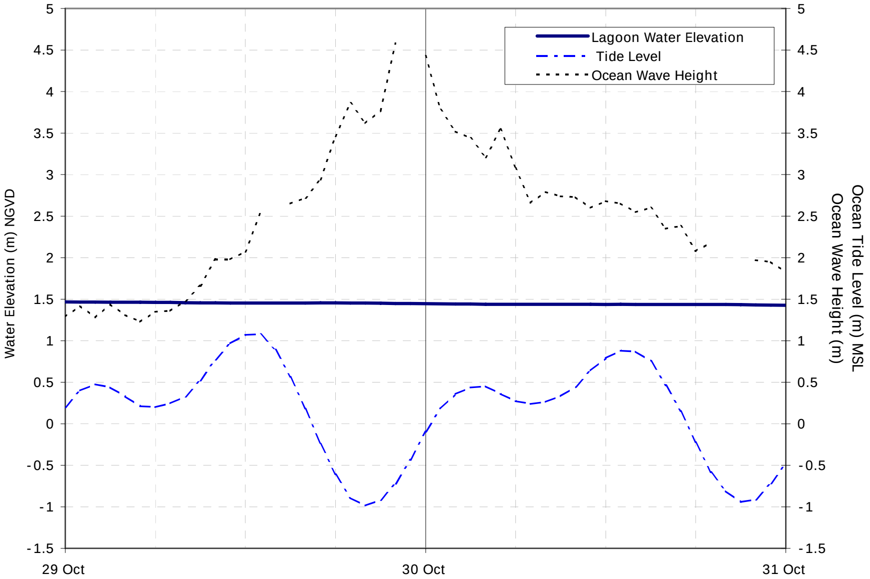


Figure 10.30 Carmel Lagoon water elevation and ocean tide elevation for October 30th, 2003.

Section 6, is that this is because the previous wave event on October 9th was larger, and had built the sandbar up out of reach of the October 30th waves. The lagoon water elevation was thus only 1.4 m (4.7 ft); a slight decrease from the levels observed two days prior.

Morning dissolved oxygen concentrations remained at a suitable level for steelhead in the upper 2 meters of the water column. Overnight air temperatures had reduced surface water temperatures. Temperatures below 1 meter remained at their previous level (Fig 10.25). There was also no change in the salinity of the lagoon.

10.6 Late Autumn/Early Winter

10.6.1 November 4, 2003

Lagoon water quality data was collected again at 14:10 on November 4th. Weather conditions were cool and breezy with clear skies. The lagoon water elevation was 1.3 m (4.3 ft), tide elevation was 0.6 m and rising, and the ocean wave height was minimal at 1.5 m (Fig 10.31). There was no evidence on the beach or in the lagoon of any recent wave overwash.

Overall, the water quality data remained stable, showing little change over the five days since the previous monitoring event (Figs. 10.25 & 10.33). Temperatures in the upper meter of the water column were slightly cooler due to continued cooler air temperatures. Afternoon dissolved oxygen levels were slightly higher than the previous collection, but this was most likely attributed to an increase in the mechanical mixing from recent windy conditions and possibly also the difference associated with the time of day that the data were collected. Salinity decreased slightly in the upper layers of the water column.

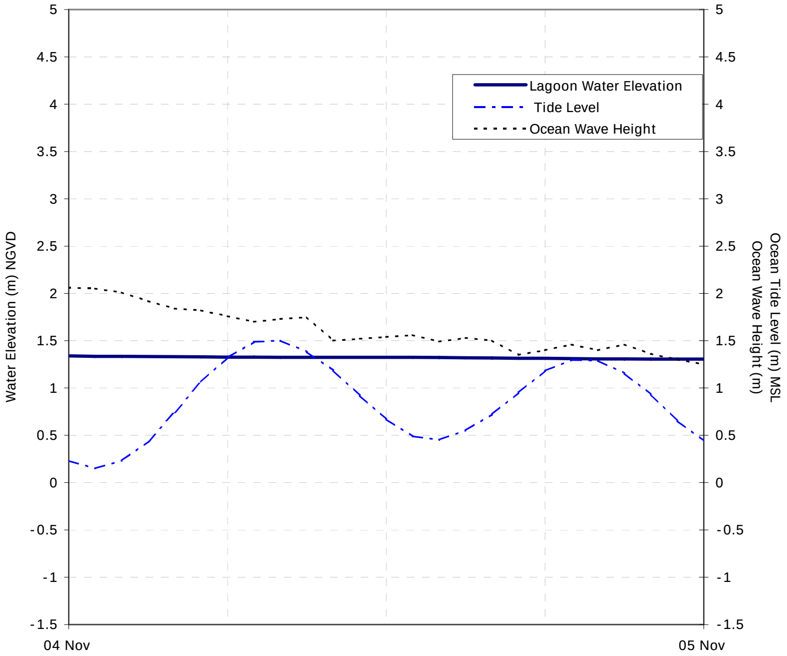


Figure 10.31 Carmel Lagoon water elevation and ocean tide elevation for November 4th, 2003.

10.6.2 November 15, 2003

On November 15th, afternoon water quality measurements were collected in the South Arm and near the sandbar. The lagoon water elevation had increased slightly to 1.4 (4.7 ft) as a result of a steady regime of through-bar flow from moderately high waves in the past week. No overwash was indicated. Temperature decreased in mid to deep layers, and oxygen decreased markedly near the sand bar. The surface of the lagoon continued on a gradually freshening progression since the wave overwash event on October 9th. Some of this may have been due to rain on the 9th, 14th, and 15th of November. But given the longevity of the trend, groundwater inputs are also likely.

