PREDICTING PATHOGENIC BACTERIA CONCENTRATIONS WITH A COUPLED MICROBIAL-PHYSICAL MODEL

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1 Dedication

I dedicate my thesis to my friend, office mate, and fellow graduate student, Kaitlan Prugger. Who's friendship and companionship made the transition to graduate school and living in Hawai'i wonderful, and who's untimely loss forever changed me and my graduate school experience. Kaitlan, because you left us before you were able to achieve your dreams and academic goals, my thesis is dedicated to you.

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Table of Contents

Dedication						
Acknowledgments						
Introduction						
3.1	Backgr	ound	2			
	3.1.1	Vibrio vulnificus	2			
	3.1.2	Ala Wai Canal	3			
	3.1.3	Modeling Project	5			
Met	hods		6			
4.1	Model	Formulation	6			
	4.1.1	Physical Model	6			
	4.1.2	Microbial Model	8			
Results and Discussion 12						
5.1	Physic	al Model Validation	13			
	5.1.1	Velocity Comparison	13			
	5.1.2	Temperature and Salinity Comparison	14			
5.2	Mean S	State of Canal	15			
	5.2.1	Temperature and Salinity	15			
	5.2.2	Velocity	17			
5.3	Mean S	State: Model Experiments	18			
	5.3.1	Wind Forcing	19			
	5.3.2	Wind and Tidal Forcing	21			
	5.3.3	Wind, Tidal and Stream Forcing	21			
	5.3.4	Wind, Tidal, Stream and Wave Forcing	23			
	5.3.5	Residence Times	23			
5.4	Kona S	Storm Events: Model Experiments	24			
	5.4.1	Kona Wind Forcing	25			
	5.4.2	Kona Wind, Tidal and Stream Forcing	26			
5.5	Microb	bial Analysis	27			
	5.5.1	Mean State and Validation	28			
	Ded Ack Intr 3.1 Met 4.1 5.2 5.3 5.4 5.4 5.5	Dedication Acknowled Introduction 3.1 Backgr 3.1 3.1.1 3.1.2 3.1.3 Methods 4.1 Model 4.1 Model 4.1.1 4.1.2 Results an 5.1 Physic 5.1.1 5.1.2 5.2 Mean \$5 5.2.1 5.2.2 5.3 Mean \$5 5.3.1 5.3.2 5.3.3 5.3.4 5.3.4 5.3.5 5.4 Kona \$5 5.4.1 5.4.2 5.5.1 Microb	Dedication Acknowledgments Introduction 3.1 Background 3.1.1 Vibrio vulnificus 3.1.2 Ala Wai Canal 3.1.3 Modeling Project Methods 4.1 Model Formulation 4.1.1 Physical Model 4.1.2 Microbial Model 4.1.2 Microbial Model 5.1 Physical Model Validation 5.1.1 Velocity Comparison 5.1.2 Temperature and Salinity Comparison 5.2.1 Temperature and Salinity 5.2.2 Velocity 5.3 Mean State of Canal 5.3.1 Wind Forcing 5.3.2 Wind and Tidal Forcing 5.3.3 Wind, Tidal and Stream Forcing 5.3.4 Wind, Tidal, Stream and Wave Forcing 5.3.5 Residence Times 5.4.1 Kona Wind Forcing 5.4.1 Kona Wind, Tidal and Stream Forcing 5.4.2 Kona Wind, Tidal and Stream Forcing 5.4.1 Kona Wind, Tidal and Stream Forcing 5.4.2 Kona Wind, Tidal and Stream Forcing <			

	5.5.2 Ke	ona Storms Analysis	 	33
6	Conclusion			38
7	Figures and '	Tables		41

3 Introduction

Recreational water activities are a significant part of life and tourism in Hawai'i, such that water quality is of utmost importance. Waikiki is a popular tourist destination and the nearby beaches are frequented by tourists and locals. Historically, Waikiki was agricultural marshland, but in the 1920s the Ala Wai Canal was built and drained the wetlands, provided a pathway for surface runoff to flow to the ocean, and allowed for coastal development. The Ala Wai Canal connects freshwater to the ocean through an estuarine environment subject to tides, surface waves, and larger ocean conditions. Through physical (hydrodynamical) modeling, these oceanographic dynamics may be predicted and their effect on dynamics in the canal may be understood.

The Ala Wai Canal's warm estuarine environment provides ideal conditions for growth of the opportunistic pathogenic bacterium, *Vibrio vulnificus*. *V. vulnificus* can infect humans through exposure of open wounds or via ingestion of seafood containing the bacterium. Infections can result in symptoms such as gastroenteritis, severe inflammation, flesh loss and in some cases, death (Jones et al., 2008). The ability to accurately predict concentrations of this bacteria could improve public safety by providing a tool to indicate times and locations where the pathogen is present at particularly high levels. Previous research (Jones et al., 2008; Nigro, 2012; Miles et al., 1997), has shown that *V. vulnificus* growth depends on the temperature and salinity of its environment. This dependence demonstrates a physical-chemical

1

control of V. vulnificus and provides a basis for modeling the population dynamics of this bacterial species, through the use of a coupled microbialphysical model. The dynamical physical model captures the physical processes that control temperature, salinity, and advection and allows for prediction of V. vulnificus concentrations. This goal of this project is to understand the controlling processes and determine the predictive capability of V. vulnificus through the use of a coupled microbial-physical model.

3.1 Background

3.1.1 Vibrio vulnificus

Vibrio vulnificus is a naturally occurring, halophilic, opportunistic pathogenic bacterium that thrives in warm estuarine environments. V. vulnificus can infect humans either through open cuts and wounds or by ingestion of contaminated raw or undercooked seafood. Preexisting cuts or open wounds are susceptible to infection through contact with water where V. vulnificus is present and can result in cellulitis, sometimes evolving to necrotizing faciitis, which can result in limb amputation. Consumption of contaminated seafood can result in gastroenteritis and septicemia, characterized by fever, chills, and nausea (Chase and Harwood, 2011; Oliver, 2005). Either type of infection can be fatal in immunocompromised patients, with an average mortality rate of 25% and 50% via blood infection or consumption, respectively (Jones and Oliver, 2009). Typically, V. vulnificus is found in warm estuarine waters, and in the United States, the coastal regions of the Gulf of Mexico, Florida, and Hawaii have all reported infections. Growth is dependent on temperature and salinity. Above about 15°C, growth rates increases systematically with increasing temperature to around 40°C (Kelly, 1982; Wang and Gu, 2005). Growth rates tend also to be highest in the salinity range from 10 to 30, dropping significantly at much lower or higher salinities (Kelly, 1982; Wang and Gu, 2005; Chase and Harwood, 2011). This dependence on temperature and salinity presents an opportunity to model *V. vulnificus* concentrations by accurately modeling temperature and salinity.

3.1.2 Ala Wai Canal

During the 1920s, the Ala Wai Canal was built by the US Army Corps of Engineers to drain the wetlands of the Honolulu Waikiki ahupua'a: a Hawai'ian land division typically encompassing a watershed region extending from the mountains to the sea. The canal construction drained the farm and marshland and made the land available for development. This area transformed into the popular tourist destination of Waikiki — home to a plethora of hotels, resorts, condominiums, timeshares, and stores. The Ala Wai Canal, approximately 3 kilometers long and varying in width from 51 to 83 meter (Glenn and McMurtry, 1995), stretches along the length of Waikiki, starting near the Waikiki public library and flows out through the Ala Wai Boat Harbor near Magic Island. Water from the Ko'olau Mountains and the Manoa and Palolo valleys drains into the Ala Wai via the Makiki stream and the Manoa and Palolo streams, which are channeled prior to flowing into the Ala Wai at a single location (Fig. 1). A storm drain, at the end of the canal, also provides a source of surface runoff to the canal. Nutrient input to the canal through runoff has been shown to be high allowing for elevated levels of primary productivity. The high level of productivity in the Ala Wai Canal is comparable to few marine ecosystems in the world (Glenn and McMurtry, 1995). This productive ecosystem supports a variety of marine and estuarine biota, including *V. vulnificus*. *V. vulnificus* is ubiquitously present in the canal; however, makes up only a small fraction of the total bacterial community. *V. vulnificus* and total bacterial abundances were estimated from Ala Wai water samples and *V. vulnificus* was observed to make up less than $10^{-4}\%$ of the total bacterial abundance on average (Nigro, 2012). This percentage can fluctuate depending on growth conditions, predator dynamics, and nutrient availability.

