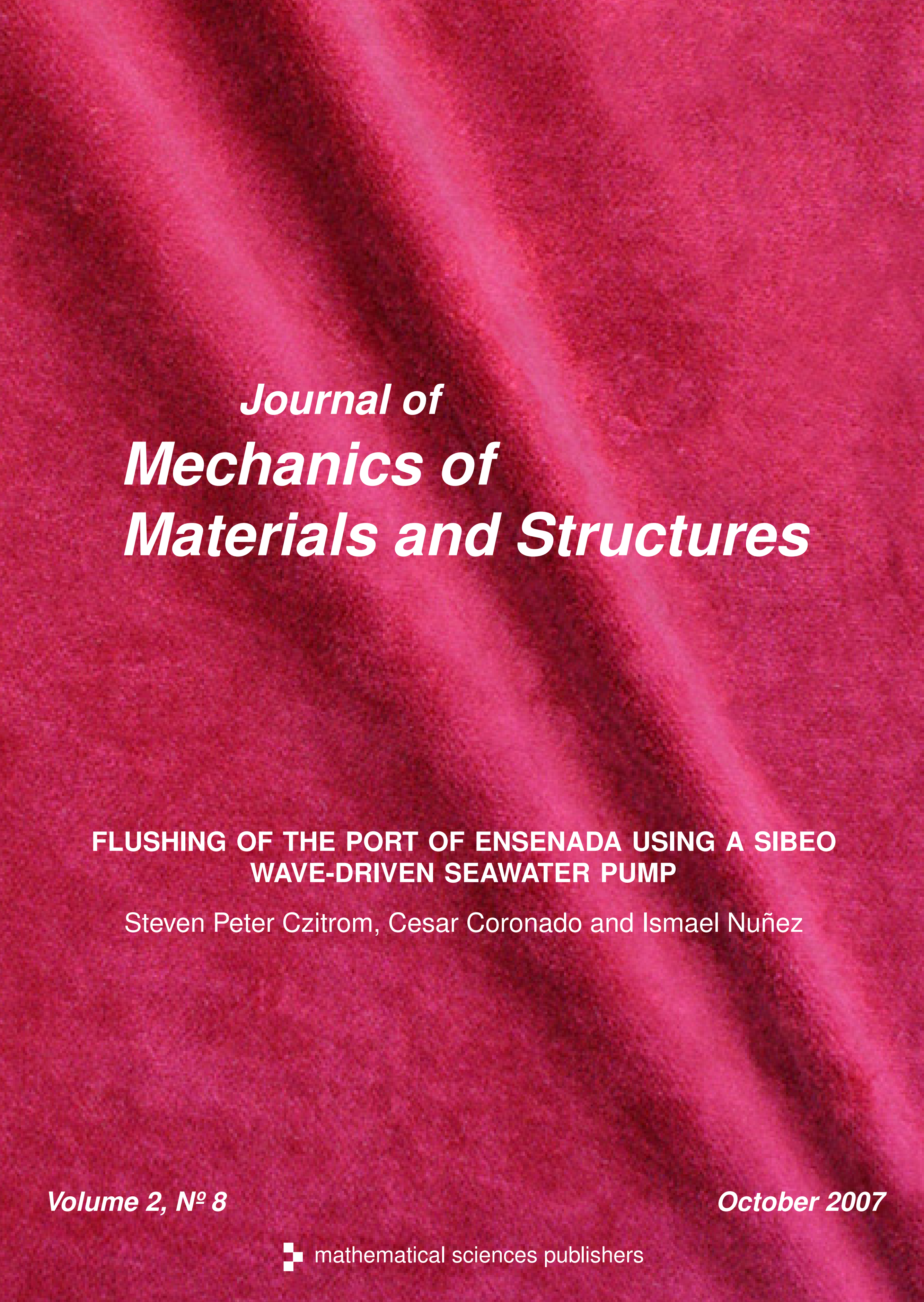

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FLUSHING OF THE PORT OF ENSENADA USING A SIBEO WAVE-DRIVEN SEAWATER PUMP

STEVEN PETER CZITROM, CESAR CORONADO AND ISMAEL NUÑEZ

A SIBEO wave-driven seawater pump is proposed to inject clean and oxygen-rich seawater from outside the port of Ensenada, Baja California, to promote flushing in the more stagnant sections of the harbor. Results from a simple two-dimensional numerical model of the port hydrodynamics shed light on how the tides cannot on their own adequately flush the system. A three-dimensional model, which includes thermal stratification, illustrates how the pumped seawater ventilation can spread throughout the harbor via a density channel set up by the seasonal thermocline.