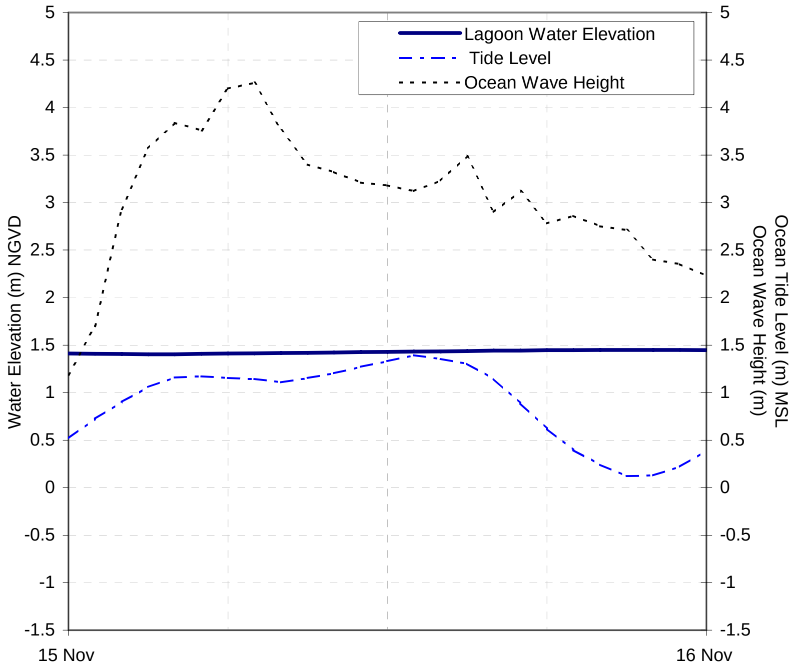
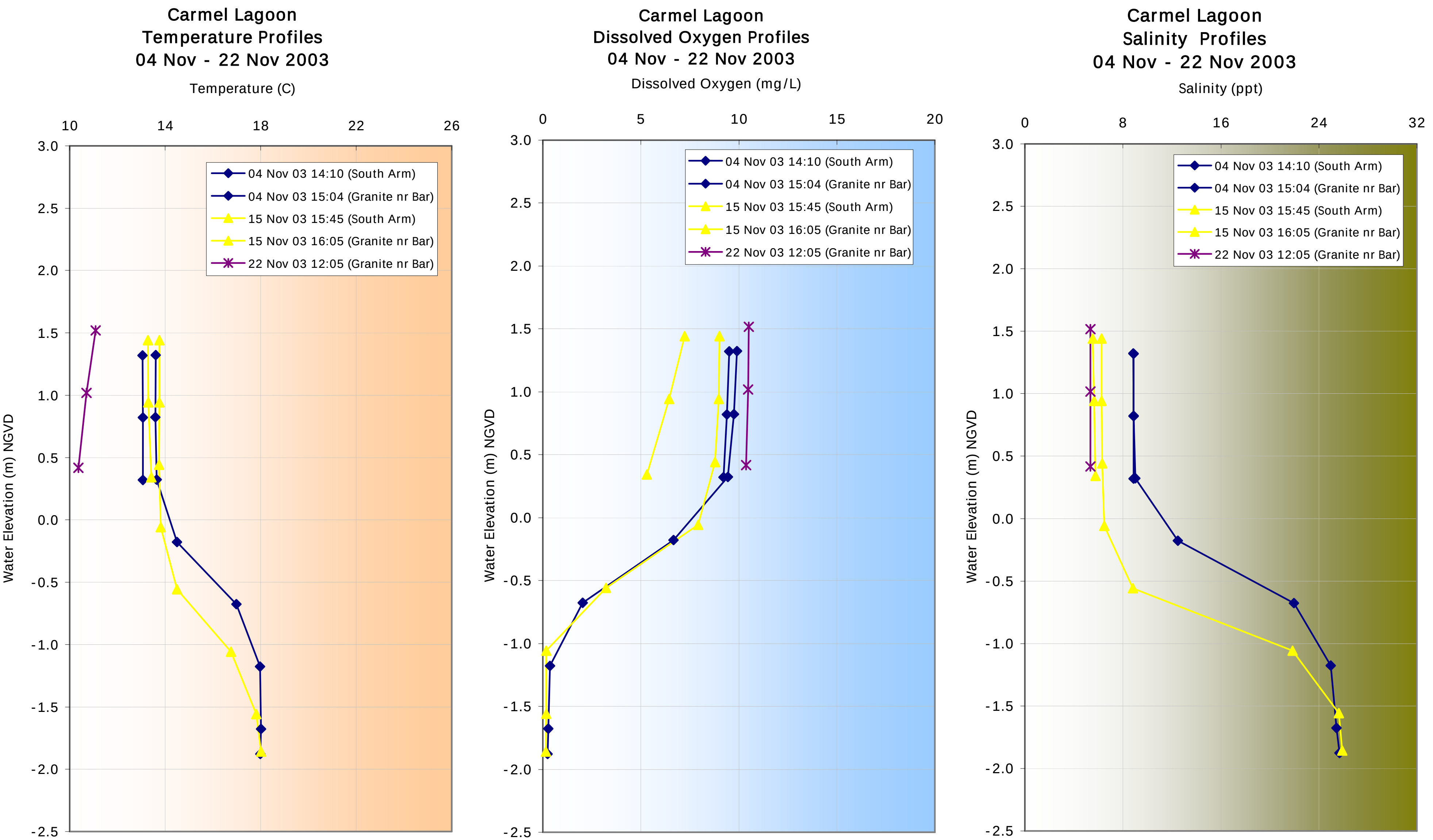


Figure 10.32 Carmel Lagoon water elevation and ocean tide elevation for November 15th, 2003.



Carmel Lagoon
Temperature Profiles
04 Nov - 22 Nov 2003

Carmel Lagoon
Dissolved Oxygen Profiles
04 Nov - 22 Nov 2003

Carmel Lagoon
Salinity Profiles
04 Nov - 22 Nov 2003

Figure 10.33 Temperature, oxygen, and salinity profiles collected at the pipe in the South Arm and at the granite rock outcrops near the sandbar as noted in the legends.

10.6.3 November 22, 2003

A profile was taken from near the sandbar on November 22nd. Water elevations had continued to gradually increase to 1.52 m (4.98 ft). Air temperatures the previous two nights were extremely cold with strong winds. This resulted in the reduction in water temperatures and the improved oxygen concentrations in the waters near the sandbar (Fig 10.33). There was no change in salinity levels in upper water column since the 15th of November.

