Restricted Exchange and Saline Blockage over a Submerged Sill

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Abstract

Results are presented from a series of large-scale experiments investigating the internal dynamics of bi-directional exchange flows generated across a submerged, trapezoidal, sill obstruction, with net-barotropic flow components in the upper fresh or lower saline water layers. High-resolution velocity fields and density profiles were obtained using particle image velocimetry and micro-conductivity probes, respectively, in the vicinity of the obstruction to measure internal-flow dynamics under a range of parametric forcing conditions (i.e. variable saline and fresh water volume fluxes; density differences; sill obstruction submergence depths). These measurements provided qualitative and quantitative interpretation of mixing and entrainment processes generated by the bi-directional exchange flows, as well as defining the parametric conditions under which the lower saline intrusion layer became blocked across the sill. An analytical two-layer hydraulic exchange flow model was developed to include frictional and entrainment effects, both of which were needed to account for turbulent stresses and saline entrainment into the upper freshwater layer, resulting in mass exchange between the counter-flowing fresh and saline layers across the sill.

1. Introduction

The presence of natural topographic flow obstructions (e.g. submerged sills) can have significant implications for the intrusion of saline marine waters into semi-enclosed estuarine impoundments or fjordic basins. For example, the restriction of exchange flows in semi-enclosed estuaries can impact adversely on ecology due to the inhibition of tidal intrusion at the river mouth, while suppression of circulation and mixing processes can exacerbate stagnation and contaminant accumulation in estuarine impoundments, tidal lagoons and fjordic basins (e.g. Cuthbertson et al., 2006; 2016). In coastal regions, some estuaries can be completely blocked from saline marine water intrusion into the river basin, while others are strongly influenced by saline water circulations in the estuary mouth, with restricted intrusion into the estuary basin flowing in the opposite direction to the overlying freshwater outflow layer (e.g. Sargent and Jirka, 1988). Similar restricted, stratified exchange flows are also observed over submerged topography (e.g. sills) in fjords (e.g. Farmer and Armi, 1999), with the generation of interfacial waves, mixing (e.g. Kelvin-Helmholtz instabilities) and entrainment between the counter-flowing layers known to be influenced by net barotropic forcing in the restricted exchange flows (e.g. Negretti et al., 2007; Fouli and Zhu, 2011).

Within such restricted, bi-directional, stratified flow problems, the internal flow dynamics are therefore expected to be sensitive to (i) the dimensions of the submerged obstruction [i.e. sill length l_s, height h_s, submergence depth $(H-h_s)$], (ii) the density difference $\Delta\rho$ between the two water bodies separated by the sill obstruction, and (iii) external barotropic forcing conditions due to tidal Q_1 and freshwater Q_2 inflows (see Figure 1).

Internal hydraulic theory has provided a useful analytical modelling approach for the preliminary interpretation of the complicated internal flow dynamics of restricted, two-layer exchange flows across a submerged sill obstruction (e.g. Zhu and Lawrence, 2000; Cuthbertson *et al.*, 2004; 2006), although these approaches tend to ignore internal flow losses due to interfacial mixing and entrainment processes. In the present study, these two-layer exchange flow models for rectangular-shaped channels have been extended to include both frictional and entrainment effects, which are required to account for turbulent stresses and mass transfer from the lower saline layer (i.e. due to entrainment). As such, the experimental results reported herein are used to validate two key parameters within this internal flow model, namely: (i) the flow rate ratio q^* of upper fresh and lower saline layers; and (ii) the mass exchange m from the lower saline layer into the upper fresh water layer. A key aim of this study is to define the parametric influences (i.e. flow, density difference and obstruction submergence depth) on shear-driven mixing and entrainment dynamics across the sill, as well as the physical mechanisms associated with the blockage of saline intrusions.

2. Physical System and Experimental Set-up

The experimental program was conducted at the Coriolis Platform II at Laboratoire des Écoulements Géophysiques et Industriels (LEGI) in Grenoble. For the experimental study, a 9 m-long by 1.5 m-wide by 1.2 m-deep rectangular channel was constructed within the circular basin of overall dimensions 13 m-diameter and 1.2 m-deep, allowing total water depths H of up to 1 m to be considered. The rigid trapezoidal sill obstruction had a horizontal sill length l_s = 2 m, at a height h_s = 0.5 m above the channel floor, and inclined sill approaches set at an angle α_s = 26.57°. A schematic of this physical system is shown in Figure 1.

