Enhancement of mixing processes in semi-deep coastal channels by a bathymetry change

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ABSTRACT: Recent investments in construction of a number of submarine outfalls in Croatia pushed the local scientific community to focus attention to hydrodynamics of numerous stratified semi-deep (60–80 m) coastal channels in the Eastern Adriatic, which are planned to receive important quantities of partially treated wastewater in the near future. In some cases, however, simple channel geometry is complicated by bottom irregularities which are suspected to be the main cause of enhancement of mixing rates between different layers of stratified fluid. As a consequence, partial or complete destruction of typical density stratification can result in surfacing of intermediate layers, where trapping of wastewater mixture is expected in normal oceanographic conditions. In order to examine hydrodynamics in the zone affected by a bathymetry change, the 3-D numerical model has been set up and tested in the channel where sea bottom irregularity, extending perpendicularly to the shore, encompasses one half of the channel width. Beside phenomenological description of this type of stratified flow, obtained results are compared with known functional relationships governing turbulent interfacial mixing in layered flows.

1 INTRODUCTION

Characteristic elongated shape of almost all islands in the Eastern Adriatic results in a number of semi-deep and narrow coastal channels extending parallel to the shore (Fig. 1). Typical channel width is 5–10 km, with depths between 60–80 m. The base flow in those highly attractive aquatic environments, characterized by steep rocky shores and flat sandy or muddy bottom, is usually governed by gradient (density) currents and tidal oscillations, creating stable SE currents aligned with the channel longitudinal axis.

With very few exceptions, numerous oceanographic studies and reports have confirmed relatively passive hydrodynamics of bottom layers with respect to intermediate and surface ones, especially in the summer season. This kind of layered flow is apparently a consequence of dampening effects.
caused by density stratification that seems to suppress all surface forcing (winds, heating, fresh water inflows), keeping their impact limited to the zone above the pycno-cline layer (typically at −20 to −30 m level) that separates the two regions with substantially different oceanographic and hydrodynamic properties.

As a recipient of all partially treated wastewater discharged via numerous existing and planned submarine outfalls, coastal channels in the Eastern Adriatic could face serious water quality problems in the absence of water column stratification. The longer the stratification survives, the smaller is the probability for the released wastewater to reach the sea surface, implying less environmental risks, aesthetic nuisances and health hazards.

In some cases, however, important sea bottom irregularities (sills), extending almost perpendicularly to the channel longitudinal axis (Fig. 1), are suspected to cause a whole series of hydrodynamic phenomena that result in significant enhancement of mixing between different layers. In the absence of direct field measurements, set-up and application of 3-D hydrodynamic model (Rasmussen et al., 1990) represents an alternative way to assess the magnitude of impacts by a bathymetry change (Fig. 2) before construction of important structures takes place.

2 MODELING OF BOTTOM TOPOGRAPHY EFFECTS

Presence of sudden changes of bottom topography in coastal channels can complicate otherwise simple channel hydrodynamics to quite a large extent. Arriving at the obstacle, bottom denser water will try to pass around it, for if the fluid can circulate horizontally without climbing, it will do so. Basically, two competing forces in the vicinity of the obstacle are the inertial forces and gravity forces. Hence, Froude number can be taken as the representative parameter that characterizes mixing of stratified fluid in the region adjacent to the obstacle. Therefore, if the Froude number is sufficiently low, the fluid will simply flow horizontally in layers around the obstacle (Fig. 3e). Beyond the zone affected by bathymetry change, where no increased vertical mass transport is expected, the overall Richardson number can be used as a parameter that governs interfacial entrainment rate and mixing between layers with different densities (Christodolou 1986).

By increasing mean flow velocity in the channel, the denser fluid in front of the obstacle will tend to rise and try to climb over the obstacle. If it succeeds, it will fall behind it and produce intensive mixing in the lee zone of the sill (Figs 3a–3d).
Figure 3. Simulation of stratified flow in the channel for different velocity boundary conditions (5, 10, 20 and 40 cm/s, respectively); surface currents and density fields (Figs 3a–3d), currents and density isolines at −30 to −40 m level (Figs 3e–3h).