The Ala Wai Canal not only provides drainage of the Waikiki ahupua'a, but is used for recreational activities. Various local canoe paddling clubs use the Ala Wai Canal for training, and boaters, swimmers and surfers frequent the adjacent coastal waters. As a favorable habitat for *V. vulnificus*, exposure to the waters of the canal carries some risk of infection. In 2006, after falling into the Ala Wai Canal and suffering scrapes and cuts, a man was infected by *V. vulnificus* and later died of septic shock. Prior to this event, raw sewage was diverted in to the canal, although *V. vulnificus* is not associated with sewage, the introduction of organic material may have contributed to the presence of *V. vulnificus* in the canal. To minimize risk of infection, it is important to understand the controls of *V. vulnificus*, in order to ultimately have the ability to predict times of elevated concentrations.

3.1.3 Modeling Project

The dependence of V. vulnificus on temperature and salinity can be exploited to develop a deterministic model. By modeling temperature, salinity, and advection using a regional coastal model of the physical environment and linking this physical model to a simple growth model, we attempt to simulate spatial and temporal changes in V. vulnificus concentrations. Our ultimate goal is predictability of temporal and spatial variability of V. vulnificus abundances, to identify times and areas with particularly high levels, which may pose a greater risk of infection.

This modeling study hindcasts V. vulnificus concentrations during a 5-month period from November 2008 to March 2009. During this period, a field study of spatial and temporal variability of V. vulnificus in the Ala Wai Canal sampled two significant storms. These storms were Kona storms, which result from the cessation and sometimes reversal in the typical wind patterns of northeasterly trade winds, and can result in heavy rainfall on the south shore of Oahu (Leopold, 1948). Storms like these are of particular interest because the rainfall increases the transport of water out of the canal, while lowering salinity significantly: the combined effect of these two processes on V. vulnificus is uncertain. Through the implementation of a coupled physical-microbial model of the Ala Wai Canal and south shore of Oahu, we aim to understand and predict the effects of canal hydrodynamics on V. vulnificus abundance.

4 Methods

4.1 Model Formulation

4.1.1 Physical Model

For this project we use a Regional Ocean Modeling System (ROMS) model of the Ala Wai Canal and surrounding south shore. ROMS is a three-dimensional regional ocean model that uses the primitive equations with hydrostatic and Boussinesq approximations, and an equation of state, potential temperature, salinity and scalar concentration tracer equations (Shchepetkin and McWilliams, 2005). In this study, the Coupled-Ocean-Atmosphere-Wave-Sediment Transport Modeling System (COAWST) version of ROMS, described in Warner et al. (2010), was used. The grid encompasses the Ala Wai Canal and the south shore from Honolulu Harbor to Waikiki, including Sand Island, Kewalo Harbor, Magic Island, and Ala Wai Boat Harbor as shown in Fig. 1. The grid has horizontal resolution of approximately 50 m $({}^{\sim}\frac{1}{2000}{}^{\circ})$ in the Ala Wai Canal and south shore, with resolution decreased at the boundaries of the grid to approximately 300 m. There are 15 vertical terrain-following layers with a thickness of a meter or less for most of the model domain. The model formulation is based upon the work in Azevedo Correia de Souza et al. (in prep) and a similar formulation is run operationally for forecasts of brown water outflow as a part of the Pacific Islands Ocean Observing System (PacIOOS) (http://oos.soest.hawaii.edu/pacioos).

Our model is forced by winds from the Weather Regional Forecast

(WRF) model, surface waves from the Simulating Waves Nearshore (SWAN) model, stream input from the Palolo-Manoa and Kalihi streams, and boundary conditions from nested outer-models. The boundary conditions were generated by downscaling from the global HYCOM (resolution ${}^\sim \frac{1}{12}{}^\circ)$ to a ROMS model of the Hawaiian Islands (resolution $\sim \frac{1}{28}^{\circ}$) (Matthews et al., 2012), to a ROMS model of Oahu (resolution ${\sim}\frac{1}{100}^{\circ})$ (Janeković and Powell, 2012), to a ROMS model of the South Shore of Oahu (resolution ${}^{\sim}\frac{1}{500}{}^{\circ})$ (Johnson et al., 2013). Stream forcing was generated from streamflow data publicly available from the USGS (http://waterdata.usgs.gov). The streamflow data was converted into units of m^3/s and then multiplied by 1.5 to account for other sources of freshwater input into the canal via small drainage pipes, rainfall, and the Makiki stream, which data was unavailable throughout the modeling period, this manipulation is similar to Johnson et al. (2013). Transport from the river is configured to simulate realistic streamflow patterns, with approximately 75% of the transport occurring in the upper 2 meters, with the remaining 25% of the flow occurring in the lower 3 meters. The transport in the lower 3 meters decays with depth, with approximately zero transport at the bottom. The stream water temperature is assumed to be the same as water in the Ala Wai, typically 25°C, therefore stream input is only prescribed with transport and salinity, and is in effect the same temperature as canal water. This assumption may bias modeled canal temperatures to be warm, as stream temperatures can be cooler than canal water; however, without measurements of stream temperature available throughout our study period, coupled with the knowledge that observed canal temperature variations are minimal (Fig 7), this formulation is sufficient. Because

stream water is fresh, it is prescribed with a salinity value of 1‰. Vertical mixing is parameterized using the $k - \omega$ generic length scale method presented in Warner et al. (2005) and originally put forth by Jones and Launder (1972).

4.1.2 Microbial Model

Based on a population growth model with laboratory growth rates of V. vulnificus and estimated mortality we developed a microbial model to numerically integrate and couple to the ROMS model. For a single spatial grid point, the equation governing V. vulnificus growth is:

$$\frac{dV(t)}{dt} = \left[\rho(V(t))k(T(t), S(t)) - \delta(z)m\beta\right]V(t), \tag{4.1}$$

where k(T(t), S(t)) is the growth rate determined by temperature T and salinity S at time t, $\rho(V(t))$ is the fractional adjustment to growth to account for carrying capacity, m is a constant mortality rate, β is the ratio of the current V. vulnificus population, V(t), to the lagged population, $V(t-\gamma)$, and $\delta(z)$ is a depth scaling.

From laboratory experiments of V. vulnificus, in ideal nutrient rich conditions, growth rates were estimated over a variety of temperatures and salinities (Nigro, 2012). Implementing these growth rates in the microbial model requires a function that resolves all physically viable temperature and salinity values. To allow for this resolution, we created a differentiable growth function to map a pair of temperature and salinity values to a specific growth rate, based on the laboratory growth rates. Radial basis functions have been used in a variety of fields including biology, meteorology, and mathematics to map sparse data to a differentiable function (Nuss and Titley, 1994; Buhmann, 2000). The general form of a radial basis function is:

$$s(\vec{x}) = \sum \alpha_i \Phi_i(|\vec{x} - \vec{x_i}|), \qquad (4.2)$$

where Φ_i are the basis functions, \vec{x} is the coordinate location, and $\vec{x_i}$ are the reference locations of known values. There are various choices for the form of the basis function, for our purposes, the multiquadric form was chosen because it is a useful interpolant of sparse gridded data (Kansa, 1990; Carlson and Foley, 1991). The multiquadric equation is:

$$\Phi(r) = \sqrt{1 + (\epsilon r)^2},\tag{4.3}$$

where ϵ is an arbitrary small parameter, and r is the radial distance from a data point, usually measured as Euclidian distance. In our formulation, the radial distance is measured as the distance of a given temperature, T, and salinity, S, from the reference T_i and S_i given in the laboratory data:

$$r(T,S) = \sqrt{(T-T_i)^2 + (S-S_i)^2}.$$
(4.4)

Thus, using the general form of the radial basis function, (4.2), the growth function becomes:

$$k(T,S) = \sum \alpha_i \Phi_i(r(T,S)).$$
(4.5)

