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Residual effects of treated effluent diversion on a seaweed farm in a tidal strait using a multi-nested high-resolution 3-D circulation-dispersal model

Yusuke Uchiyama[a,b,*], Xu Zhang[a], Yota Suzue[a,1], Taichi Kosako[b], Yasumasa Miyazawa[c], Akihiko Nakayama[d]

[a] Department of Civil Engineering, Kobe University, Kobe, Japan
[b] Coastal and Estuarine Environmental Department, Port and Airport Research Institute, Yokosuka, Japan
[c] Application Laboratory, Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan
[d] Department of Environmental Engineering, Universiti Tunku Abdul Rahman, Kampar, Perak, Malaysia

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ABSTRACT

A high-resolution 3-D model was developed to assess the impact of a diversion outfall at the Tarumi Sewage Treatment Plant (TSTP) on an adjacent seaweed farm in Osaka Bay, Japan. The model was extensively validated to ensure a reasonable agreement with in situ observations. The western part of the farm is largely influenced by tidal currents, whereas the eastern area is mainly affected by subtidal residual currents that are primarily due to surface wind stress. The released effluent is transported by counterclockwise residual circulation formed off the TSTP. The model reveals that the diversion adequately suppresses the influence on the farm. While the instantaneous effluent concentration is diminished by about 50%, the effluent accumulated on the farm decreased from $2.83 \times 10^4\,m^3$ to $2.01 \times 10^4\,m^3$ due to the diversion, demonstrating an approximately 28% reduction of the effluent from the TSTP by the diversion outfall.

1. Introduction

The Seto Inland Sea (SIS) is the largest semi-enclosed estuary in Japan, encompassing a total water area of 23,203 km^2 (Fig. 1a). It has unique geographical characteristics and consists of seven main sub-basins interconnected by narrow straits and > 3000 islands, which form a complex "basin–strait" system. The SIS is a partially stratified tidal estuary that is concurrently affected by: 1) energetic tidal currents up to 3 $m s^{-1}$ near straits (Fujiwara et al., 1994) under dominant semidiurnal, mesotidal conditions with a maximum tidal range of ± 1.2 m; 2) seasonally varying freshwater discharge from 28 major rivers; and 3) quasi-persistent eastward residual circulation (the SIS through-flow) primarily driven by the eastward drifting Kuroshio offshore of the two openings that connect the SIS with the Pacific (e.g., Kosako et al., 2016). The Kuroshio is known to have a considerable impact on the SIS circulation due to sporadic intrusions (Takeoka et al., 1993; Tada et al., 2017) and meandering of the Kuroshio path (e.g., Kawabe, 1987, 1995). In such a strait–basin system, the water is well mixed near straits due to strong tidal currents, while it is rather stratified in basins under more quiescent conditions (e.g., Guo et al., 2004; Chang et al., 2009).

Approximately 24% of Japan's population resides within its watershed basins (Tsuge and Washida, 2003), which leads to heavy nutrient loading of the SIS (Miller et al., 2010) and thus an increased occurrence of harmful algal bloom (HABs; e.g., Imai et al., 2006). Historically, the SIS has been extensively used by fisheries and in aquaculture, although it is viewed as a general dumpsite for wastewater from sewage treatment plants. This has caused the critical deterioration of the water quality and coastal marine ecosystems for many years (Tsujimoto et al., 2006). The number of "red tide" events due to HAB, an indicator of eutrophication, has raised remarkably with the increased nutrient loading (Takeoka, 2002; Imai et al., 2006). Red tides have occurred much more frequently and in a larger area in the SIS since the 1960s due to Japan's economic development and the associated pollutant emission, with the maximum of 299 incidents in 1976 (Imai et al., 2006). The aquaculture and marine ecosystem have been seriously affected by deterioration. Terawaki et al. (2003) reported that ~6400 ha of seaweed and seagrass beds along the Japanese coast have been destroyed from 1978 to 1991. A series of environmental preservation policies that regulate the total amount of nitrogen and phosphorus in effluent has been enacted, which had adequately improved the water quality in recent years (Tomita et al., 2016). However, deterioration is not entirely avoidable; ~100 red tides have occurred

* Corresponding author at: Department of Civil Engineering, Kobe University, Kobe, Japan.
E-mail address: uchiyama@harbor.kobe-u.ac.jp (Y. Uchiyama).
[1] Present affiliation: CTI Engineering Co., Ltd., Nagoya, Japan.