The initial, undisturbed experimental configuration was one in which the rectangular channel was filled with freshwater of density ρ_1, submerging the trapezoidal sill to a depth $h_b = H - h_s$. Saline water of density ρ_2 was then introduced at the bottom of basin M at an initially low volume flux Q_2 to allow a dense stratified layer to develop, whilst minimising mixing with the overlying fresh water layer. Once this layer was established, the saline water volume flux Q_2 was increased to a prescribed flow rate and a dense water intrusion was initiated across the submerged sill before flowing down the inclined sill slope into basin I and out of the channel as a bottom gravity current. After this saline intrusion developed into a quasi-steady saline overflow across the sill, a counter-flowing upper freshwater layer of density ρ_1 and volume flux Q_1 was initiated across the sill. This upper freshwater layer was also allowed to adjust to quasi-steady conditions before being increased incrementally throughout the experiment to investigate the influence of an increasing net-barotropic flow component ($Q_1 > Q_2$) on the saline intrusion layer.

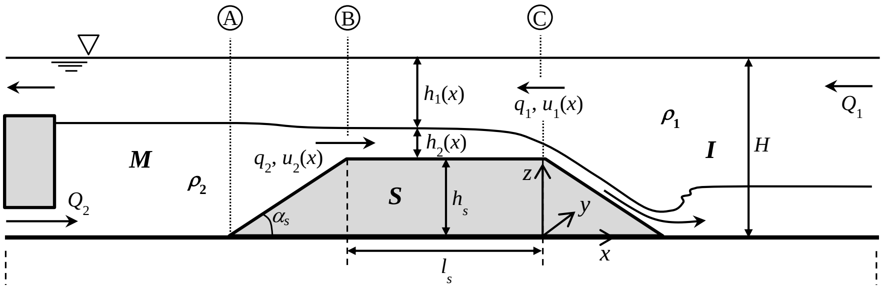

Figure 1: Schematic representation of physical system under investigation.

Experimental measurements were focused mainly on high resolution density and velocity fields both across the sill obstruction and at selected locations within basins M and I for the range of different bi-directional, stratified flows tested. Two-dimensional Particle Image Velocimetry (PIV) was used to measure velocity fields in a vertical (XZ) plane along the channel centreline, while high-resolution density profile measurements were obtained at key locations across the sill and in basin M using an array of motorized micro-conductivity probes [see Cuthbertson *et al*. (2016) for more details].

3. Results

Figure 2 present examples of synoptic, time-averaged velocity vector fields and corresponding colour maps of the horizontal U velocity component for these net exchange flows generated across the horizontal sill and down the inclined slope into impoundment basin I. Figure 2(a) shows the presence of a strong saline intrusion layer across the sill with a counter-flowing upper freshwater layer for $Q_1 \approx Q_2$. The thickness h_2 and velocity u_2 of this saline intrusion layer was generally shown to diminish as the freshwater volume flux Q_1 increased incrementally, until a point where it was blocked completely across the sill by a dominant net-barotropic freshwater flow (i.e. $Q_1 >> Q_2$) [Figure 2(b)].

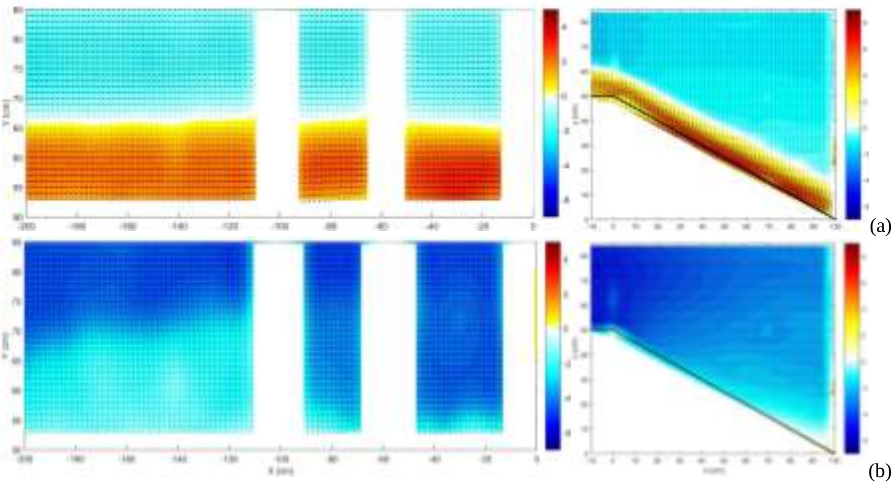

Figure 2: Synoptic PIV velocity fields for (a) stable exchange flows across sill obstruction and saline intrusion into basin I for Q_1/Q_2 = 1.15 and $q_1^2/(g'h_b^3) = 3.978\times10^{-3}$, and (b) complete blockage of the saline intrusion for Q_1/Q_2 = 4.32 and $q_1^2/(g'h_b^3) = 5.594\times10^{-2}$.