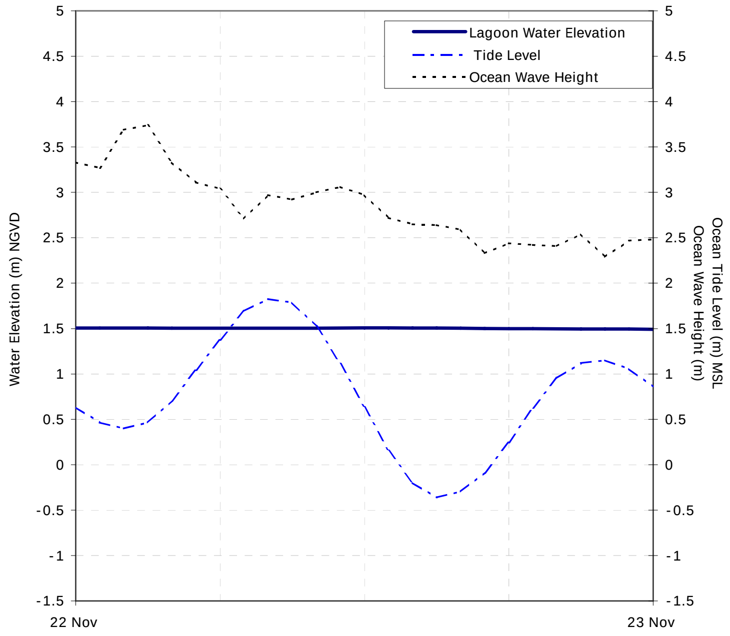


Figure 10.34 Carmel Lagoon water elevation and ocean tide elevation for November 22nd, 2003.

10.6.4 December 2, 2003

On December 2nd, a joint team consisting of members from the Carmel Steelhead Association (CSA), NOAA Fisheries and CCoWS, seined various areas of the lagoon to detect the presence/absence of steelhead smolts. In addition, a water quality profile was collected at approximately 9:00 near the sandbar of the lagoon. Water elevation in the lagoon decreased slightly to 1.49 m (4.90 ft).

Temperatures were cool, rising slightly since the 22nd of November. Oxygen concentrations were lower than previous monitoring, however these measurements were collected in the early morning when oxygen levels would be at their daily minimum.

Salinity continued its declining trend. Again, both groundwater inputs, and rainfall on the 30th of November and 1st of December are likely explanations for this. The Carmel River itself remained dry.

Overall, lagoon water quality was suitable for the steelhead in the lagoon. Six seine hauls were taken in various areas of the lagoon, yielding approximately 650 steelhead. Fish were found in a variety of sizes ranging from 60 mm to 200 mm based on observation alone. However, a majority of the steelhead did not appear to have any noticeable characteristics of undergoing the smoltification process (i.e. black tip to caudal fin, silvering in color, etc.) and many fish still had their parr markings and rainbow coloring. One would expect to find fish with characteristics associated with smolts at this time of year, especially when considering the amount of exposure to brackish conditions. A large majority of these fish were planted into the lagoon in early August. Since that time, surface salt concentrations in the lagoon fluctuated between 2.5 ppt on September 26, 2003 to 16.6 ppt on October 10, 2003, suggesting that these fish were well adapted to salt water.

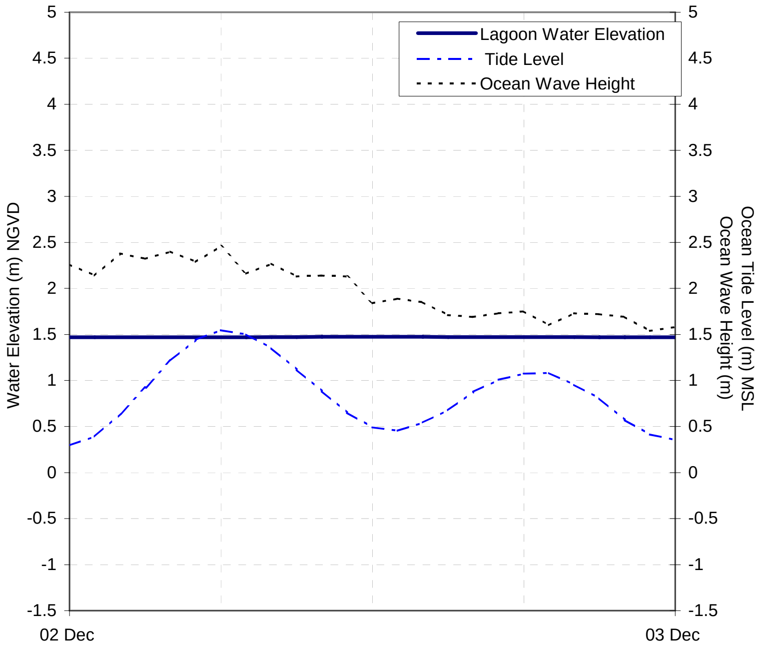


Figure 10.35 Carmel Lagoon water elevation and ocean tide elevation for December 2^{nd}, 2003.