As homogeneous deeper layers try to climb over the sill, dynamic balance between gravity and inertial forces results in a number of macroscopic hydrodynamic phenomena confirmed by the numerical experiments and recorded in the literature (Farmer & Armi 1999, Baines 1984). Some of the most important that can be observed in Figures 3–4 are: occurrence of internal solitary waves.
Figure 4. Simulation results (density (kg/m$^3$) in Figs 4a–4c and turbulent energy production (m$^2$/s$^2$) isolines in Figs 4d–4f, respectively) in the longitudinal mid-section through the model extracted in stationary flow conditions with different prescribed boundary velocity conditions (10, 20 and 40 cm/s, respectively).

both upstream and down-stream to the obstacle, resulting in regular surface modulations above the sill (Fig. 4a); partial blocking of the flow at lower mean flow Reynolds numbers, bifurcation of currents resulting in general turn of the main stream toward the shore downstream to the sill (Fig. 3); set-down of density interface in frontal region of the sill (Fig. 4a); local instabilities at higher Reynolds numbers and increased interfacial mixing across sheared density interfaces upstream to the sill (Figs 4a–4c); plunging of denser water down the lee face of the sill and accompanying partial or complete destruction of stratification in the lee zone of the sill (Figs 4b–4c); piling-up (upwelling) of denser bottom water along the frontal slope of the sill, resulting in partial and much less intensive homogenization of initial density profile (Figs 4b–4c).

Although the model grid resolution has not permitted detailed analysis of turbulent structure of this type of stratified flow, some interesting conclusions about macroscopic properties of turbulence generation, dampening and collapse can be derived from simulation results. As demonstrated in Figure 4, the sill in the channel can be viewed as a source of turbulent energy, whose transport and dissipation rate depends strongly on preservation of stratification of water column, especially at profiles downstream to the bottom irregularity. Being detached and transferred by convection into downstream region of the channel, recorded turbulent energy “pockets” contribute additionally to the intensification of mixing rates, giving rise to flow instabilities that result in complete homogenization of initially stratified water column.

Figures 4 and 5 clearly show that the bulk of turbulent energy is generated in horizontal and vertical model contractions and along the lee face of the sill. It is interesting to note that at lower mean flow Reynolds number the turbulence energy generated in surface layer remains confined in surface layer as long as stratification persists, while further gradual homogenization of water column results in merger of turbulent energy pockets until the entire water column is not fully mixed.

Presented numerical calculation results have illustrated how direct simulations of large-eddy structures can be capable of resolving a number of basic phenomena that occur in coastal channels.
with a bathymetry change. Highlighted importance of preservation of stable stratification, that has obvious influence on the decay and eventual collapse of produced turbulence, can have important practical application when, for example, the optimum wastewater outfall site is to be selected. From that standpoint, performed simulations have clearly indicated that the zone upstream (in the direction of flow) to the sill seems to be much better choice than the zone behind the irregularity.

3 ENTRAINMENT COEFFICIENT CALCULATION

Depending on the interfacial mixing mechanism, four governing laws, all of a power form, were proposed by Christodoulou (1986). The validity of those entrainment laws (stated in terms of the mean flow characteristics) was numerically tested in the region of the model sufficiently away from the sill in upstream direction (computational point i, j, k = 70, 30, 3), where stable horizontal
layered flow was recorded in all experiments (i.e. out of reach of recorded turbulent energy “pockets” and increased vertical mass transport areas). Computed entrainment coefficient data, plotted vs. Richardson number based on the mean velocity data (Fig. 6) are apparently in good congruence with known functional relationships (Christodoulou 1986) governing turbulent interfacial mixing in layered flows.

4 CONCLUSIONS

Obtained numerical results, congruent with previous experimental and theoretical considerations, clearly show that substantially different mixing regimes can be expected in the frontal and lee zone of shallow sills in semi-deep stratified coastal channels. Due to much more intensive mixing in the lee zone behind the bottom irregularity and resulting total destruction of initial stratification (which would otherwise ensure that the wastewater plume would remain submerged), it seems reasonable to suggest to avoid those areas as locations for submarine release of wastewater via deep sea outfalls.

REFERENCES