1. Introduction

Many human coastal settlements use the adjacent ocean to dispose of domestic and industrial refuse. Substantial growth of these settlements has resulted in an increased concentration of pollutants in the ocean, sometimes reaching levels that are dangerous for human habitation and the ecosystem health. This problem is further exacerbated in semienclosed coastal water bodies such as ports with breakwaters [Fischer et al. 1979].

The port of Ensenada, to the north of the Baja California Peninsula, Mexico, has witnessed brisk activity since it was established in the 19th century, and is today an important hub of development. The fishing, manufacture and tourist industries, among others, have grown substantially in support of social and economic development, increasing living standards of the local and state populations. In the last few decades growth has witnessed an explosion in size and diversity. This activity, however, has not been without cost to the port's ecosystem where domestic and industrial refuse have been dumped. Since the construction of breakwaters to protect shipping, a large section of the port has become increasingly isolated and stagnant, making it more vulnerable to the accumulation of pollutants.

There are essentially two ways to diminish the concentration of pollutants in a body of water. The first is to restrict the flow of contaminant by diminishing its input and/or providing treatment. The second is to increase the flow of unpolluted water through the system to encourage the expulsion of the accumulated contaminants. A combination of both measures is probably the most adequate allowing ventilation to be achieved in less time. Note that the added flushing should not be taken as a free ticket to increase the discharge of pollutants. This combination of solutions must take into account that it is not healthy in the long run to take the adjacent ocean as a universal and inexhaustible digester, into which one can pour endless quantities of contaminants [Fischer et al. 1979]. This, unfortunately, has been common practice throughout time in most parts of the world.

In the case of the port of Ensenada, in the last decade or so sewage treatment plants and a more strict enforcement of antipollution legislation have substantially diminished the input of contaminants

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Keywords: wave energy, flushing of stagnant coastal water bodies.

to the harbor. High levels of pollution remain, however, despite the flushing action of the tides [Orozco and Gutiérrez 1983; Delgadillo and Orozco 1987; 1989; Segovia and Rivera 1988; Portillo and Lizárraga 1997; Macías et al. 1997]. An additional flow of clean and oxygen-rich water from the adjacent ocean into the stagnant and contaminated sections of the port is quite likely to promote a more effective ventilation. This flow would dilute the polluted waters and, as they are displaced towards sectors with a greater circulation, spread ventilation to a growing area.

In this paper the application of a wave energy driven seawater pump is discussed as a means of delivering clean and oxygen-rich seawater into a stagnant polluted marine area to promote its ventilation. Hydrodynamic numerical models of the water circulation in the harbor of Ensenada are used to shed light on why significant pollution remains in the water and sediments of the northern section of the port, despite the flushing action of the tides, and by which mechanisms the flow of clean and oxygen-rich water from a wave-driven seawater pump can help ventilate the Ensenada harbor.

2. The SIBEO wave-driven seawater pump

Starting in the late 1980's, research has been conducted at the Instituto de Ciencias del Mar y Limnología of the National University of Mexico (UNAM) to develop technology which uses wave energy for pumping seawater. Czitrom [1997] proposed a wave-driven seawater pump (SIBEO[1]) in which a mechanical oscillator, composed of an air spring flanked by two water masses in ducts, is excited by the waves.

A schematic diagram of the SIBEO can be seen in Figure 1. The pump is primed by a partial vacuum that brings water up from the ocean and the receiving body of water to a working level in the compression chamber. The variable pressure signal induced by the waves at the resonant duct-mouth drives an oscillating flow which spills water in the compression chamber with each passing wave. The spilt water gathers in the chamber and descends by gravity to the receiving body of water via the exhaust duct; see also [Carey and Meratla 1976].

