Locating Sources of Surf Zone Pollution: A Mass Budget Analysis of Fecal Indicator Bacteria at Huntington Beach, California

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The surf zone is the unique environment where ocean meets land and a place of critical ecological, economic, and recreational importance. In the United States, this natural resource is increasingly off-limits to the public due to elevated concentrations of fecal indicator bacteria and other contaminants, the sources of which are often unknown. In this paper, we describe an approach for calculating mass budgets of pollutants in the surf zone from shoreline monitoring data. The analysis reveals that fecal indicator bacteria pollution in the surf zone at several contiguous beaches in Orange County, California, originates from well-defined locations along the shore, including the tidal outlets of the Santa Ana River and Talbert Marsh. Fecal pollution flows into the ocean from the Santa Ana River and Talbert Marsh outlets during ebb tides and from there is transported parallel to the shoreline by wave-driven surf zone currents and/or offshore tidal currents, frequently contaminating >5 km of the surf zone. The methodology developed here for locating and quantifying sources of surf zone pollution should be applicable to a wide array of contaminants and coastal settings.

Introduction

The coastal ocean is both a critical natural resource and a final repository for all manner of human waste. The latter inexorably diminishes the former, as evidenced by a wide spectrum of coastal ills, including frequent postings and closures of popular swimming beaches (*1*−*3*). Coastal pollution often comes to light during the course of routine surf zone monitoring programs, in which samples are periodically collected from a series of monitoring stations and analyzed for one or more pollutants. In this paper, we demonstrate that the loading of pollutants into the surf zone (rate of input in pollutant mass per time) can be computed from a mass budget analysis of surf zone monitoring data, thereby providing critical information about the location, magnitude, and timing of specific inputs of pollution to the coastal ocean. The mass budget analysis described here is complementary to chemical and microbiological pollutant source tracking methodologies (*4*), for which the goal is typically to characterize the relative contributions of specific types of fecal pollution; for example, from human, bird, cow, etc. The approach is also complementary to other modeling approaches; for example, forward modeling of pollutant fate and transport in the ocean (*5*−*7*) and surf zone (*8*−*10*). The latter approaches rely on a *microscopic* mass balance modeling of pollutant fate and transport in which one or more differential equations are derived and solved (either exactly or numerically) subject to suitable initial and boundary conditions. In contrast, the approach described in this paper relies on a *macroscopic* mass balance, in which application of the Reynolds Transport Theorem leads to algebraic equations that can be employed to calculate the loading of pollutants in to and out of the surf zone.

The paper is organized as follows. Nearshore currents affecting the transport and mixing of pollutants in the surf zone are reviewed, followed by observations of fecal indicator bacteria pollutant transport in the surf zone at Huntington State Beach. These observations motivate the development of the mass budget analysis and its application to measurements of fecal indicator bacteria in the surf zone at Huntington State Beach. To make the results and analysis accessible to a broad audience, each section begins with a question around which the section is focused together with an answer supported by the data and modeling.

Nearshore Currents

Question: *What are the dominant nearshore currents that affect the fate and transport of pollutants introduced into the surf zone?*

Answer: *Pollutants entrained in the surf zone are carried parallel to shore by wind and wave-driven currents and cross-shore by rip currents, vertically stratified shear flows, and offshore forced currents (e.g., internal waves). Just offshore of the surf zone, pollutants are transported by coastal currents that respond to tides, winds, and remote forcing. The combination of longshore and cross-shore advective transport enhances the longshore spreading of nearshore pollution by dispersion. The region of the surf zone impacted by coastal pollution can be influenced by the tidal phasing of pollutant input to the surf zone (e.g., from tidal outlets along the shoreline), the tidal phasing of coastal currents, and the prevailing wave climate.*

The fate and transport of pollutants in the surf zone is controlled by a set of highly dynamic currents that determine longshore transport and exchange with offshore. These can be broadly classified as *surf zone currents*, which are primarily wave-driven, and *coastal currents* offshore of the wave-driven surf zone, which are primarily driven by tides, winds, and remote forcing (Figure 1). Wave-driven surf zone currents flow parallel to the shoreline (so-called "longshore drift") in a direction controlled by the angle at which waves approach the shore. In the simple case of a straight sandy beach bordering a uniformly sloping submarine shelf, the surf zone current takes on the direction of the approaching deep-water waves (*11*, *12*). At beaches bordering more complex bathymetry (e.g., with submarine headlands and canyons), refraction of the deep-water waves can generate surf zone

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10.1021/es034831r CCC: $27.50
Published on Web 03/24/2004