To solve for α_i , (4.5) sets up a least squares problem:

$$\Phi \alpha = k \tag{4.6}$$

Where Φ is an $n \times n$ matrix of the radial distances mapped into the multiquadric basis function, α is the vector of coefficients, and k is the vector of growth rates. With the laboratory data from Nigro (2012), Φ and k(T, S) are known, for the T and S values tested in the lab, and the coefficients α are unknown. By solving for α in (4.6), we obtain the coefficients, that are stored in the model. Substituting T and S into (4.5) provides the growth and can easily be computed during integration of the model. This process saves computational time and storage space, making the calculation of growth and implementation of the model more efficient. Since nutrients in the Ala Wai Canal are not infinite, V. vulnificus is subject to a carrying capacity. To simulate the effect of the carrying capacity, the growth calculated from (4.5) is scaled as the population approaches carrying capacity. This scale is calculated by:

$$\rho(V(t)) = 1 - e^{1.25(V(t) - C)}, \tag{4.7}$$

where V(t) is the current abundance of V. vulnificus and C is the carrying capacity. After (4.7) is calculated, ρ multiplies growth and this scaled growth is input to (4.1). As V(t) approaches C, ρ decreases from 1 to 0, thus decreasing growth, simulating the decrease in population growth as the population reaches carrying capacity. Mortality of V. vulnificus in the canal, m, has not been quantified well, thus to simulate realistic mortality conditions in the canal a mortality scheme was developed. Due to the high productivity of the Ala Wai Canal, typical microbial grazing rates for tropical oligotrophic water were insufficient to control the growth of V. vulnificus. We assume that mortality due to grazing, infection by viruses, and natural mortality to be constant in the canal. Because V. vulnificus is a fractional percentage of a larger microbial population and does not have closely coupled predator-prey dynamics with a particular predator, V. vulnificus abundance does not influence abundance of predators. Our interest is in V. vulnificus, not all microbial species in the canal, therefore to account for dynamic predatory pressure, we scale the mortality by, β , which equals the ratio of current abundance, V(t), to lagged abundance, $V(t - \gamma)$.

To set the constant mortality, m, we assume that the net growth balances loss of V. vulnificus through advection. Based on this assumption, we calculated the e-folding time for V. vulnificus at the mean temperature and salinity and the constant mortality was set by ensuring the e-folding time scale was approximately equal to the residence time of water in the canal (we discuss residency times in the next section). This constant mortality is scaled by β , because we assume mortality in the canal to be constant, as V. vulnificus grows, this constant mortality is stronger, and with decay, the constant mortality is weaker. In addition to this population ratio, we scale the mortality by a depth scaling, $\delta(z)$, which increases linearly as depth increases. This depth scaling is an attempt to account for changes in ecosystem dynamics in the coastal and open ocean, where V. vulnificus abundance and growth are diminished.

The microbial model is coupled online to the ROMS model and is updated at each time step. The microbial model accounts for the changes in concentrations of V. vulnificus due to fluctuations in temperature and salinity by integrating (4.1) and using (4.5); however, in addition to local growth and decay, concentrations of V. vulnificus are altered by advection, turbulent mixing, and dispersion. To account for advective processes, V. vulnificus is a passive tracer in the ROMS model and tracked via the scalar concentration tracer equation:

$$\frac{\partial V(x, y, z, t)}{\partial t} + \vec{v} \cdot \nabla V(x, y, z, t) = \nabla^2 V(x, y, z, t)$$

$$+ \left[\rho(V(x, y, z, t)) k(T(t), S(t)) - \delta(z) m\beta \right] V(x, y, z, t)$$
(4.8)

where V(x, y, z, t) is *V. vulnificus* over space and time and \vec{v} is the velocity field. *V. vulnificus* concentrations are calculated for the entire grid by local growth, mortality, and advection.

5 Results and Discussion

To understand the physical dynamics in the Ala Wai Canal, we examine the mean state of the canal through the 5-month period and compare the physical model with available observations.

5.1 Physical Model Validation

5.1.1 Velocity Comparison

We do not have velocity measurements within the canal; however, Kilo Nalu was a cabled observatory on the south shore of Oahu (approximately 2.4 km west of the Ala Wai Canal) and comprised of a suite of instruments measuring physical-biogeochemical processes including current profiles, temperature, salinity, turbidity, chlorophyll fluorescence, and acoustic backscatter (Sansone and Kevin Stierhoff, 2008). Available data include a 1200-kHz acoustic Doppler current profiler (ADCP) that provides a 0.25 meter resolution vertical profile of currents at the observatory, measured at high frequency, typically less than 1 s^{-1} . The ADCP was located at the Kilo Nalu site at 21.29°N, 157.87°W in 11 meters of water.

To confirm that the ROMS model captures the relevant coastal dynamics, we compared model output at the grid point with the approximate latitude, longitude and depth of the Kilo Nalu observatory to the ADCP data. Hourly block averages were computed and subsampled to compare the hourly model output to the ADCP data. Both velocity data were rotated to split the current field into along and cross shore components. The vertical structure of the currents was examined by averaging over three depth bins; the deepest depth bin being 11 to 8 meters deep, mid from 8 to 3 meters deep, and lastly, 3 to just over 1 meter below the surface. The model and ADCP data were compared over a time period where ADCP data was continuously available, January through March 2009. The model was free running and unconstrained by the data, so the forcing captured the observed events and phase of the storms in both the along and cross shore (Fig 2,4). The magnitude of the velocity is comparable and the observed and modeled tidal signal are in phase at each depth bin (Fig 2,4).

To quantify the energy found at particular frequencies and the cascade of energy from low to high frequencies, a spectral analysis of the observed and modeled velocities was performed. The spectra of the modeled and observed along and cross shore velocities are comparable (Fig 3,5). Similar magnitude of energy is seen across frequencies and the slope of the spectra are approximately equivalent. Energy at the tidal frequencies in the observations and model output are similar, particularly at the semi-diurnal frequency, which is important for canal dynamics.

5.1.2 Temperature and Salinity Comparison

During our period of study, observations of temperature, salinity, turbidity, and chlorophyll were collected as part of the PacIOOS. A Sea-Bird Electronics (SBE) 16plus V2 SEACAT C-T Recorder was fixed to the side of the canal. The instrument was fixed to a stationary post; hence, the depth of the instrument varied during the tidal cycle; however, the absolute depth was not recorded. Without knowing the actual depth, comparing to the model is difficult. We estimated the depth from the bottom of the canal to the sensor, and used this fixed depth to estimate sensor depth through time. The model output was extracted and interpolated to the estimated sensor depth. Comparison of the time series of temperature and salinity observations and model output show that the model generally captures the observed temporal variation (Fig 6A, 7A). The major low salinity events observed, occur during Kona storms (Table 1) and are captured in the model. The cascade of energy from low to high frequencies is comparable in the observations and model output; however, the observations generally have more energy overall (Fig 6B, 7B). This discrepancy can be accounted for by the fact that the nearshore sensor tracks changes of temperature and salinity in a parcel of water, whereas the model, due to its discretization, tracks changes of temperature and salinity over a volume of water on the order of tens of meters. Because our modeling interest is in microbial dynamics, and microbes cannot instantaneously adapt to their environment, this filtering of high frequency changes does not limit out modeling ability.

5.2 Mean State of Canal

5.2.1 Temperature and Salinity

Understanding the dynamics of temperature and salinity is imperative to comprehending *V. vulnificus* dynamics and its controls. Daily and seasonal variations of solar heat input and fluctuations in rainfall and streamflow into the canal affect the spatial and temporal structure of temperature and salinity in the Ala Wai Canal. We examine the 5-month mean of temperature and salinity in the canal to understand the typical distribution. Variations across the canal are minimal; therefore, we examine the average spatial distribution of temperature and salinity along the canal versus depth (Fig 8). Temperature variations are within 1°C, with cooler waters in the surface and warmer waters below. The Manoa-Palolo stream input (marked on figures with \wedge), creates local divergence allowing for the warmer bottom waters to extend to the surface. The structure of salinity in the canal is influenced by freshwater input of the Manoa-Palolo stream and intrusion of seawater due to tidal currents in and out of the canal. The 5-month average of salinity in the canal ranges between 28 ppt and 35 ppt, with fresher water at the surface and a persistent salt wedge at depth, intruding into the canal from the ocean (Fig. 8).