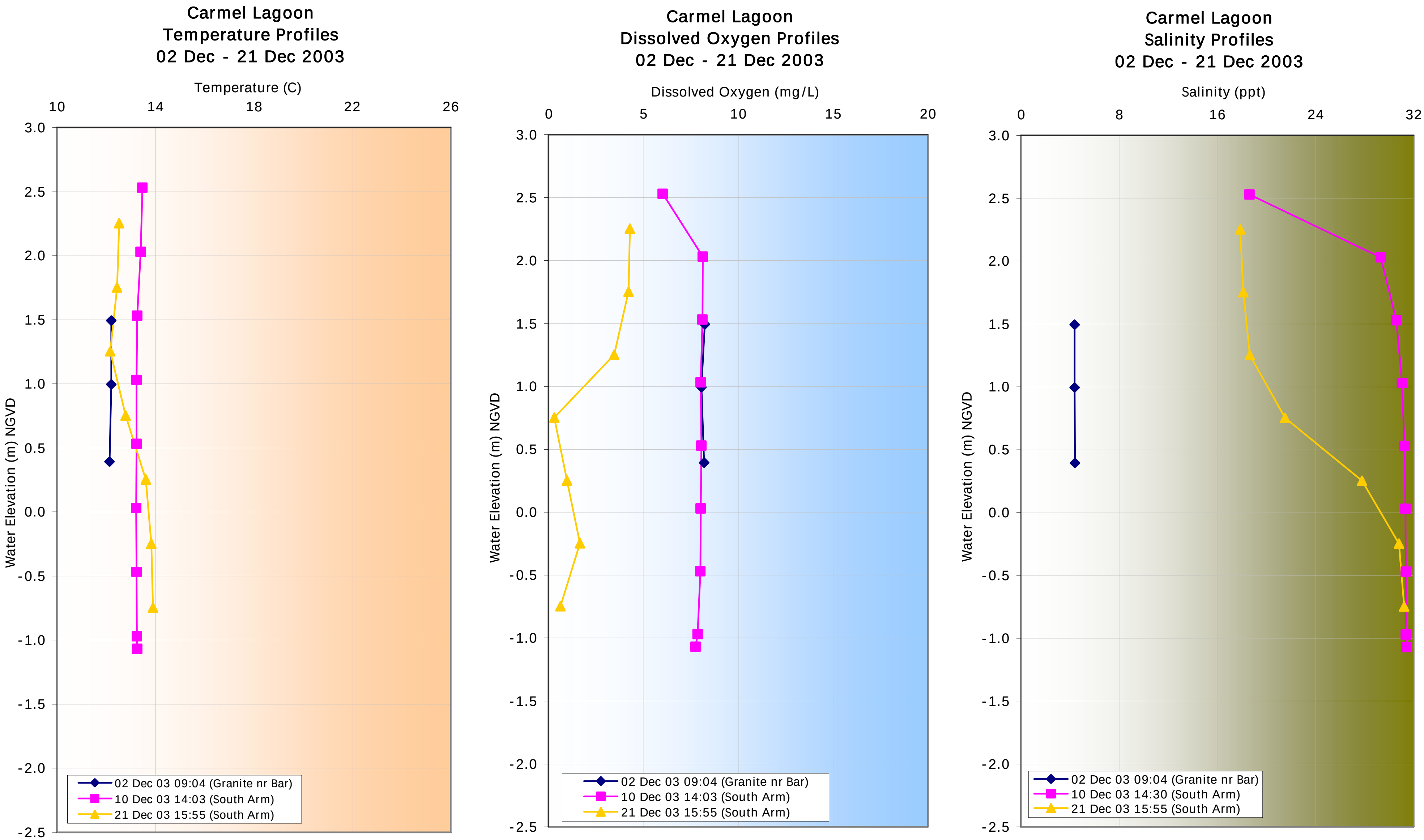


Figure 10.36 Temperature, oxygen, and salinity profiles collected at the pipe in the South Arm and at the granite rock outcrops near the sandbar as noted in the legends. **Note**: true bottom depths were not reached on December 10 and 21. Access to the deeper part of the south arm was limited.

10.7 Early Winter

10.7.1 December 10, 2003

On December 9th large ocean swells began hitting the coast of Central California (Figs. 8.3 & 10.37). Many of these waves entered the Carmel Lagoon adding a significant volume of salt water to the lagoon. The lagoon elevation increased rapidly to 2.5 m (8.3 ft) with no incoming streamflow. In addition to seawater, the wave event delivered a significant amount of sand and kelp into the lagoon as well.

The large incoming waves provided temporary well-mixed conditions in the lagoon. Temperatures increased at all depths due to the addition of slightly warmer ocean water. Surface dissolved oxygen concentrations remained similar to the previous measurements and showed significant mixing down to the bottom. The slight reduction of oxygen at the surface is unclear. It could be attributed to a rapid mixing of decomposing organic matter that floated to the surface following the large wave over-wash event.

The change in salinity was drammatic. Prior to this event, concentrations at the surface were brackish (5-6 ppt). The addition of the seawater increased the salinity levels to 17 ppt at the surface and to 30 ppt below 1 meter.

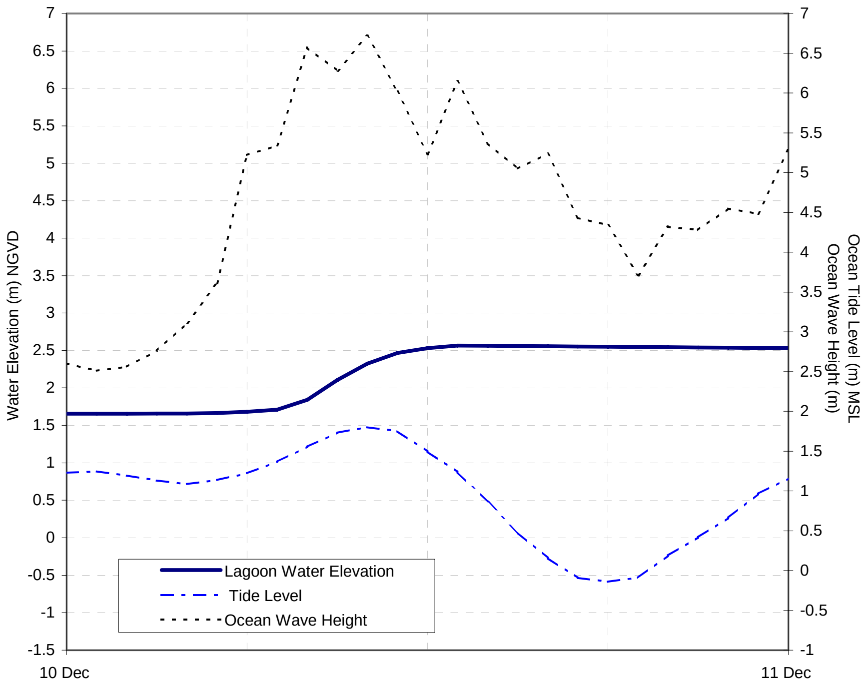


Figure 10.37 Carmel Lagoon water elevation and ocean tide elevation for December 10th, 2003.