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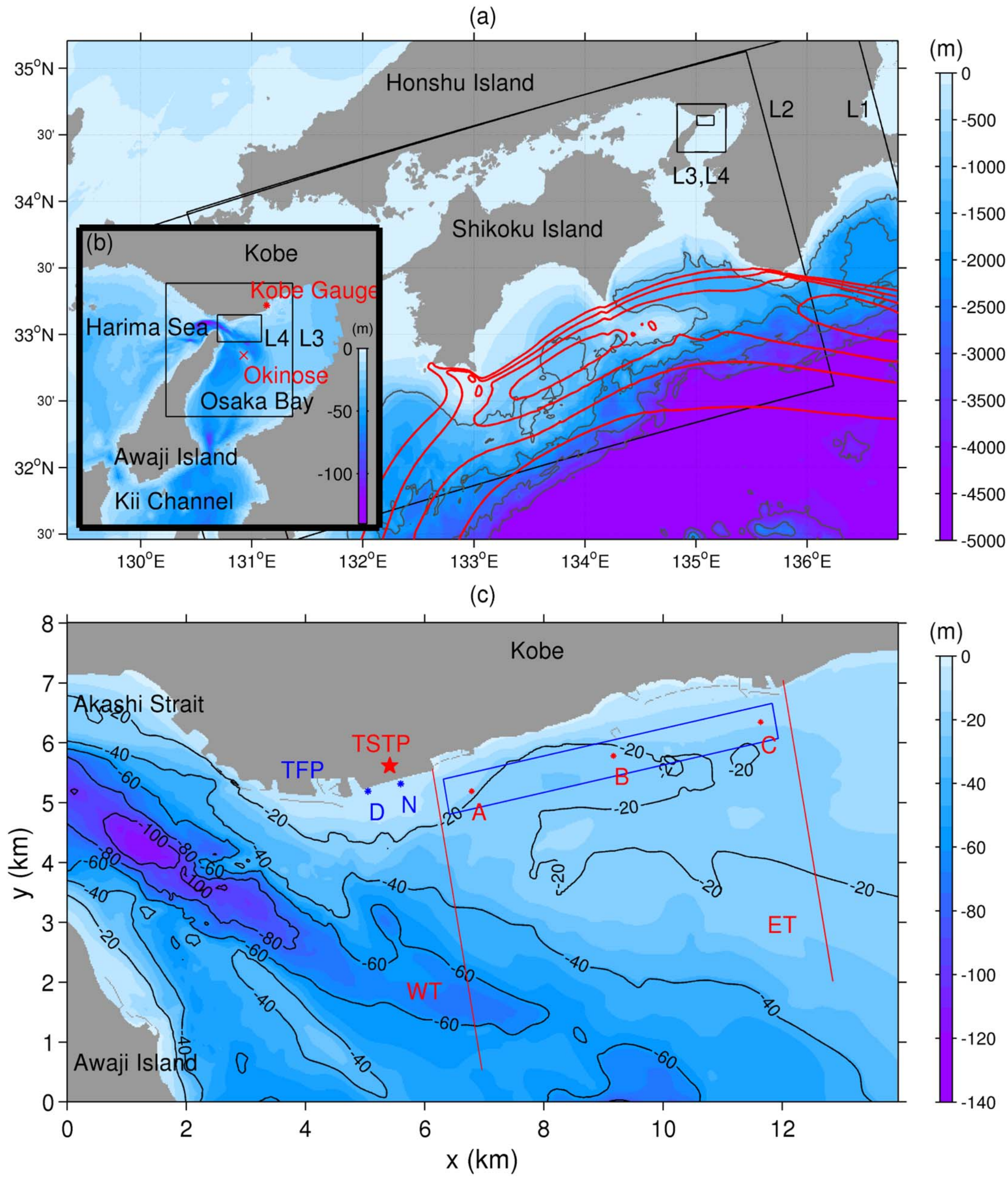

Fig. 1. Quadruple-nested ROMS model domains and bathymetry (color: m). (a) The ROMS-L1, L2, L3, and L4 domains (black boxes) embedded in the JCOPE2 domain (outside of the perimeter of the L1). The gray contours are the isobaths at intervals of 1000 m, while the red contours indicate the approximate Kuroshio region with surface velocity magnitudes ≥ 0.5 m/s at intervals of 0.25 m/s. (b) The enlarged area around Osaka Bay encompassing the L3 and L4 domains. The red dot and cross indicate the locations of the Kobe tidal gauge and shallowest part of the "Okinose" shoal at a depth of 23 m. (c) The entire L4 domain with isobaths at intervals of 20 m. The blue box is the approximate extent of the seaweed farm area; TFP is the Tarumi Fishery Port area; the red star shows the location of the Tarumi Sewage Treatment Plant (TSTP); the blue dots are the two outfalls (D: diversion, N: normal); the red dots (Stations A-C) are used for the time series plots in Figs. 5, 6, 7 and 11; and the red lines are two transects used for the cross-sectional plots of Figs. 9 and 10. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

per year in the SIS since the 2000s. Osaka Bay, located in the eastern part (Fig. 1b) with the most densely populated hinterland around the SIS, still suffers from severe water pollution.

The Tarumi Sewage Treatment Plant (TSTP), one of the largest wastewater treatment plants in Osaka Bay, is situated in the 3.6 km narrow Akashi Strait with a maximum depth of 140 m (Fig. 1c) and prevailing energetic and complex tidal flow. A sandbank known as the "Okinose" shoal (Fig. 1b) with the shallowest depth of 23 m is formed southeast of the strait, influenced by intense tidal currents and residual clockwise circulation (Fujiwara and Nakata, 1991; Fujiwara et al., 1994). The area around the Akashi Strait is famous for seaweed farming in the nation. Edible seaweed ("nori" in Japanese) is very common in Asia, which is made from a type of red algae, *Porphyra*, including widely cultivated *Porphyra yezoensis* and *Porphyra tenera* (Niwa and Aguga, 2006). Local fishermen keep complaining about the possible impact from sewage effluent on seaweed farming to the east of the TSTP (blue box in Fig. 1c). In seaweed farming, spores are rather vulnerable to the surrounding environment, in particular to nutrients and salinity. They grow rapidly from December to March and are harvested in April. Therefore, to avoid overdose that stunts seaweeds, a reduction of nutrients in the effluent is inevitable in fall. The City of Kobe, the local government, has constructed a new western diversion outfall ("D" in Fig. 1c) 500 m away from the central normal outfall ("N" in Fig. 1c) in the TSTP to reduce the possible impact of the effluent on farming by seasonal diversion from October to December. However, the effects of the western diversion have not been fully investigated, particularly in