To get a sense of how this mean structure varies on a daily basis, we examine temporal temperature fluctuations via daily average, minima, and maximum temperature values observed in the canal. The magnitude of diurnal temperature fluctuations in the canal is typically between 1 and 3°C. To account for differences in temperature solely due to the average vertical temperature structure, we examine the range of daily minima and maximum temperatures in the surface layer and bottom layer separately. In the surface, the magnitude of diurnal temperature fluctuations is less than 1°C; whereas, at the bottom the magnitude is 1 to 3°C. This suggests that despite surface water being exposed to sunlight, winds cool the surface waters, so that the difference between the minimum and maximum temperature stays within 1°C; whereas, the bottom waters, which are protected from winds, are able to warm during the day, due to their shallow depth, and cool off at night. Because stream input is prescribed with only transport and salinity, the input itself does not affect the vertical structure of temperature, suggesting that winds and solar heating control the structure.

Daily average salinity values show more variation than temperature with maximum values around 35 ppt and minimum values ranging from 33 ppt to 2 ppt. During times of low stream input, minimum salinity values are around 33 ppt; however, during Kona storms, minimum salinity values can be as low as 2 ppt. These storm driven low salinity events highlight the significance of rain and stream input on salinity in the canal. During these Kona storms, low salinity abruptly decreases, however, lower salinity persists in the canal for varying duration. The 5-month mean structure of salinity shows a clear two-layer structure, therefore, we examine minimum and maximum salinity values at the surface and bottom separately. At the surface, salinity fluctuates between 35 ppt and 2 ppt, whereas, at the bottom, fluctuations range between 35 ppt and 30 ppt. This difference in the magnitude of salinity variability suggests that stream flow has a greater effect on surface salinity that the bottom.

5.2.2 Velocity

While the temperature and salinity determine the local *V. vulnificus* growth, the advection and transport of water in the canal changes the spatial distribution of temperature, salinity, and *V. vulnificus*. To understand the dynamics of advection and transport, we examine the 5-month mean of the along and cross-canal velocities in the Ala Wai Canal. For discussion of velocity and transport in this paper, outflow will be synonymous with flow towards the canal exit (negative) and inflow into the canal (positive). The along-canal velocity structure shows two distinct flow patterns in the canal: one from the stream input to the mouth of the canal, and one from the stream input to the back of the canal. We first examine the flow pattern from the stream input to the mouth of the canal (0 meters along canal distance). There is a two-layer flow with surface outflow, 6 cm/s, and weaker inflow, 4 cm/s, in the lower layer (Fig 9). Vertically integrating the along-canal transport shows there is net outflow, and this net outflow is equivalent in magnitude to the mean streamflow into the canal (0.5 m^3/s). From the stream to the back of the canal a more complicated recirculation flow is set up, adjacent to the stream input there is a three-layer structure, with inflow in the surface and bottom waters and outflow in the mid-waters (Fig 9). This three-layer structure deteriorates at the back of the canal, and inflow is observed in the bottom waters and outflow in the surface waters. In addition to a different structure, the magnitude of the velocities from the river to the back of the canal are significantly smaller than the canal mouth.

The cross-canal velocities are small in magnitude throughout most of the canal, notable exceptions are at the stream input. The structure of the cross-canal velocities is generally from north to south in the surface waters and the opposite in the bottoms waters. At the stream, cross-canal velocities at the surface are variable, but on average are around $-0.04 \ m/s$ and opposite in the bottom waters.

5.3 Mean State: Model Experiments

The Ala Wai Canal has four primary forcing mechanisms: wind, tides, stream input, and surface waves. The Manoa-Palolo stream typically discharges

less than 0.5 m^3/s into the Ala Wai Canal, but during heavy rainstorms this transport of water can increase to maximum values upwards of 100 m^3/s (Table 1). In addition to stream input, the canal is forced by ocean processes, such as tides and waves, at the mouth of the canal. Also, strong winds can impart momentum to the canal resulting in advection. To isolate the effects of these forcings on the dynamics of the Ala Wai, four model experiments were conducted: (i) wind forcing, (ii) wind and tidal forcing, (iii) wind, tidal, and stream forcing, and (iv) wind, tidal, stream, and wave forcing (full dynamics). These experiments will be referred to as the wind, tide, stream, and wave cases respectively. These experiments were run from November 11th, 2008 through December 31st, 2008 to capture typical trade wind and low streamflow conditions, as well as Kona storm conditions. We examine typical low streamflow and trade wind conditions from November 25, 2008 to November 30, 2008 and a Kona storm from December 10, 2008 to December 13, 2008. In this next section we will discuss the analysis of the typical conditions.

5.3.1 Wind Forcing

With wind forcing only, the spatial variability of temperature and salinity in the canal is minimal, with variations of 0.5° C and 0.2 ppt respectively. Because the temperature and salinity variations are small, density in the canal is uniform at approximately 1023.4 kg/m^3 . Examining diurnal temperature variations shows that maximum surface temperatures tend to be less than maximum bottom temperatures, supporting the hypothesis about wind cooling of surface waters; however, this difference is on the order of less than 0.5° C and can be reversed. Because density is uniform in the canal, vertical mixing may be greater, allowing for an essentially uniform temperature structure, whereas in the mean state of the canal, the vertical density gradient limits mixing and helps to create the temperature structure. Winds, in this case, do not have a significant effect on the temperature and salinity structure in the canal; however, winds are important for the structure of velocity in the canal. During typical conditions, north-easterly trade winds are present and set up a two-layer flow. Due to the location of the canal and the direction of the trade winds, this two-layer flow is characterized by outflow in the surface waters and inflow in the bottom waters, with surface outflow constrained to the upper 1 meter, with a maximum magnitude of approximately 0.5 cm/s (Fig 10). This outflow is set up by the friction of wind stress at the surface advecting water out of the canal. Friction on the surface of the water from the wind forces water along the canal and creates an along-canal pressure gradient, with depressed sea surface height at the back end of the canal and increased sea surface height at the front of the canal. Friction from the interaction of the inflow in the bottom waters and the bottom topography is important as well. As the bottom water flows along the canal, friction with the bathymetry acts to diminish this flow. Since winds do not change the flux of mass in the canal, the friction of the winds and the pressure gradient it sets up, are the two dominant terms of the momentum balance (Fig 11). Advection of momentum is the next largest term in the momentum balance; however, during trade wind conditions, advection is not significant.

5.3.2 Wind and Tidal Forcing

We now examine the effect of tides on the structure of the wind-forced system. During the typical trade wind period, the mean structure of the velocity in the canal is not significantly changed; however, there is variation throughout the tidal cycle. As the tide propagates through the canal, the tidal flow dissipates with the geometry of the canal and bottom friction and so in the back of the canal the tidal flow is diminished. Despite this decrease in tidal amplitude along the canal, transport along the canal is tidally dominated throughout the canal. The M_2 tide dominates this transport. The mean structure of the tidal forcing case is approximately identical to the structure of the wind forcing case (Fig 10); however, we know the temporal along-canal transport is affected by tides. During the flood tide, the inflow transport typically increases by 5-10%, while the outflow at the surface is decreased by approximately 5%. Conversely, at the ebb tide, outflow typically increases by 5-10% in the surface and the bottom inflow decreases by less than 5%.

5.3.3 Wind, Tidal and Stream Forcing

With forcing from the freshwater stream flow, the dynamics of the canal change dramatically. Due to the transport of water into the canal from the stream, the structure is altered and the magnitude of the velocities in the canal increase from approximately $1 \ cm/s$ to $6 \ cm/s$. The addition of stream input sets up recirculation dynamics in the back of the canal (Fig 12A), which was observed in the mean (Fig 9), with flow to the back of the canal in the surface and bottom waters and outflow in the mid waters.

Since the stream introduces fresh water into the canal, not only are the dynamics in the canal changed, but the density structure is significantly altered. The stream water is rain-driven and fresh with a prescribed salinity of 1, making the surface waters fresher with a mean lens of salinity 28 ppt overlying saltier water of 35 ppt (Fig. 13B). The structure of temperature is altered, not through the introduction of colder water, but because of local divergence in the surface waters at the stream input and local convergence in the mid-waters, allowing for upwelling of warmer water (Fig. 13A). Because the temperature in the canal varies less than a degree, the structure of density in the canal is mostly determined by salinity (Fig.8). With the input of stream freshwater, a stratification structure is established in the canal.