10.7.2 December 21, 2003

An afternoon water quality profile was collected on December 21 in the South Arm of the lagoon; no samples were collected near the sandbar because the site was inaccessible. The water elevation in the lagoon dropped to 2.25 m (7.39 ft) since the previous monitoring. Weather conditions were partly cloudy, cool and calm while the two previous days were overcast with rain. The Hastings Ranch in Carmel Valley, recorded approximately 30.5 mm of precipitation between the 10th and 19th of December, yet stream flow in the lower Carmel River was still absent (Fig 8.4). The upper 2 m had freshened considerably since the previous wave event.

Dissolved oxygen was lower than at any other time measured during the study. The entire profile was below 5 mg/L. This is attributed to decomposition of organic matter. Visibility in the lagoon was poor; a secchi disk reading measured 0.3 m. The color of the water had turned dark brown, or tea colored, resembling the same conditions observed following a similar wave event in December of 2002 (Casagrande and Watson, 2003). Substantial amounts of kelp and other debris were found throughout the lagoon, including the South Arm, but especially near the sandbar (See Figures 10.39 & 10.40).

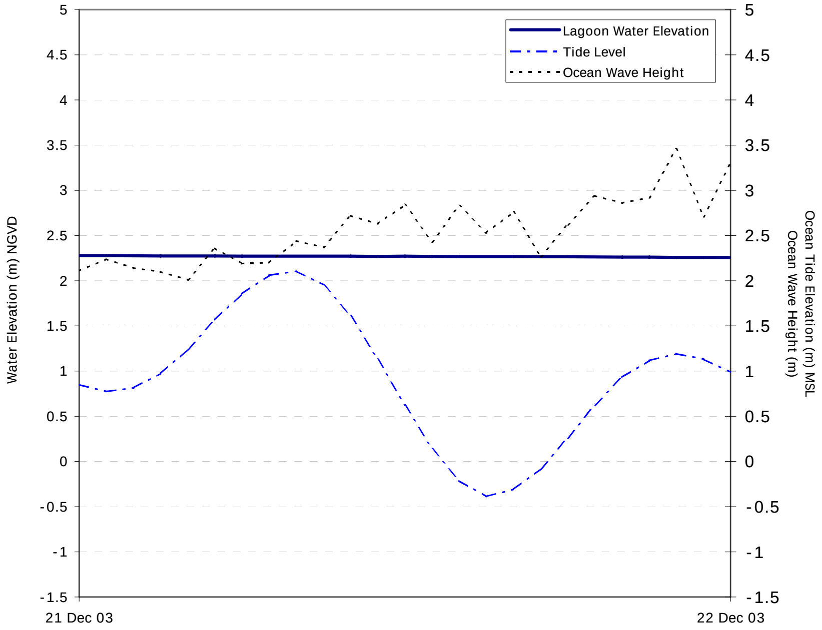


Figure 10.38 Carmel Lagoon water elevation and ocean tide elevation for December 21st, 2003.

Figure 10.39 The sandbar at the Carmel Lagoon on December 21, 2003. Note the amount of debris on the beach after the large wave event. Photo: Joel Casagrande, December 21, 2003.

Figure 10.40 The sandbar at the Carmel Lagoon. Wave events in mid-December deposited a substantial amount of sand into the lagoon. Note the entrance to the North Arm in the background of the picture. Photo: Joel Casagrande, December 21, 2003.

As rainfall continued throughout the month of December, streamflow finally commenced in the lower Carmel River at approximately 3:00 hours on December 30th. Later that morning, the lagoon water elevation rose to over 3.1 m (10.3 ft) and the lagoon was breached by early afternoon (Fig 10.41).

Figure 10.41 The Carmel Lagoon after the sandbar was manually breached on December 30th. Photo: Joel Casagrande, December 30, 2003.

10.8 Early Spring

In the months following the initial breach of the sandbar water quality measurements were not recorded until the stream flow in the Carmel River began to decline in early March. During periods of high streamflow and open exchange with the ocean, water quality in the lagoon is in a constant state of daily fluctuation with the ebb and flow of the ocean tides. One can expect that dissolved oxygen levels are kept usually within suitable levels for steelhead due to constant mechanical mixing from both stream flow inputs and incoming ocean waters. Salinity fluctuates with the tides, especially at the mid-water column layers. Water temperatures, which are highly influenced by both incoming stream flow (at surface) and ocean water inflow (at sub-surface), remain cool throughout the water column. Although note from Figure 10.5 that a stable warmer layer persists throughout almost the entire winter at –0.5 m NGVD. As with previously discussed warmer layers, this is probably caused by stratification, and solar heating of absorptive water at the top of the saline layer (probably some form of organic matter, either dead or alive).

Figure 10.42 Sand deposits at the entrance to the South Arm. South Arm entrance is at the center of the photograph. Sand deposits are shown from right to left under the kayak. Photo: Thor Anderson, June 2003

During the transition from late winter to early spring, both streamflow volume entering the lagoon and high ocean waves associated with winter swells begin to decline. These conditions are usually followed by a series of repeated sandbar closures and re-openings (both mechanical and natural). These brief closures and re-openings of the lagoon also occur during the spring smolt migration into the lagoon from the upper watershed. New smolt arrivals to the lagoon are not yet adjusted to salt water conditions. The optimal water quality conditions for new arrivals would be predominantly fresh habitat in the main body with lightly stratified conditions in the deeper areas of the South Arm. The presence of some brackish conditions in the lagoon along the bottom should be enough to begin the adjustment to saltier conditions.

10.8.1 March 10, 2004

On March 10th the sandbar was open with a sharp turn towards the south (Fig 10.43). The water elevation in the lagoon was 1.3 m at 8:45. Streamflow entering the lagoon was approximately 5.6 m^3/s (190 cfs.

Morning water quality conditions were typical of a well-mixed lagoon. Vertical temperature profiles were uniform. In the South Arm dissolved oxygen concentrations were well above suitable conditions for steelhead at the surface with lower concentrations at depth, although still suitable. In the main body of the lagoon concentrations were well mixed due to significant mechanical mixing from incoming streamflow. Fresh water was dominant in the main body with brackish conditions at depth in the South Arm. The slightly brackish conditions are favorable for new arriving steelhead young-of-the-year and yearlings to the lagoon.