The parametric conditions under which this saline blockage occurred were explored by plotting the non-dimensional source freshwater volume flux $q_1^2/(g'_0 h_b^3)$ versus the volume flux ratio $q^* = q_1/q_2$ (where q_1, q_2 are the fresh and saline water fluxes per unit width) in Figure 3(a). Here, it is shown that a critical value $q_1^2/(g'_0 h_b^3) > \sim 0.125$ exists where the saline intrusion is blocked across the sill, irrespective of the magnitude of the fresh and saline volume flux ratio q^*. This suggests that a specific parametric combination of high freshwater volume flux q_1 and lower submergence depth h_b and reduced gravity g'_0 is required for saline layer blockage to occur. In this context, reduced g'_0 and/or h_b values also appear to increase shear-driven interfacial mixing across the sill, leading to enhanced entrainment of saline water by the dominant upper fresh water layer, especially at higher $q^* > 1$ values. The influence of saline layer entrainment on locally-calculated flux ratios Q_2/Q_1 at both ends of the sill (i.e. x/l_s = -1.0 and -0.15) is shown in Figure 3(b). Here, a relative reduction of up to 86% in the saline flux Q_2 (in relation to Q_1) occurs in the direction of the intrusion along the sill; clearly indicative of the interfacial mixing and entrainment of saline water into the dominant, counter-flowing upper freshwater layer (i.e. under high q^* conditions). These mixing and entrainment characteristics were also analysed in terms of the relative elevations of the velocity and density interfaces between the counter-flowing saline and fresh water layers, the isopycnal separation in measured density profiles, and through quantitative assessment of Thorpe overturning length scales over the range of parametric conditions tested.

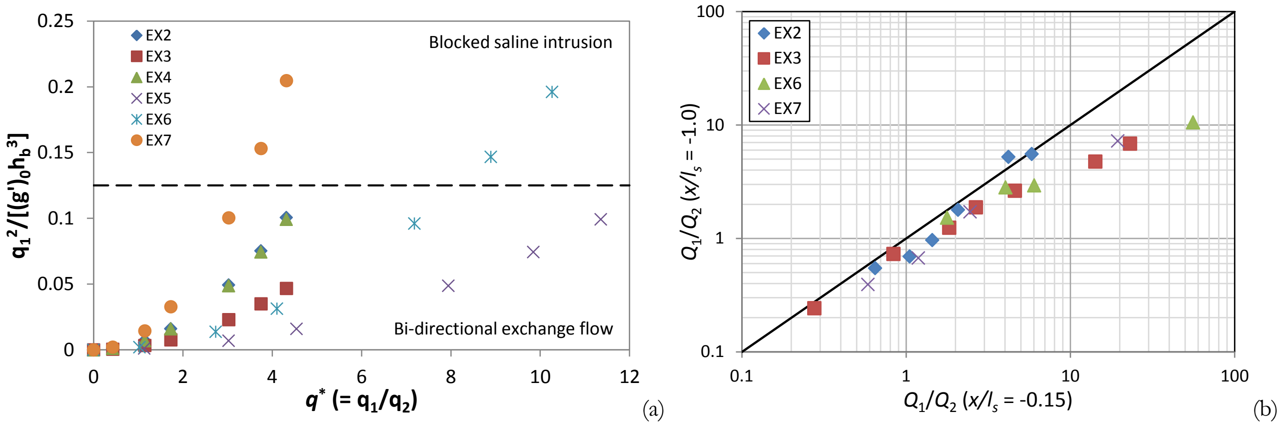

Figure 3(a): Normalised upper freshwater volume flux $q_1^2/[(g')_0 h_b^3]$ versus fresh to saline volume flux ratio $q^* = (q_1/q_2)$; (b) Local fresh-saline water flux ratios across the sill at x/l_s = -1.0 (i.e. basin *M* end) and x/l_s = -0.15 (i.e. impoundment *I* end).

4. Conclusions

Large-scale experiments have been conducted to investigate restricted exchange flows with net-barotropic components generated across a trapezoidal submerged sill. Velocity and density profile measurements indicate that interfacial mixing and entrainment processes are the key driver of the blockage of saline water intrusion across the sill and define the parametric conditions under which this blockage occurs. An internal-flow hydraulic model has also been developed to predict interface elevations at the two control sections *A* and at a sill section *BC* (Figure 1), assuming that maximal exchange flow conditions are generated across the sill. The experimental results are also utilised to validate two key model parameters: (i) the volume flux ratio q^* between the counter-flowing upper fresh and lower saline layers; and (ii) the mass loss from the lower saline layer due to entrainment into the upper fresh layer.

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