Contrary to the wind and tide cases, the momentum balance in the stream case is dominated by the pressure gradient and viscosity set up by the introduction of mass from the stream (Fig 14). In the wind case, friction from wind stress set up an along-canal pressure gradient; however, in this case, mass accumulates at the stream input, creating a pressure gradient away from the stream input (Fig 14), with elevated sea surface at the stream input and decreased sea surface elevation along the canal on either side of the input. Stream flow introduces mass, but also increases advection in the canal, particularly at the stream input, therefore at the input the advection of momentum becomes a relevant source of momentum (Fig 14).

5.3.4 Wind, Tidal, Stream and Wave Forcing

Lastly, we aim to understand how surface waves affect the canal. In the coastal waters adjacent to the mouth of the canal, the maximum wave breaking energy occurs approximately 700 meters from the mouth of the canal offshore. The magnitude of the wave breaking energy decreases by an order of magnitude 500 meters offshore and decreases by five orders of magnitude by the mouth of the canal. Wave energy is dissipated well outside of the canal and is found to have essentially no effect on the canal dynamics (not shown).

5.3.5 Residence Times

As mentioned previously, the velocity structure in the canal is altered through time by tidal forcing at the mouth of the canal. The M_2 tide dominates the tidal signal in the canal and can be seen in a time series of transport along the canal. During the flood tide, along-canal tidal velocities are positive, meaning outflow is diminished and inflow strengthened. During the ebb tide, the opposite effect occurs. The magnitude of along-canal tidal velocities during the flood and ebb tide is approximately 2 cm/s; therefore, despite the effect of the tides on the canal dynamics, tidal flow is smaller than the mean outflow due to stream input.

In addition to temporal variation in transport, it is important to understand the residence time of water parcels in the canal. We focus on 2 regions: the bend to the stream and the stream to the back of the canal, which are approximately equivalent volumes. Volume in the canal does not

vary significantly through time and so stream input and mean inflow and outflow were assumed to be in steady state for residency times calculations. Using the stream input, mean inflow, and volume of each region, residency times were calculated to be 2.2 and 8.9 days, from the elbow to the stream and the stream to the back of the canal respectively. These times suggest that, on average, it takes 4 times longer for water to be replaced in the back of the canal versus an equivalent volume of water on the other side of the stream input. These calculations only take into account mean flow and not the effect of tides. To estimate the residence times based on tidal flushing, the tidal prism method (Dyer, 1973) was used and residence times were found to be to be 2.11 and 2.55 days for the 2 regions (elbow to stream and stream to back of canal). This result suggests that tides would tend to shorten the residence times calculated from the mean flow. Gonzalez (1971) estimated residency times in the elbow to stream region of the canal around 4 tidal cycles, or 2 days, depending on the strength of the winds and stream flow. Unfortunately, Gonzalez (1971) was unable to estimate residency times for the back of the canal, but speculated that residency times in the back of the canal could be much longer than the front part of the canal.

5.4 Kona Storm Events: Model Experiments

During Kona storms, the typical northeasterly trade wind pattern is halted and the direction of the wind can reverse to southwesterly winds. These southwesterly winds sometimes bring heavy rains to the south shore of Oahu, greatly increasing the streamflow of freshwater into the canal. With an average transport of less than 0.5 m^3/s during typical conditions, the Manoa-Palolo stream can intensify 200 times during these Kona storms. To understand the effect of the change of wind and stream flow, we examine our model experiments during a storm in December 2008, starting on December 10th lasting for 3 days. Because wind and stream flow change during these storms, we will focus our discussion on the wind and stream experiments.

5.4.1 Kona Wind Forcing

The general two-layer flow structure of the along-canal velocity seen during typical conditions is maintained during Kona storms. Due to the increase in the magnitude of the wind stress from approximately $0.02Nm^{-2}$ to $0.1Nm^{-2}$, the vertical extent of the surface outflow increases to approximately 2 meters. The magnitudes of both the surface flow and the bottom flow increase during the Kona storm. The surface flow increases by a magnitude of approximately 2 cm/s and the bottom flow increases by a magnitude of approximately 1 cm/s. The momentum balance is still dominated by friction and pressure gradient; however, due to the increase in magnitude of wind stress, the advection of momentum becomes more important in the surface waters. Despite this increase, the advection of momentum is still rather insignificant. Not only does the magnitude of the wind stress increase, but the direction of the winds shifts. This shift does not alter the direction of flow along the canal, but it reverses the cross-canal flow to northward in the surface and southward in the bottom waters.

During the Kona storm, the temperature and salinity in the canal re-

main mostly uniform and varying by $0.3 \circ C$ and 0.4 ppt respectively. These temperature and salinity variations lead to an average density in the canal of 1023.1 kg/m^3 , which is slightly less dense than during typical trade wind conditions; however, the difference is small and the structure in the canal is still uniform.

5.4.2 Kona Wind, Tidal and Stream Forcing

During Kona storms, heavy rainfall increases the Manoa-Palolo stream flow and alters the dynamics in the canal. The maximum stream flow observed during this storm was 102.6 m^3/s (Table 1), this strong influx of water increases the average vertical extent of the surface outflow to about 4 meters deep in addition to increasing the magnitude of the flow to 6 cm/s (Fig.12B). Increased stream input does not only strengthen outflow, but alters the structure and increases the magnitude of the recirculation flow in the back of the canal (Fig.12B). The recirculation flow in the back of the canal is restructured as more of a two-layer flow, with the surface inflow and the bottom outflow with magnitudes of 1 cm/s. During the times of increased stream flow, the vertical extent of the surface outflow extends throughout the entire water column, but is confined to the surface waters within 24 hours of the large pulse. This barotropic outflow occurs during the onset of rain events throughout the canal from the stream input to the front of the canal.

In addition to changing the dynamics in the canal, the stream also changes the structure of the temperature and salinity in the canal. Temperature in the canal ranges from approximately 18 ° C to 25 ° C, with the cooler temperatures concentrated in the surface waters in the back of the canal (Fig.13C). Due to the influx of freshwater in the surface waters and the mean structure of the along-canal velocity, salinity develops a distinct two layer structure, with fresher waters, approximately 17 ppt in the upper 1 meter, overlying saltier water, approximately 33 ppt (Fig.13D).

5.5 Microbial Analysis

Based solely on the velocity structure, one would expect to find higher V. vulnificus concentrations in the back of the canal, as a result of inflow at the bottom and recirculation in the back. This flow structure would tend to keep particles in the water longer in the back of the canal. This hypothesis is supported by longer residency times observed in the back of the canal. Inflow from the coastal waters is low in V. vulnificus and thus, might act to dilute concentrations. Therefore, concentrations may decrease from the back of the canal to the front in the bottom waters. Temperature and salinity are not uniformly distributed in the canal, and thus growth rates have spatial structure. From this structure, the surface waters have the highest growth rates due to the salinity and temperature range, thus V. vulnificus should be present in the surface waters, depending on whether this growth can overcome persistent outflow. Combining growth rate and velocity, we hypothesize a mean distribution with higher concentrations in the back of the canal and low concentrations at the mouth of the canal and in the surface waters. This mean distribution will be altered through time via changes in advection and growth rate. During Kona storms, advection increases in the canal

and freshwater is introduced. The increased advection should act to deplete *V. vulnificus* concentrations; however, introduced freshwater will mix with saline canal water and create increased growth rates, allowing for growth to potentially balance advection.

5.5.1 Mean State and Validation

Our goal is to understand and predict concentrations of V. vulnificus in the canal. We coupled the V. vulnificus population growth model (4.1) into ROMS and repeated the wave experiment (full physics) through the 5-month study period. Initial examination of the mean distribution of V. vulnificus shows several notable characteristics: concentrations tend to decrease toward the canal exit and concentrations are higher in the surface waters (Fig. 15). As hypothesized, concentrations are higher in the back of the canal and lower at the mouth. In the bottom waters, V. vulnificus concentrations are low, extending from the mouth of the canal past the stream. This area of low concentrations corresponds to the high salinity wedge intruding from the sea, suggesting that seawater helps to dilute concentrations in the bottom waters. In the surface waters, concentrations are higher than the water below, suggesting that, despite advection, growth rates allow for a persistent population. Concentrations in waters adjacent to the stream input are elevated, but at the stream, concentrations are lower. Advection is greatest at the stream input and acts to flush V. vulnificus out of the canal.