The lagoon was revisited later that evening at 17:45. Both the lagoon water elevation and incoming streamflow levels were the same as the morning observations.

Weather conditions were warm and clear with a slight breeze for the past three to four days. As a result, afternoon surface water temperatures in the South Arm had increased considerably from 14.6 in the morning to 18.2 ºC. Water temperatures in the main body of the lagoon had also increased from 13.5 in the morning to 16.2 in the afternoon. Both dissolved oxygen and salt concentrations had remained the same between morning and afternoon measurements.

Figure 10.43. Carmel Lagoon sandbar conditions on March 10, 2004. Photo: Joel Casagrande, March 10, 2004.

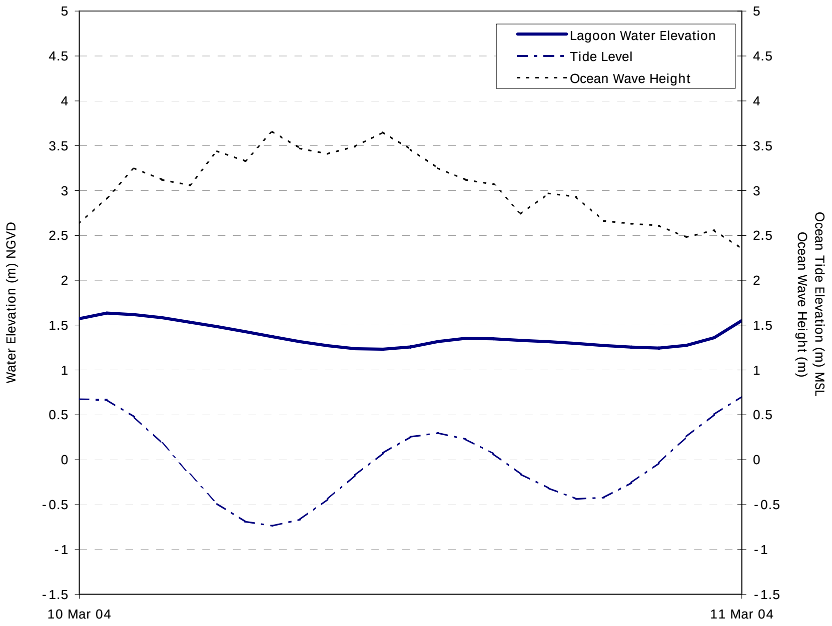


Figure 10.44 Carmel Lagoon water elevation and ocean tide elevation for March 10th, 2004.

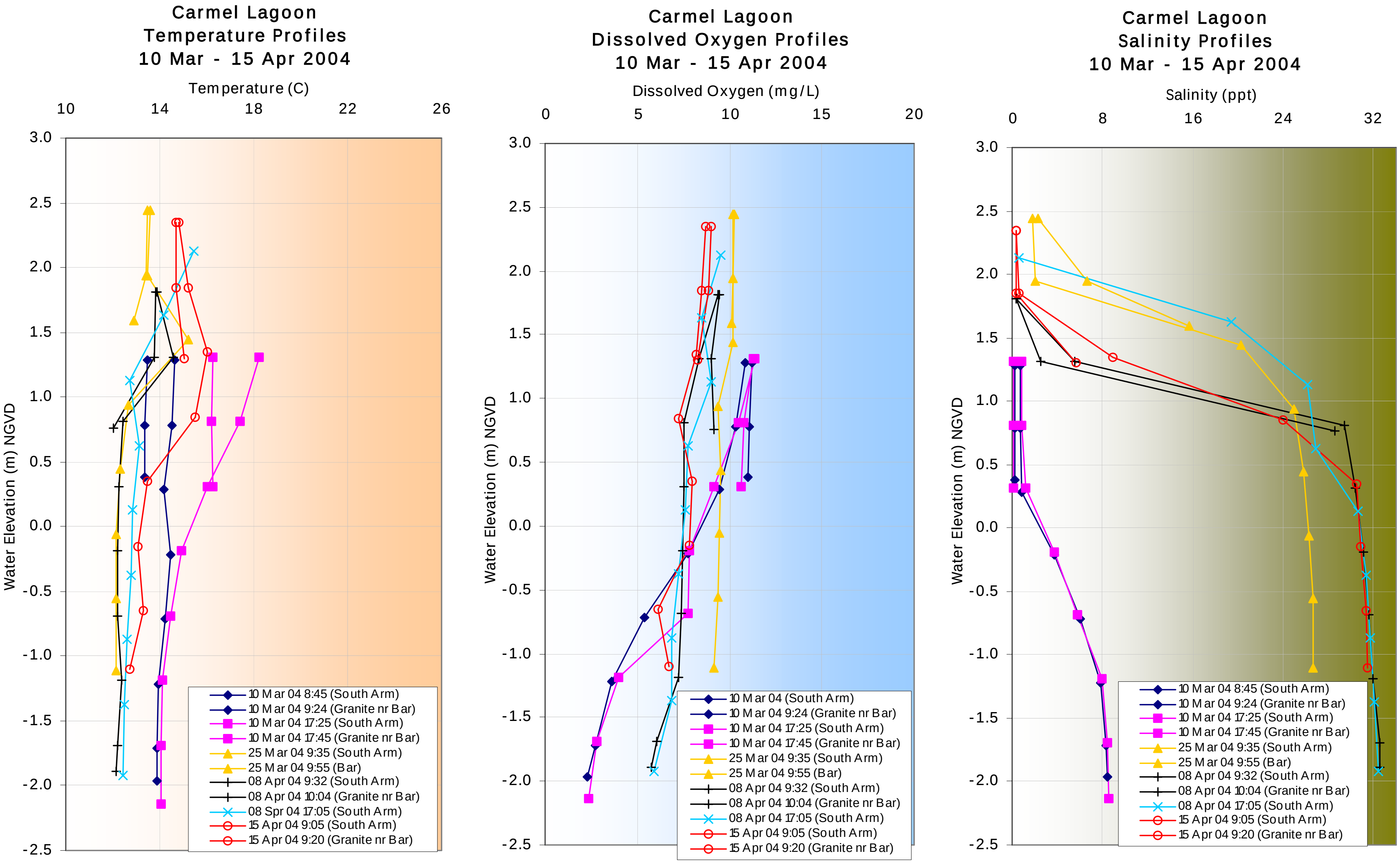


Figure 10.45 Temperature, oxygen, and salinity profiles collected at the pipe in the South Arm and at the granite rock outcrops near the sandbar as noted in the legends. **Note**: true bottom depths were not reached on March 25 and April 15. Access to the deeper part of the South Arm was limited.

