Estuarine, Coastal and Shelf Science xxx (2015) 1–15

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

The fine-scale vertical variability of a wastewater plume in shallow, stratified coastal waters

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A R T I C L E I N F O

Article history:
Received 23 October 2014
Received in revised form
29 July 2015
Accepted 13 August 2015
Available online xxx

Keywords:
Wastewater plume dispersion
Stratified systems
Internal waves
Effluent plumes
Stirring and mixing
Phytoplankton blooms

A B S T R A C T

We observed the fine-scale vertical variability of a wastewater plume discharged into shallow, stratified coastal waters with a set of wave-powered profiling moorings and bottom-mounted Acoustic Doppler Current Profilers. These *in situ* observations demonstrated that the effluent plume occupied a variable portion of the water column, but was typically at or above the pycnocline. The plume was characterized by small vertical scales away from the surface, while complicated patterns of vertical temperature and salinity compensation were found in the plume above the pycnocline. The particular design of the diffuser led to an effluent plume that was roughly split between depth-trapped and trapped at the surface. Estimates of dilution from temperature/salinity diagrams indicated that the plume dilution ranged between 60 and 120, and that the environmental mixing end-members ranged from waters well below the pycnocline to the waters at or near the surface. Far from the outfall, oceanographic variability at frequencies equal to and higher than the diurnal frequency dominated the vertical shear in local currents and thus the vertical and temporal distribution of the plume. Mixing driven by the high frequency non-linear internal waves and bore-like manifestations of the cross-shore baroclinic tide, as suggested by elevated inverse Richardson number within the leading and trailing edge of the bores, was likely the primary source of mixing between the plume and ambient waters far from the outfall. Complicated patterns in plume water characteristics demonstrated the complexity of the plume dilution even in a surfacing plume. The co-occurrence of elevated chlorophyll fluorescence and plume waters was evident in the later part of the diversion period, but the overall response of the phytoplankton to the effluent diversion was limited. Implications for outfall wastewater monitoring and diffuser design are briefly considered.

1. Introduction

Ocean wastewater outfalls are designed to discharge effluent offshore with the minimum impact on the shoreline and coastal zone. Variability in the local oceanographic environment and the design of the wastewater outfall play major roles in determining the fate of discharged effluent (Jirka and Akar, 1991; Brooks, 1960; Roberts, 1989). As it is typically undesirable for an effluent plume to reach the shoreline, outfall design requires knowledge of local oceanic exchange mechanisms. Early lessons regarding cross-shore exchange led to the outfall design criteria that outfalls extend far offshore, reach well below the surface (preferably below an internal density interface such as the thermocline), and are provided with a mechanism to rapidly dilute effluent with ambient waters. To that end, the terminal sections of most modern wastewater outfalls are in relatively deep waters and are equipped with a multi-port diffuser for rapid effluent dilution. While diffuser geometries vary, they are designed to cause rapid near-field dilution of the discharged effluent due to entrainment of and mixing with the surrounding waters (i.e. the ‘receiving waters,’ Jirka and Akar, 1991). The aim is to trap the plume at depth, thereby isolating the plume from the shallow waters of the coastal zone.

The behavior of discharged waters depends on both the momentum imparted by the discharge process and on the buoyancy difference between the effluent and the surrounding environment. These momentum and buoyancy fluxes can be calculated if the diffuser geometry, discharge volume flux, and the characteristics of the receiving waters are known. The magnitude of these fluxes, in

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http://dx.doi.org/10.1016/j.ecss.2015.08.010
0272-7714/

combination with environmental properties (e.g. the vertical distribution of density and currents), can be used to estimate the scales of important transitions in the discharged water. For example, the vertical position of the plume under the influence of stratification (known as the plume rise height, H_{plume}) can be estimated from the diffuser buoyancy flux and the vertical stratification of the receiving waters (Fischer et al., 1979). Similar scaling estimates form the basis of models used in outfalls design and in the environmental impact assessment process associated with discharge permitting (e.g. the United States Environmental Protection Agency (US-EPA)-supported Cornell Mixing Zone Expert System (CORMIX), Jirka et al., 1997). Yet these estimates, widely used by regulators, policy-makers, and dischargers, rely on simplifications of both the hydrodynamics within the discharge plume and the temporal and spatial variability of the local environment.

Significant effort has been devoted to gathering observations of both the temporal and spatial variability of receiving waters and the lateral and vertical distributions of wastewater plumes adjacent to ocean outfalls (e.g. Washburn et al., 1992, Petrenko et al., 1997, 1998, Ramos et al., 2005, Rogowski et al., 2012). Such observations are used to calculate the dilution of the discharged waters, their trajectory, and their evolution. Plumes are tracked through their distinct temperature and salinity characteristics compared to the surrounding oceanic waters of the same density, and elevated concentrations of materials detectable by optical instrumentation (e.g. turbidity Washburn et al., 1992 and chromophoric dissolved organic matter (CDOM) Rogowski et al., 2012). However, while effluent plumes are generally detectable, they tend to be patchy in space (and in time, when viewed from fixed location). This complicates the prediction of the ultimate fate of plume constituents, the assessment of diffuser design on plume behavior, and the validation of scalings relied upon in effluent plume models.