This modeled mean structure of V. vulnificus can be compared to monthly samples at 11 stations along the Ala Wai Canal collected throughout 2008 and 2009 (Nigro, 2012). At these stations, temperature and salinity were taken in situ, and the V. vulnificus concentrations were estimated in the laboratory via quantitative polymerase chain reaction (qPCR). Due to the model's discretization, only 9 of these sample stations fall in distinct grid cells. Sample stations that fell within the same grid cell were averaged together before comparing to the model output. The time mean of the sampled V. vulnificus concentrations were compared to the modeled concentrations (Fig 16). The modeled concentrations show highest concentrations at the back of the canal, decreasing to the mouth of the canal. Observed concentrations display lower concentrations and a more spatially uniform distribution; however, similarities can be seen. Both the modeled and observed concentrations are decreased near the stream input, with higher levels moving away from the stream. The sampled V. vulnificus concentrations are highly variable through time, so the standard deviation about their mean is large; therefore, we must also examine concentrations through time.

Since temperature and salinity were sampled along with concentrations, we can get a sense of how well the model is capturing *V. vulnificus* growth dynamics, as well as concentrations. Three locations along the canal were chosen to compare observations with model data to understand spatial differences in modeling ability. The first location was near the back end of the canal, the second was located near the elbow, and the third was near the mouth of the canal. In the back of the canal, temperature is captured well in the model (Fig 17A). Observed temperatures are typically within 1°C of modeled values and display the same trend through time. Salinity is not represented as well, modeled salinity tends to be saltier than observations, particularly during storm events (Fig 17B). This discrepancy during events may be because stream input is the only source of fresh water in the canal for the model, whereas, in reality, freshwater is also introduced from rain falling directly in the canal, from surface runoff along the canal length, and at point sources via storm drains. Despite the differences, the temperatureand salinity-controlled growth dynamics seem to be represented reasonable well; however, modeled V. vulnificus concentrations are significantly different than observed (Fig 17C). The magnitude of modeled concentrations is much larger than observed at the times of sampling. Near the elbow of the canal a similar trend occurs (Fig 18). Temperature through time is reasonably represented; however, there are some larger discrepancies between the model and observations than at the back of the canal (Fig 18A). Salinity at the elbow is saltier than observations throughout the entire time period (Fig 18B). These discrepancies suggest that not including the Makiki stream, which enters near the elbow of the canal, is biasing our growth rates and may account for the difference between modeled and observed V. vulnificus concentrations (Fig 18C). At the last location, near the Ala Wai Boat harbor, temperature and salinity are both well represented in the model (Fig 19). Salinity during rain events is fresher in observations than modeled; however, during low stream flow periods, the salinity is similar (Fig 19B). At the mouth of the canal, observed V. vulnificus concentrations are more comparable to modeled concentrations than any other location in the canal (Fig 19C). Modeled and observed concentrations are low at most of the sampling times, but both increase dramatically in December to comparable levels (Fig 19C). These three points show that freshwater input into the canal is underrepresented in the model, particularly during rain events. As mentioned previously, the lack of freshwater input at the Makiki stream may be a major factor, as well as the absence of rainfall and other surface runoff into the canal during these Kona storms. This bias for saltier values could have a significant influence on *V. vulnificus* growth rates, particularly during storms. Because extremely low salinities correspond to low growth, modeling saltier values, during storms, may allow for higher growth rates than reality. Another trend seen at all three locations is modeled *V. vulnificus* concentrations are low in February and March 2009, which suggest that a population crash occurred. When February and March concentrations are examined separately they exhibit similar behavior as November, December, and January, but are orders of magnitude smaller (not shown). Despite these similar dynamics, concentrations after the crash are uncertain and unknown, and do not rebound to similar pre-crash levels.

Despite discrepancies in modeled concentrations, we can still analyze and understand what controls these modeled concentrations. Given the mean temperature and salinity distribution from the hydrodynamics, the fastest average growth rates are found in the lower salinity waters at the surface (Fig. 15B). If growth rate determined the distribution of V. vulnificus, the mean concentration would mirror the mean distribution of growth; however, this is not the case. The mean distribution of V. vulnificus shows the highest concentrations in the surface and back end of the canal where in situ growth is relatively low (Fig. 15A). This distribution can be explained by the velocity structure in the canal. As discussed previously, the back end of the canal has a recirculating flow pattern in the back of the canal
with residency times of 8.9 days – 4 times longer than the other side of the stream (Fig. 9). This flow allows for V. vulnificus levels in the surface waters in the back of the canal to be elevated on average, despite relatively low in situ growth. Another notable deviation from the growth rate distribution is lower concentrations at the stream. In the surface, at the stream, V. vulnificus growth rate is highest (Fig. 15). Despite this high growth rate, outflow transport is increased due to the streamflow. Low concentrations at the stream suggests that concentrations are advected away faster than the growth rate or source of V. vulnificus can account for. Towards the mouth of the canal and bottom waters, the concentrations. Growth rates are low in the bottom waters and seawater dilutes any existing concentration due to inflow, particularly on the flood tide. From this analysis it is clear that both growth rates and velocity determine the structure of V. vulnificus.

To quantify the relationship between V. vulnificus growth rate and advection, normalized cross correlations were calculated between V. vulnificus concentrations and both the growth rate and along canal velocity. Each cross correlation was calculated at every grid point along the canal with depth. Correlation between V. vulnificus concentrations and along canal velocity is weak, with the magnitude of maximum correlations approximately 0.3 (Fig. 20A). Despite these weak correlations, the structure of positively versus negatively correlated areas is of interest. In the surface waters, from the stream to the mouth of the canal, correlation is positive, meaning there is a relationship between higher V. vulnificus concentrations and more positive surface velocities (inflow or the weakening of outflow). This suggests

that if outflow weakens, the growth rate is able to make up for advective loss and concentrations may increase. In the mid and bottom waters, concentrations and velocity are anticorrelated, meaning that as outflow increases, V. vulnificus concentrations will increase. This anticorrelation suggests that inflow lowers concentrations, and with less inflow or slight outflow, concentrations may be higher. Growth rate and V. vulnificus concentrations are strongly positively correlated in the lower waters, with an average correlation of approximately 0.8 (Fig. 20B). Correlation in the surface waters is weak, approximately 0.3. This structure suggests that in the surface waters growth rate does not significantly determine concentrations, however in the bottom waters, growth rate becomes more relevant. This relationship supports the hypothesis that the influx of seawater in the bottom waters acts to dilute concentrations; however, these correlations are very weak and suggest only slight possible relationships. On the other hand, it is clear that growth rates have a significant role in determining the mean distribution of V. vulnificus, particularly in the bottom waters.

5.5.2 Kona Storms Analysis

As discussed previously, Kona storms have drastic effects on the structure of temperature, salinity, and velocity in the Ala Wai Canal. Two major Kona storms occurred during the 5 month study period: December 10th - 13th and March 9th - 14th (Table 1). By analyzing these two time periods, we aim to understand the dynamics of V. vulnificus in the Ala Wai Canal during storms.

December Beginning late December 8th Kona southerly winds began to blow. This change in wind direction coincided with heavy rainfall. Two notable pulses in streamflow in the Manoa/Palolo stream occurred: December 10th and 13th. The December 10th and 13th streamflow values were 102.6 m^3/s and 45.44 m^3/s respectively. During these surges, outflow increased significantly and deepened from the surface to 2 m (initially entire water column and then reduced to 2 m within 12 hours). Increased streamflow led to low salinity in the canal, while temperature remained similar. Due to this change, the maximum *in situ* growth rate increased from approximately 9 gene copies/day to over 11 gene copies/day. Despite the increased growth rate, concentrations of V. vulnificus collapsed during the storm because of the increased stream flow. Within 24 hours of each freshwater pulse, the V. vulnificus concentrations rebounded (Fig. 22A). As shown in Fig. 22, V. vulnificus concentrations decreased dramatically when outflow in the canal is strong. Due to this influx of freshwater, growth rates increased significantly (Fig. 22C), and allowed for rebound and growth. This increase in V. vulnificus does not occur ubiquitously in the canal, but is confined to the surface waters in the back end of the canal, where growth rates are elevated and advection concentrates V. vulnificus.