10.8.2 March 25, 2004

The lagoon water quality measurements were recorded on the morning of March 25th. Streamflow entering the lagoon had subsided to 2.06 m3/s (75 cfs). The lower stream flows along with high surf caused the sandbar to close (Fig 10.46). The lagoon water elevation was at 2.44 m (8 ft) at 9:35.

Ocean wave in-wash had increased the lagoon salinity significantly compared to levels observed on March 10th (Fig 10.47). Morning water temperatures were cool throughout with high, well mixed dissolved oxygen concentrations (Fig 10.45).

Several steelhead were observed feeding at the surface in the South Arm.

Figure 10.46 Carmel Lagoon sandbar conditions on March 25th. Photo: Joel Casagrande, 25 Mar 2004.

10.8.3 April 8, 2004

On the 8th of April, morning and afternoon water quality conditions were assessed in the South Arm and near the sandbar. Streamflow entering the lagoon was approximately 1.8 m^3/s (65 cfs). Ocean waves were observed entering the lagoon during both the morning and afternoon visits (Figs. 10.49 & 10.50).

The morning temperature profiles show slightly warmer waters at the surface in both the South Arm and the main body near the sandbar due to warmer incoming streamflow. Mechanical mixing from continued ocean wave inputs resulted in suitable dissolved oxygen concentrations throughout the water column. The continued wave inputs also increased salinity levels throughout the day (Fig 10.45). Several steelhead were observed feeding at the surface during the morning monitoring.

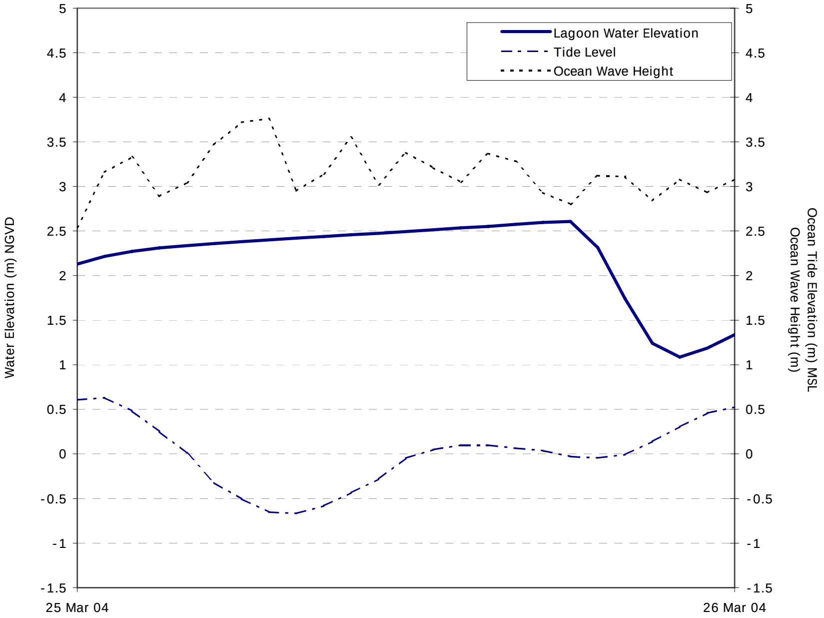


Figure 10.47 Carmel Lagoon water elevation and ocean tide elevation for March 25th, 2004.

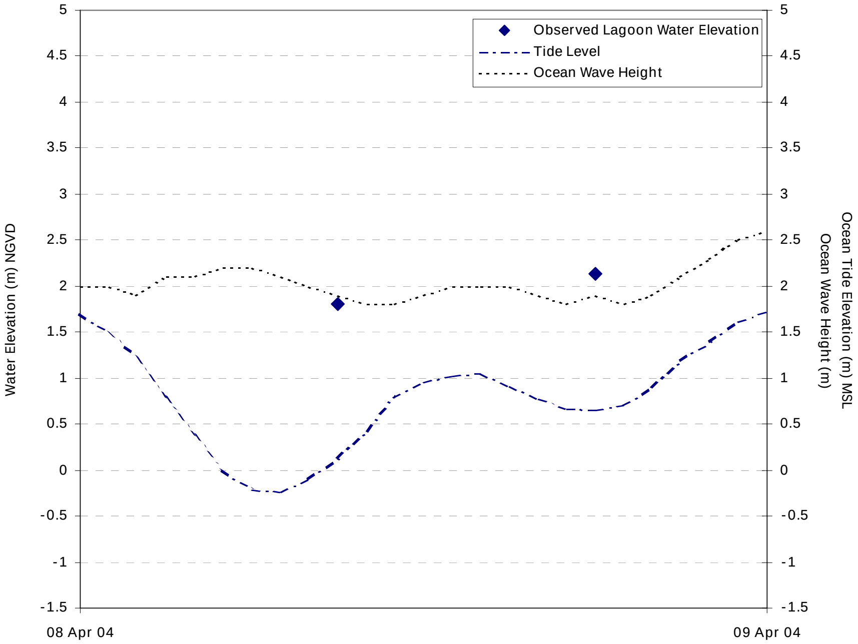


Figure 10.48 Carmel Lagoon water elevation and ocean tide elevation for April 8th, 2004.

Figure 10.49 Ocean wave in-wash on April 8th 2004. Photo: Joel Casagrande 08 Apr 2004.