The system operates optimally at resonance when the frequency of the driving waves coincides with the SIBEO natural frequency of oscillation. A condition of resonance can be maintained, in an evolving

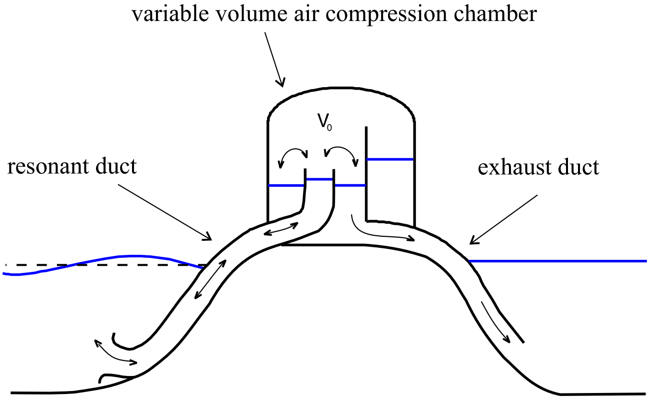

Figure 1. Schematic diagram of the SIBEO wave-driven seawater pump.

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[1] SIBEO is an acronym for the Spanish Sistema de Bombeo por Energía de Oleaje.

wave field, by means of a variable volume compression chamber which adjusts the hardness of the mechanical oscillator air spring. The SIBEO natural frequency of oscillation can thus be matched to that of the most energetic driving waves at all times.

In practice, the wave field is composed of various frequencies with particular energies associated to each. Tuning to the highest energy frequency can be carried out automatically under control of a programmed microchip that samples the wave field and adjusts the volume of air required for resonance at the appropriate frequency. This tuning device, which can be used in other oscillating water column wave-energy conversion devices (see, for example, [Falnes and McIver 1985]), was patented through the National University of Mexico [Czitrom 2002].

Extensive theoretical and experimental studies back the SIBEO development. The pump equations were derived by applying the Bernoulli equation to streamlines in the resonant and exhaust ducts and adding terms for the losses due to viscosity, vortex formation and radiation damping [Czitrom 1997; Czitrom et al. 2000a]. A numerical model of the SIBEO, which solves the pump equations, reproduces 1:25 scale wave tank test data remarkably well [Czitrom et al. 2000b]. A SIBEO prototype was temporarily installed and field tested on the coast of Oaxaca, Mexico, with the help of a fisherman's cooperative [Czitrom 1996; 1997].

3. The port of Ensenada, Baja California

A general disposition of the port of Ensenada can be seen in Figure 2. At first glance it is apparent that the corner at the base of the main breakwater is one of the sections of the port most isolated from the adjacent ocean. The natural location for the SIBEO is near the breakwater base, where it is highly exposed to the incoming Pacific Ocean waves, and can have a greater impact over one of the more stagnant sections of the harbor.

Figure 2. Aerial view of the port of Ensenada, Baja California. North is at approximately one o'clock on this figure.

The pump numerical model was used to estimate the flow which would be generated throughout the year by the SIBEO with a 1.4 m diameter resonant duct (Figure 3). Maximum and minimum flows for each month were computed with the extreme values of wave amplitude and period observed in that lapse of time. An average yearly flow of some 200 liters/second can be expected from the SIBEO, varying between 50 and 300 l/s, mainly due to changes in the wave size.

A very crude indication of the effect a 200 l/s flow might have on the harbor is the time it takes to inject an equivalent volume of water. The port of Ensenada is approximately 1.9 km long, 0.8 km wide and 10 m deep with equivalent volume $\sim 1.5 \times 10^7$ m^3, so that it would take 2.4 years to inject an equivalent volume of water using a single SIBEO. This figure suggests that, in the first few months, the ventilating effect would only be noticeable close to the location of the exhaust point. As an example, a volume of water equivalent to that contained in a quadrant of 500 m radius, at the base of the breakwater, would be injected by the SIBEO in somewhat less than 4 months.

By contrast with the SIBEO, the tides input a much greater volume of water through the navigation channel. The M_2 constituent at Ensenada is the most significant with a range of about 1 m so that, given the area of the port, an average flow of 70 m^3/s enters during the 6 hours of the flood tide. This input is 350 times greater than that of the SIBEO making it clear that questions must be answered concerning the SIBEO effectiveness against that of the tides in their capacity to flush the port. In the first instance it is necessary to understand why tidal flushing has such a reduced ventilating effect on the contaminated waters and sediments of the northern section of the port. In the second we must clarify how a much smaller but focused flow from the SIBEO pump might more effectively achieve the desired ventilation.