Because we know that V. vulnificus concentrations are related to growth rate and advection when examining the full 5-month period, we examine the relationship between concentrations with both growth rates and velocity during the 3 days of the storm. Cross correlations of V. vulnificus concentrations and growth rates and velocity were calculated for each canal grid point (Fig. 21). As shown in Fig. 21, there is more spatial structure in the cross correlations in the canal for both growth rate and velocity. If we examine correlation between concentrations and growth rate, we see that there is a strong positive correlation ($^{\sim}0.8$) along the front of the salt wedge in the mid waters of the canal (Fig 21B). In the back of the canal, there is a relatively strong positive correlation ($^{\circ}0.6$) in the surface waters. Since the residency time of water in the back of the canal is longer, strong positive correlation of concentrations with growth rate makes sense. Water parcels, and V. vulnificus, are not quickly replaced, allowing for V. vulnificus to be strongly influenced by *in situ* growth rates. Strong positive correlation with growth rate along the front of the salt wedge follows less logically, but to fully understand we examine the relationship between concentrations and velocity. V. vulnificus concentrations and velocity are strongly negatively correlated in the back of the canal and along the salt wedge (Fig 21A). This relationship suggests that as inflow increases (or outflow decreases), concentrations go down. In the back of the canal, this suggests that if inflow increases, the recirculation flow is expedited, decreasing the residency time and *in situ* concentrations. Along the salt wedge, negative correlations with velocity suggest that if inflow is decreased concentrations can increase. This relationship supports the hypothesis that an inflow of seawater acts to dilute concentrations. These correlations only suggest general relationships between advection, growth, and concentrations. These relationships are nonlinear and small changes in stream flow or growth can have unexpected effects on V. vulnificus concentrations.

March On March 10th, 2009 there was a cessation of the trade winds, and a shift to north-westerly winds by the end of March 11th. After a couple days of north-westerly winds, the winds shifted to southerly winds. This wind pattern coincided with increased rainfall which resulted in two large pulses of increased streamflow on March 10th and 14th. Streamflow values on March 10th increased to 52.01 m^3/s and 110.88 m^3/s on March 14th. The average temperature in the canal just prior to the storm was approximately $24^{\circ}C$ with the minimum and maximum temperatures within a degree. After the first stream event on March 10th, the temperature range increased from 22 to $26^{\circ}C$. Despite this increased temperature range, the average temperature in the canal was still around $24^{\circ}C$. Surface salinity in the canal decreased to approximately 5 ppt during the two river pulses. Unlike temperature, salinity decreases abruptly at the time of increased stream flow and increases within 24 hours. Despite this increase in surface salinity values, the surface values are still fresher than average providing increased growth rates. Growth rates in the surface waters during and between both rain events are elevated from typical values around 9 gene copies/day to almost 11 gene copies/day (Fig. 23C). As mentioned previously, V. vulnificus concentrations, after February 2009, had crashed and therefore are unknown; however, we still see some similarities to the December storm. As before, during increased streamflow the along-canal velocities are higher and V. vulnificus concentrations are low initially and increase after advection decreases (Fig. 23B). Because concentrations just prior to the March storm were extremely low, V. vulnificus concentrations increased on the order of 1000%. This increase may be a result of rebounding from the crash, rather than the effect

of the storm dynamics.

To quantify the relationship between V. vulnificus concentrations and growth rate versus velocity, we calculated cross correlations for each canal grid point during the March storm. The spatial structure of the correlations for the March storm are similar to the spatial structure of the correlations for the December storm (Fig. 21). The similarity in spatial structure suggests that the similarity in dynamics controlling the canal during these two periods affect V. vulnificus similarly. Correlation in the surface, between concentrations and growth, show much weaker correlations than December, particularly in the back of the canal; however, along the salt wedge correlation is stronger and extends further to the back of the canal (Fig. 21D) In the correlation between concentrations and velocity, correlation is stronger than December with the magnitude of the correlations ($^{\circ}0.7$) (Fig 21C). The discrepancy between V. vulnificus correlations in December and March, can partially be explained by the fact that concentrations were rebounding from prior environmental conditions, which resulted in population crash, therefore V. vulnificus dynamics were less related to growth rate, but still strongly affected by advection. Despite these differences, it appears that growth rate and advection affect concentrations similarly during different Kona storms. Growth rates are more uniformly significant throughout the canal when looking over long periods of time; however in particular areas growth can be significant during the storm. Over long periods, advection has little impact on V. vulnificus; however, during storms, advection becomes significant.

6 Conclusion

With this project we aimed to understand the controls, and predict V. vulnificus concentrations in the Ala Wai Canal using a coupled microbial-physical model. From the analysis of the physical dynamics in the canal, we determined that wind and stream input are the main drivers in the mean canal dynamics, through the set up of a two-layer flow from the river to the mouth of the canal and a recirculation flow in the back end of the canal. In the mean, V. vulnificus concentrations are determined by both growth and circulation, with the front end of the canal being controlled more by flow and the back controlled by growth. By examining canal dynamics during a Kona storm, we determined that mean velocities in the canal increase greatly during the storm. However, due to the intermittent nature of these strong streamflow pulses, transport out of the canal extends through the whole water column during the input of river flow during heavy rainfall, but quickly restores to a two-layer flow with persistent slightly increased along canal velocity. During these Kona storms, V. vulnificus concentrations, because of increased along canal velocity, initially drop to low levels despite high *in situ* growth, but are able to rebound to pre-storm levels as the magnitude of the alongcanal velocity decreases. In the front of the canal, growth and velocity are approximately equally correlated with V. vulnificus concentrations and in the back of the canal, growth is positively correlated and velocity is negatively correlated. This relationship suggests that in the back of the canal as recirculation is enhanced during the storm, V. vulnificus concentrations go down, but as the magnitude of the flow decreases, elevated growth rates help

concentrations rebound.

Momentum in the absence of stream input is dominated by friction and a pressure gradient set up by the wind stress on the canal waters. With stream input, the introduction of mass dominates the momentum balance; however, friction and pressure gradient are still the two dominant terms and friction from flow along the bottom is important. Since the canal is known to have large sediment sills (Glenn and McMurtry, 1995), the velocity structure may be different than the bottom topography used in this study. In future studies, a more realistic bathymetry, taking into account the accumulation of sediment in the canal, as well as the addition of Makiki stream input, may give more accurate concentrations and may account for discrepancies between the modeled and observed concentrations. Discrepancies between observed and modeled concentrations also suggest that mortality may be underestimated in our formulation. Future work in determining more accurate in situ mortality may be helpful in providing the accurate magnitude of concentrations. Despite potential errors in magnitude, the model formulation provides insight into the drivers of increased V. vulnificus concentrations, and can provide aid for optimizing sampling and water quality decision making.

Water quality concerns are not confined to the Ala Wai Canal, but extend to adjacent beaches frequented by locals and tourists. In the initial onset of a freshwater pulse into the canal, we observed decreased levels of V. vulnificus in the canal that resulted from strong advection out of the canal. This advection of canal waters offshore allows for the potential for V. vulnificus to reach the adjacent beaches. Johnson et al. (2013) concluded that during southerly winds these freshwater plumes are pushed to deeper depths onshore and westward because of the balance between the winds and an offshore pressure gradient. With predicted plume dynamics there is a possibility for V. vulnificus levels at local beaches to be elevated if the plume is pushed onshore and is not well mixed. However, as V. vulnificus move offshore, predation dynamics and nutrient availability are altered. Nutrient availability is diminished, decreasing the ability for V. vulnificus to survive predation.

Predictive modeling of pathogenic bacteria, such as we have attempted for *V. vulnificus*, provides insight into the controls on the dynamics of environmental bacteria. By further improving upon the coupled biologicalphysical modeling techniques developed here, it may become possible to develop an on-line resource that provides real-time predictions of pathogen concentrations. Such tools would be a valuable complement to traditional methods of water quality monitoring that have low spatial coverage and long lag times.

7 Figures and Tables



Figure 1: Bathymetry of Ala Wai and South Shore ROMS model domain denoted in rectangle. Manoa-Palolo stream input (1), Waikiki Beach(2), Ala Moana Beach (3), and Honolulu Harbor (4) denoted.