Figure 10.50 Ocean wave-inwash debris and foam collecting in the river arm of the Carmel Lagoon. Kelp floating in the main body of the lagoon is visible on left side of the photo. Photo: Joel Casagrande, 08 Apr 2004.

10.8.4 April 15, 2004

On the morning of April 15th, water quality profiles were measured in the South Arm and near the sandbar. The sandbar was closed and streamflow at the USGS Via Mallorca gage declined to 0.87 m^3/s (31 cfs). Small ocean waves were observed entering the lagoon, although the wave heights measured at the NOAA M1 Buoy were significantly higher than those recorded on April 8th (Figs. 10.48 & 10.51).

Warmer daily air temperatures along reduced and possibly warmer incoming streamflows resulted in an increase in the lagoon's water temperatures from levels measured on the morning of April 8th. Dissolved oxygen concentration remained well mixed from top to bottom. Also since the April 8th measurements a slightly thicker freshwater lens had formed in both the South Arm and near the sandbar. Several steelhead were observed feeding at the surface in the South Arm.

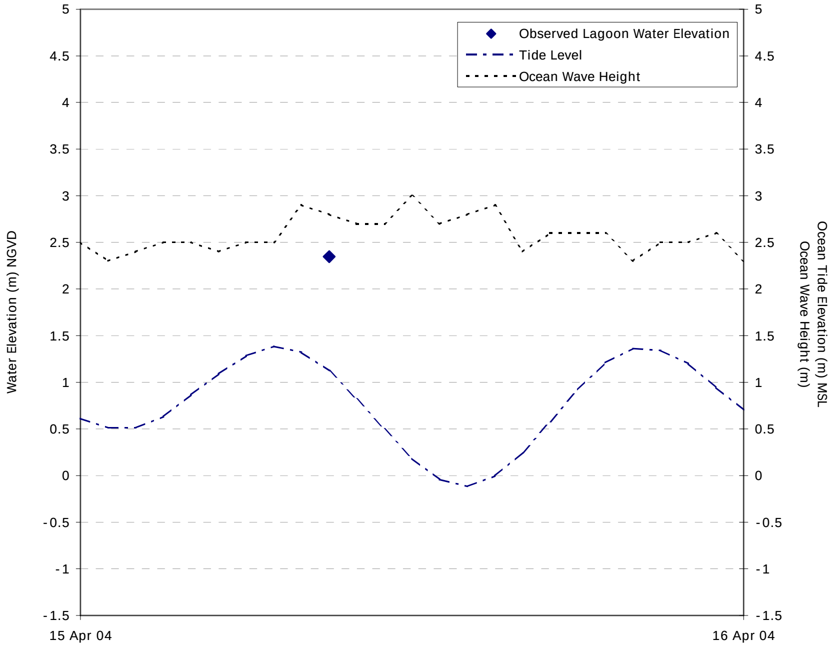


Figure 10.51 Carmel Lagoon water elevation and ocean tide elevation for April 8th, 2004.

11 References

Casagrande, J. Watson, F. Anderson, T. Newman, W. (2002). Hydrology and Water Quality of the Carmel and Salinas Lagoons Monterey Bay, California 2001/ 2002, The Watershed Institute, California State University Monterey Bay, Rep. No. WI-2002-04.

Casagrande, J. & Watson, F. (2003). Hydrology and Water Quality of the Carmel and Salinas Lagoons Monterey Bay, California 2002/ 2003, The Watershed Institute, California State University Monterey Bay, Rep. No. WI-2003-14, 118 pp. http://science.csumb.edu/~ccows/pubs/reports/CCoWS_LagoonBreaching2002-2003_030630.pdf

Cole, G.A., 1994. *Textbook of Limnology, Fourth Edition*, Waveland Press Inc., Prospect Heights, Illinois.

Feeney, M.B. (2002) Conservation Agreement Monitoring Plan for Increases Pumping Rate at Lower Carmel Valley. Prepared for California-American Water Company, 12 pp.

Feeney, M.B. (2004) Monitoring Program for Increased Pumping Rate in the Lower Carmel Valley – Quarterly Report. California-American Water Co./National Marine Fisheries Service Conservation Agreement. Prepared for Cal-Am. April 30, 2004. 11 pp.

Hagar Environmental Science (HES). 2002. Carmel River Lagoon Breach Monitoring Report 2001-2002. Prepared for the Monterey County Water Resources Agency (MCWRA), 29 pp.

Hookes, R. & Jeeves, T., 1961. “Direct Search” solution of numerical and statistical problems. J. Assoc. Comput. Mach. 8, 212–229.

Smith, J. 1990. The effects of sandbar formation and inflows on aquatic habitat and fish utilization in Pescadero, San Gregorio, Waddell and Pomponio Creek estuary/lagoon systems, 1985-1989, Report prepared under interagency agreement 84-04-324, between trustees for California State University and the California Department of Parks and Recreation. 38 pp. + appendix

Staal, Gardner & Dunne (SGD) (1989). Hydrogeologic investigation, Carmel River aquifer, coastal portion, Monterey County, California. Monterey Peninsula Water Management District open-file report. 25 pp., 6 appendices, 4 map sheets, scale 1:2,400.

Watson, F.G.R., Newman, W., Anderson, T., Alexander, S., Kozlowski, D. (2001) Winter Water Quality of the Carmel and Salinas Lagoons, Monterey, California: 2000/2001. Watershed Institute, California State University Monterey Bay, Rep. WI-2001-01, 42 pp.

Wetzel, R.G., 2001. *Limnology Lake and River Ecosystems Third Edition*, Academic Press, San Diego, CA.

Appendix: Sandbar photo sequence

The following photographs were taken from the top of the stairway located at on the southern bank near the sandbar of the Carmel Lagoon. The photos document temporal change in general sandbar conditions and they are an effective tool for evaluating ocean wave in-wash events by comparing the change in sandbar shape, estimated elevation change and the occurrence of recent kelp deposits.

October 4, 2003

October 10, 2003

October 17, 2003

October 28, 2003

November 4, 2003

December 10, 2003

December 21, 2003

December 30, 2003


March 10, 2004


April 8, 2004


April 15, 2004