4. Port hydrodynamics

In order to answers these questions, two numerical models of the tidal and wind-driven hydrodynamics of the port of Ensenada were implemented. A two dimensional single layer version of the Hamburg Shelf Ocean Model (HAMSOM), a semiimplicit model known for its simplicity and proven performance

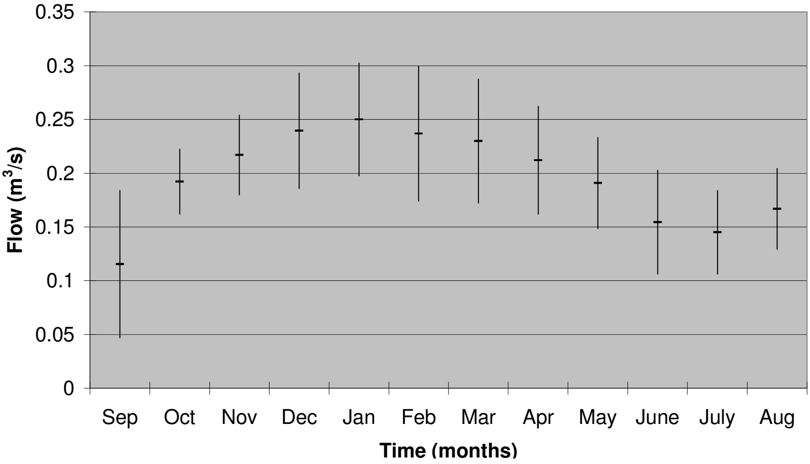

Figure 3. Estimated SIBEO flow, using wave data measured at the breakwater from 1986 to 1987 [Martínez Díaz de León et al. 1989].

[Backhaus 1983; 1985; Huang 1995] was chosen to provide relatively straightforward first estimates. The HAMSOM model can be easily set up to include external flows such as that of the SIBEO and has been applied with success to places such as the North Sea [Backhaus 1985], the delta of the Colorado River [Carbajal et al. 1997], and a coastal lagoon with river discharge on the west coast of Mexico [Núñez Riboni 2000], among others. A full account of the implementation of this model to the port of Ensenada can be found in [Czitrom et al. 2003].

Three-dimensional modeling has become a practical way of simulating circulation and the thermohaline field in coastal lagoons [Ramírez and Imberger 2002; Balas and Özhan 2002], and estuaries [Cheng et al. 1993; Cheng and Casulli 2002]. The three dimensional Estuary and Lake Computer Model (ELCOM), which uses a semiimplicit finite difference solution scheme and includes thermodynamic effects, was developed by Hodges et al. [2000]. ELCOM can reproduce the first-order three-dimensional baroclinic physical response of an estuary to environmental and tidal forcing on a coarse grid with efficient CPU usage. The model has been recently applied to predict internal wave propagation in Lake Kinneret in Israel [Hodges et al. 2000]. Laval et al. [2003] improved the scalar and momentum mixing scheme used in ELCOM and successfully reproduced internal wave motions in Lake Kinneret. A full description of the application of the ELCOM model to the port of Ensenada, including calibration procedures and comparison to field measurements, can be found in [Coronado 2003; Coronado et al. 2007]. Results of this application are used here to examine the mechanisms by which the SIBEO flow can spread its ventilating effects throughout the harbor at times when the water column is stratified.

The Ensenada port bathymetry can be seen in Figure 4. The simulation domain for the two-dimensional HAMSOM model was cut off at the port entrance navigation channel while a section external to the port was included in the three-dimensional simulations to account for the influence of the stratified water column there. The harbor has a surface area of approximately 1.51 km^2 and opens into Todos Santos Bay. It is protected by a 1640 m long breakwater and a 570 m long El Gallo jetty. Semidiurnal tides, with