Figure 2: Modeled and observed along shore current velocities at Kilo Nalu A) 3 to 1 meters, B) 8 to 3 meters, and C) 11 to 8 meters deep



Figure 3: Modeled and observed along shore current spectra at Kilo Nalu A) 3 to 1 meters, B) 8 to 3 meters, and C) 11 to 8 meters deep



Figure 4: Modeled and observed cross shore currents at Kilo Nalu A) 3 to 1 meters, B) 8 to 3 meters, and C) 11 to 8 meters deep



Figure 5: Modeled and observed cross shore current spectra at Kilo Nalu A) 3 to 1 meters, B) 8 to 3 meters, and C) 11 to 8 meters deep



Figure 6: A) Modeled and observed salinity at nearshore sensor in Ala Wai Canal and B) spectra of modeled and observed salinity at nearshore sensor



Figure 7: A) Modeled and observed temperature at nearshore sensor in Ala Wai Canal, and B) spectra of modeled and observed temperature at nearshore sensor



Figure 8: 5 month average (November 2008 - March 2009) of along canal cross section of modeled A) temperature and B) salinity



Figure 9: 5 month average (November 2008 - March 2009) of along-canal velocity



Figure 10: Along-canal velocities from wind case during typical trade wind conditons



Figure 11: Along-canal momentum balance A) pressure gradient, B) friction, and C) advection of momentum during typical trade wind period (wind case)



Figure 12: Along canal velocities for stream case during A) typical trade wind conditions and B) December Kona storm



Figure 13: A) Temperature and B) salinity in the canal during typical trade wind conditions and C) temperature and D) salinity during a Kona storm (NOTE: scales are different between plots)



Figure 14: Along-canal momentum terms, A) pressure gradient, B) friction, and C) advection of momentum during typical trade wind conditions (stream case)



Figure 15: Vertical along-canal cross section of average modeled A) V. vulnificus concentrations and B) growth-rates over the 5-month study period (November 2008 - March 2009)



Figure 16: Modeled and observed surface concentrations of V. vulnificus along the canal, error bars denote standard deviation of sample time series.



Figure 17: Modeled and observed A) temperature, B) salinity, and C) *V. vulnificus* concentrations (model axis on left, sample axis on right) through 5-month study period (November 2008 - March 2009) at sample location near the back end of the canal.



Figure 18: Modeled and observed A) temperature, B) salinity, and C) *V. vulnificus* concentrations (model axis on left, sample axis on right) through 5-month study period (November 2008 - March 2009) at sample location near elbow of canal.



Figure 19: Modeled and observed A) temperature, B) salinity, and C) *V. vulnificus* concentrations (model axis on left, sample axis on right) through 5-month study period (November 2008 - March 2009) at sample location near mouth of canal and Ala Wai Boat Harbor.l



Figure 20: Cross section of along-canal distribution of correlation of V. vulnificus concentrations with A) along-canal velocity and B) growth rates over 5-month study period (November 2008 - March 2009)



Figure 21: Cross section of along-canal distribution of correlation of *V. vulnificus* concentrations with A) along-canal velocity and B) growth rates over the duration of December Kona storm, and correlations of concentrations with C) along-canal velocity and B) growth rates over the duration of March Kona storm.



Figure 22: A) Percent change of V. vulnificus concentrations from concentrations pre-December event, B) vertically integrated along canal velocity, and C) in situ growth rate at point in canal near stream input



Figure 23: A) Percent change of V. vulnificus concentrations from concentrations pre-March event, B) vertically integrated along canal velocity, and C) in situ growth rate at point in canal near stream input

Table 1: Date, Duration, and Max Streamflow of Major Rain Events

Date	Nov. 21 - 22, 2008	Dec. 10 - 13, 2008	Dec. 29, 2008 to Jan 3, 2009	Mar. 9 - 14, 2009
Duration (hours)	4.5	76	82.5	125.04
Max stream flow (m^3/s)	46.56697464	102.60129	20.702679	110.88329

References

- Azevedo Correia de Souza, Joao Marcos; Li, Ning, and Powell, Brian. Influence of wave-current interaction when modeling the near-shore ocean in the south shore of oahu - hawaii. in prep.
- Buhmann, Martin Dietrich. Radial basis functions. Acta Numerica 2000, 9: 1–38, 2000.
- Carlson, Ralph E and Foley, Thomas A. The parameter R² in multiquadric interpolation. Computers & Mathematics with Applications, 21(9):29–42, 1991.
- Chase, Eva and Harwood, Valerie J. Comparison of the effects of environmental parameters on growth rates of vibrio vulnificus biotypes i, ii, and iii by culture and quantitative pcr analysis. Applied and environmental microbiology, 77(12):4200–4207, 2011.
- Dyer, Keith R. Estuaries: a physical introduction. 1973.
- Glenn, Craig R and McMurtry, Gary M. Scientific studies and history of the ala wai canal, an artificial tropical estuary in honolulu. *Pacific Science*, 49 (4):307–318, 1995.
- Gonzalez, F. A descriptive study of the physical oceanography of the ala wai canal, 1971.
- Janeković, Ivica and Powell, Brian. Analysis of imposing tidal dynamics to nested numerical models. Continental Shelf Research, 34:30–40, 2012.

- Johnson, Abby E; Powell, Brian S, and Steward, Grieg F. Characterizing the effluence near waikiki, hawaii with a coupled biophysical model. *Continen*tal Shelf Research, 54:1–13, 2013.
- Jones, Melissa K and Oliver, James D. Vibrio vulnificus: disease and pathogenesis. *Infection and immunity*, 77(5):1723–1733, 2009.
- Jones, Melissa K; Warner, Elizabeth, and Oliver, James D. Survival of and in situ gene expression by vibrio vulnificus at varying salinities in estuarine environments. Applied and environmental microbiology, 74(1):182–187, 2008.
- Jones, WP and Launder, BEi. The prediction of laminarization with a twoequation model of turbulence. *International journal of heat and mass transfer*, 15(2):301–314, 1972.
- Kansa, Edward J. Multiquadrics—a scattered data approximation scheme with applications to computational fluid-dynamics—i surface approximations and partial derivative estimates. Computers & Mathematics with applications, 19(8):127–145, 1990.
- Kelly, MICHAEL T. Effect of temperature and salinity on vibrio (beneckea) vulnificus occurrence in a gulf coast environment. Applied and Environmental Microbiology, 44(4):820–824, 1982.
- Leopold, Luna B. Diurnal weather patterns on oahu and lanai, hawaii. Pacific Science, 2:81–95, 1948.

Matthews, Dax; Powell, BS, and Janeković, Ivica. Analysis of four-

dimensional variational state estimation of the hawaiian waters. *Journal* of Geophysical Research: Oceans, 117(C3), 2012.

- Miles, David W; Ross, Thomas; Olley, June, and McMeekin, Thomas A. Development and evaluation of a predictive model for the effect of temperature and water activity on the growth rate of vibrio parahaemolyticus. *International journal of food microbiology*, 38(2):133–142, 1997.
- Nigro, Olivia D. Environmental controls on Vibrio vulnificus and other pathogenic vibrios in tropical and subtropical coastal waters. PhD thesis, UNIVERSITY OF HAWAI 'I AT MĀNOA, 2012.
- Nuss, Wendell A and Titley, David W. Use of multiquadric interpolation for meteorological objective analysis. *Monthly Weather Review*, 122(7): 1611–1631, 1994.
- Oliver, JD. Wound infections caused by vibrio vulnificus and other marine bacteria. *Epidemiology and infection*, 133(03):383–391, 2005.
- Sansone, Francis J and Kevin Stierhoff, Christopher Colgrove. kilo nalu. Oceanography, 21(4):173, 2008.
- Shchepetkin, Alexander F and McWilliams, James C. The regional oceanic modeling system (roms): a split-explicit, free-surface, topographyfollowing-coordinate oceanic model. *Ocean Modelling*, 9(4):347–404, 2005.
- Wang, Yanling and Gu, JiDong. Influence of temperature, salinity and ph on the growth of environmental aeromonas and vibrio species isolated from mai po and the inner deep bay nature reserve ramsar site of hong kong. *Journal of basic microbiology*, 45(1):83–93, 2005.

- Warner, John C; Sherwood, Christopher R; Arango, Hernan G, and Signell, Richard P. Performance of four turbulence closure models implemented using a generic length scale method. *Ocean Modelling*, 8(1):81–113, 2005.
- Warner, John C; Armstrong, Brandy; He, Ruoying, and Zambon, Joseph B. Development of a coupled ocean–atmosphere–wave–sediment transport (coawst) modeling system. Ocean modelling, 35(3):230–244, 2010.