In this manuscript, we investigate the vertical and temporal variability of an effluent plume discharged into stratified waters from a shallow multi-port diffusers during a planned wastewater diversion event (the 2012 Orange County Sanitation District diversion). Vertically well-resolved observations gathered from a set of profiling moorings elucidated the behavior of the plume subsequent to discharge, allowed for an estimate of dilution associated with the discharge process, and provided a view of plume dispersal when local environmental dynamics are prominently, or exclusively, involved (i.e. the ‘far-field’ evolution of the plume). *In situ* measurements like these can improve our ability to predict the impact of discharged waters on the coastal zone, and thus improve coastal water quality.

1.1. Stratified coastal waters

The waters of Southern California are stratified throughout much of the year. Stratified shallow waters are often subject to energetic physical variability within the internal wave band (i.e. from the buoyancy frequency at the pycnocline to the local inertial frequency). These dynamics, which include tidal and near-inertial oscillations, drive cross- and alongshore currents and large vertical excursions of the pycnocline. They also influence the distribution and fluxes of heat, salt, nutrients, and phytoplankton in Southern California coastal regions (e.g. McPhee-Shaw et al. , 2007, Lucas et al., 2011a, 2011b, Omand et al., 2011, among many others). Along with wind-forcing, internal waves provide much of the energy for mixing in stratified coastal regions. Therefore, these dynamics are likely to influence the fate of effluent plumes by impacting both advection and diffusion in the evolving plume. For example, the internal tide has been implicated in controlling the vertical position and lateral transport of effluent plumes in Malama Bay, Oahu, Hawaii (Petrenko et al., 2000) and offshore of Huntington Beach, CA. (Boehm et al., 2002).

1.2. The 2012 Orange County Sanitation District diversion

In September 2012, the Orange County Sanitation District (OCSD) conducted a planned wastewater diversion in order to make repairs to their primary outfall (3 m (120″) diameter discharge pipe, 7 km offshore in 56 m water depth, Fig. 1). The diversion, lasting from 11-Sept. to 3-Oct. 2012, resulted in an average discharge of 137 million gallons d^{-1} (6 m^3 s^{-1}) of secondary-treated effluent through the secondary outfall (2 m (78″) diameter discharge pipe, 1.6 km offshore in 16.7 m depth). The discharge rate was variable over the course of each day, with an average maximum in the afternoon of 175 million gallons d^{-1} and an average minimum in the early morning of 72 million gallons d^{-1} (Fig. 2). Day-to-day variation in discharge rate was minimal during the course of the diversion.

The main diffuser on the secondary outfall is 300 m long, with one hundred and twenty 16-cm diameter circular ports along its length. The terminus of the diffuser is equipped with a weighted flap-gate, which was pinned closed during the diversion. The main diffuser section is a retrofit; the original design was modified in the 1960s to address persistent impact of the plume on shoreline (G. Robertson, Orange County Sanitation District. *pers. comm.*). This diffuser (hereafter ‘retrofitted diffuser’) was connected to the original outfall via a large wye. In the initial retrofit, eight 30 cm by 60 cm ports grouped over a distance of ~6 m at the original termination of the outfall were sealed closed. Prior to the diversion, the secondary outfall was inspected and cleaned by a team of divers. The report associated with that inspection indicated that all ports were cleaned and opened, including the eight large ports in the original outfall. As we show below, the presence of open ports before the retrofitted diffuser significantly impacted the behavior of the discharge, leading to a vigorous, surfacing plume and a consistent surface ‘boil’ above the wye.

Preliminary near-field modeling of the secondary outfall plume characteristics with CORMIX, conducted in anticipation of the diversion, indicated an expected dilution of 28–37 in the near-field of the diffuser, given historical temperature stratification at the site during those months and assuming no current (the most conservative case). Including a realistic range of ambient currents in the model slightly increased the expected dilution, and led to the expectation of the plume being trapped below the thermocline (Associates, 2010).

The secondary treated effluent being discharged during the diversion was expected to provide significant nutrient-loading to the coastal waters. For example, ammonium concentration in the effluent was ~27 mg L^{-1}, driving a consistent supply of ~8 μM ammonia to the surface waters at realistic dilutions (see Kudela et al. *this issue* for details regarding the chemical composition of the effluent).

Given the depth-dependence of many physical oceanographic dynamics at play in the coastal ocean, the vertical distribution of an effluent plume directly influences its downstream evolution, and therefore is of interest to policy-makers concerned with the impact of the effluent on the coastal ocean. For example, a surface plume generally exhibits a greater risk of impacting the coastline than a plume at or below the pycnocline due to on-average elevated velocities in near surface waters. Aside from impacting coastal water quality, nutrient loading associated with wastewater input has the capacity to alter the form and function of the local ecosystem, particularly in a surface plume. A prior diversion in the region (at the Hyperion Wastewater Treatment plant, in Santa Monica Bay, approximately 50 km to the north), apparently drove a significant phytoplankton bloom due to nutrient-loading in the surface waters