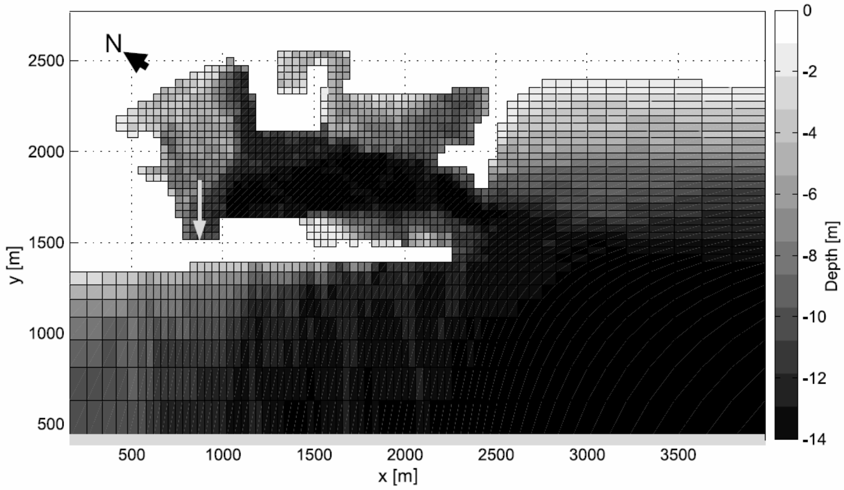

Figure 4. Bathymetry of the port of Ensenada [Coronado 2003]. A grey arrow points to the proposed location for the SIBEO exhaust.

a maximum range of 2 m, propagate from Todos Santos Bay via a 350 m wide channel entrance. The bathymetry of the harbor is characterized by a 13 m deep navigation channel, which runs parallel to the breakwater.

5. Two-dimensional model results

In order to visualize the dispersion of inert particles in the harbor, and thus shed light on the flushing characteristics of the port, the modeled two-dimensional circulation was used to simulate the trajectory of labeled water parcels released within the harbor during a period of 6 months. Clusters of 1000 color labeled water parcels were released at various points within the port and traced from one time step to the next using the velocity fields derived from the hydrodynamic model.

The erratic movement of water particles which occurs in turbulent flow causes them to disperse in spreading trajectories. Turbulent dispersion was simulated by introducing random variations in the particle velocity at each computational step. The lagrangian trajectories, which include advection as well as turbulent diffusion, can help identify the regions where particles are trapped in eddies and can thus be used to find the best location and flow intensity for the SIBEO to adequately flush the port.

Figure 5 shows the distribution of labeled water parcels after 6, 16 and 26 weeks of dispersion simulation for the case of the M_2 tides without the SIBEO discharge in the port. With the exception of a couple of stagnation points, it is clear that most of the particles from the southern section of the harbor eventually reach the navigation channel through which they exit the system to the adjacent ocean. In the northern section the particles remain gyrating in a series of closed eddies from which they cannot escape. It appears that the tides have a flushing effect restricted to the southern section of the harbor while driving closed circulation patterns in the north which in effect trap the particles released there. This result seems to explain why the tides are not capable of renewing seawater in the more stagnant northern section of the Ensenada harbor, which thus remains contaminated despite the flushing action of the tides.

Figure 6 shows the distribution of particles after 6, 16 and 26 weeks of dispersion simulation by the M_2 tides, with a 0.6 m^3/s flow from 3 SIBEOs pumped into the north-west corner of the port, and an

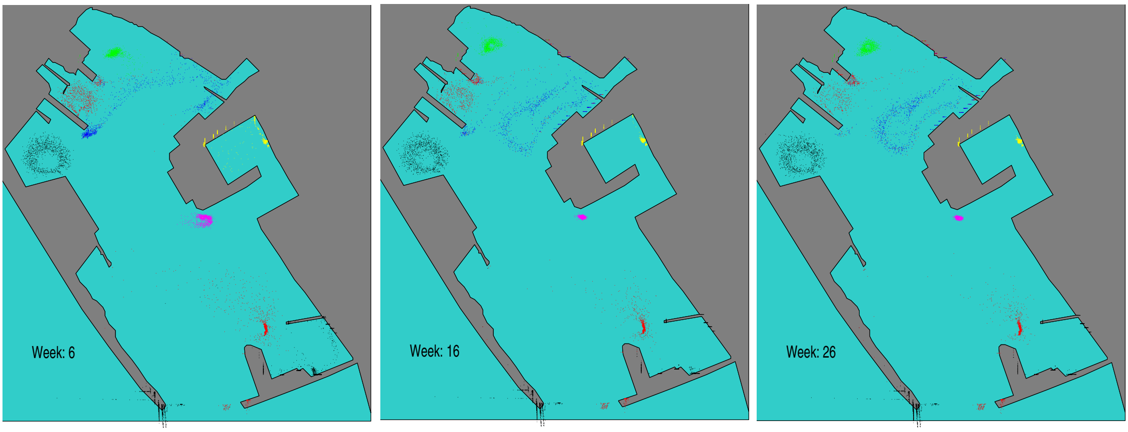

Figure 5. Dispersion of color labeled water parcels in the Ensenada Harbor by the M_2 tides after 6, 16 and 26 weeks of simulation.

additional 0.4 m^3/s flow from 2 SIBEOs to the north; the SIBEO discharge points are marked with dots. Similar to the previous case, the southern portion of the harbor is adequately flushed by the tides. In the northern section, the corners at which the SIBEO pumps discharge are swept clean of particles by the injected water. The sequence of images suggests that a combined flow of 1 m^3/s at the two corners is adequate to flush the northern section of the port, displacing the particles southward, where the influence of the tides can eventually expel them through the navigation channel. The 1 m^3/s flow seems sufficient to alter the closed residual circulation eddies generated by the M_2 tides in the north.

6. Three-dimensional model results

The two-dimensional model results provide reasonable answers to the questions posed in Section 3 when the water column is vertically mixed. During the spring and summer months, however, heating at the surface stratifies the water column, and a seasonal thermocline develops in the port and the continental shelf around. At this time, circulation and mixing processes are best described using a three-dimensional approach, for which the ELCOM model is most adequate.

In Figure 7 the SIBEO water concentration in vertical sections along and perpendicular to the main navigational channel are shown after 12 hours' and three weeks' simulations, respectively. The 1 m^3/s SIBEO flow was input at the surface near the breakwater base. It is apparent that the pumped water from the neighboring ocean first sinks to its density level within the port and then spreads along the thermocline. After 12 hours, the effect of the pumped water is noticeable only near the discharge point, reaching most of the port after a few weeks.

In Figure 8 the depth averaged modeled SIBEO water concentration throughout the harbor is shown at various time intervals up to 4 weeks. It is clear that in the first few hours the effect of the SIBEO water is noticeable near the discharge point at the base of the breakwater. After one week, however, the ventilating effect of the SIBEO water reaches most of the port, while in successive weeks, water external

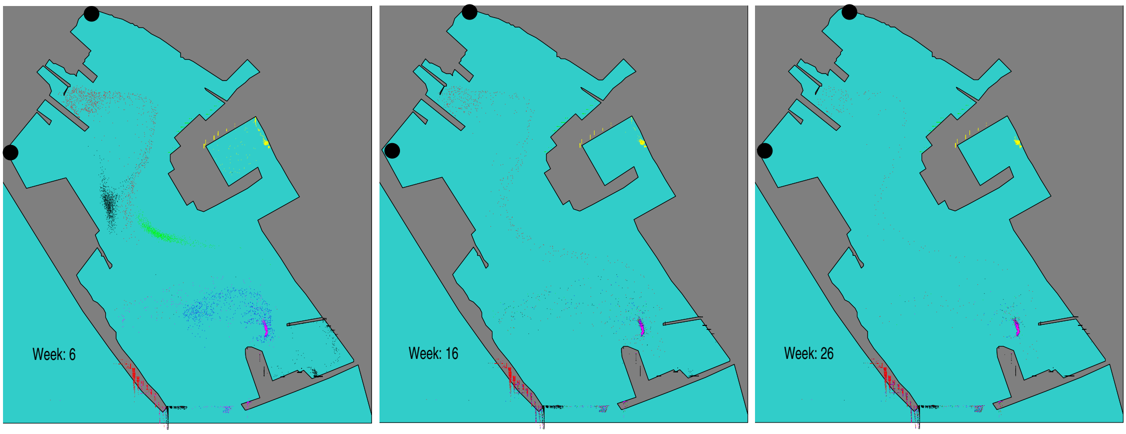

Figure 6. Distribution of color labeled water parcels after 6, 16 and 26 weeks of dispersion simulation by the M_2 tides. SIBEO flows of 0.6 m^3/s and 0.4 m^3/s were injected to the north west and due north corners of the harbor, respectively, at the positions marked with circles.

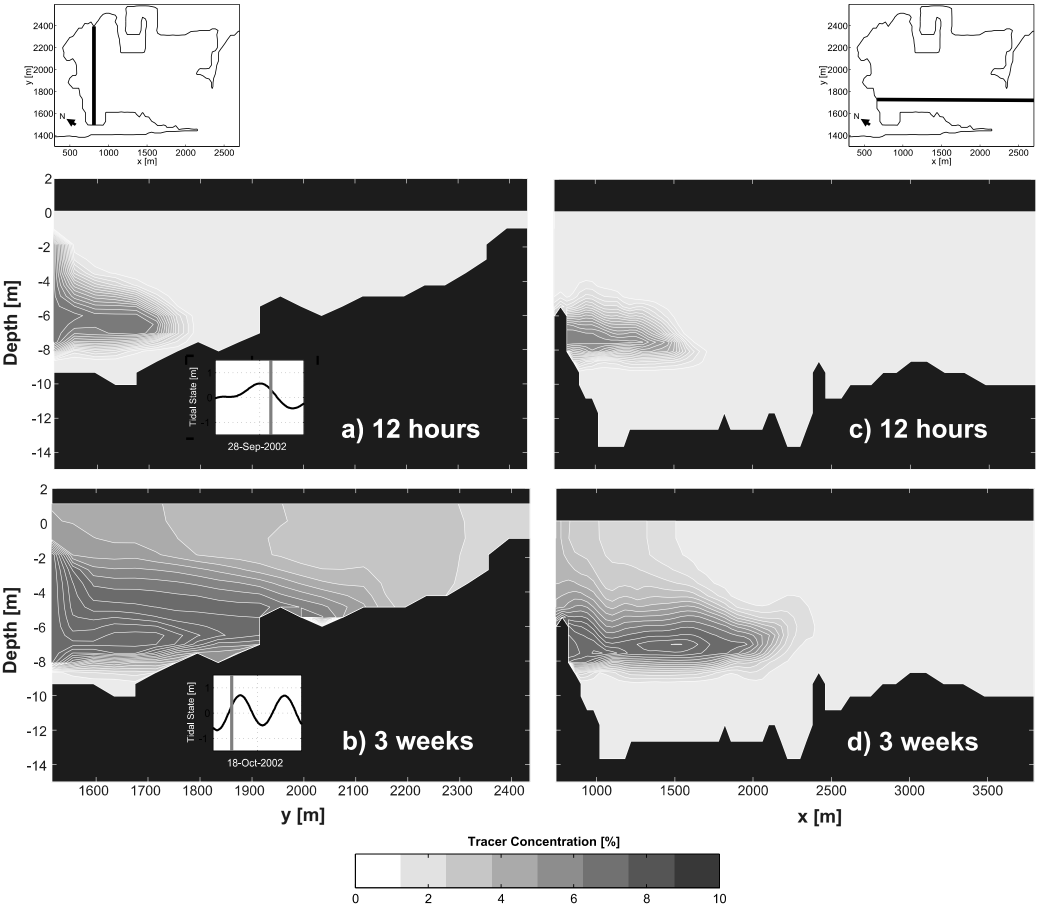

Figure 7. Snapshots of vertical distribution of the SIBEO water tracer along a transect at the head of the harbor (left panels) and along the main navigational channel (right panels). (a) and (c) show the tracer distribution after 12 hours of simulation, (b) and (d) after 3 weeks. Tide state is indicated in (a) and (b). Note that the horizontal scales in left panels differ from the right ones. Discharge location is at the left of each panel.

to the port spreads in patterns which are less noticeably linked to the SIBEO exhaust position. In the last panel, higher concentrations appear in the northern section of the port, which is in effect the most polluted and where the ventilating effect of clean and oxygen-rich water is most beneficial.

7. Conclusions

At times when the water column is vertically mixed, closed eddy circulation patterns driven by the tides in the northern section of the port of Ensenada inhibit flushing of the stagnant polluted waters there. A proposed 1 m^3/s flow of clean and oxygen-rich seawater from outside the port, forced into this section by SIBEO wave-driven seawater pumps, would alter these patterns enough to flush the contaminated waters southward, where the tides are able to expel them from the port.

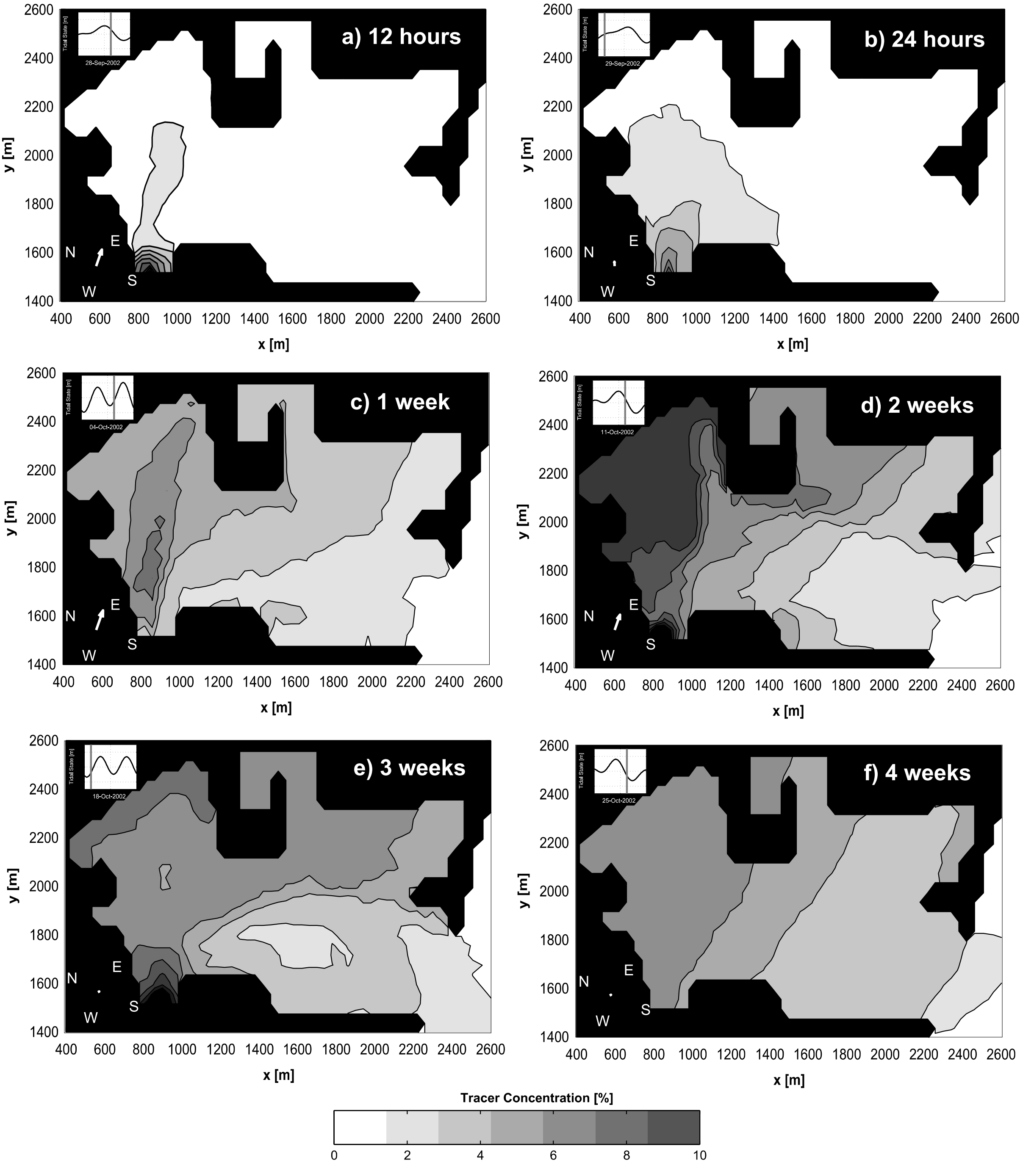

Figure 8. Snapshots of the depth-averaged distributions of the SIBEO water tracer after (a) 12 hours of simulation, (b) 24 hours, (c) 1 week, (d) 2 weeks, (e) 3 weeks and (f) 4 weeks. Tidal state and wind vector at snapshot instant are in each panel.

At times in summer when the water column is stratified due to heat input at the surface, the clean and oxygen-rich water from outside the port sinks to its density level, spreading the beneficial ventilating effect throughout the port via the density channel formed by the pycnocline.

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