Secondary estuarine circulation and the related vertical mixing at the sill of Ambon Bay, eastern Indonesia

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Secondary estuarine circulation and the related vertical mixing at the sill of Ambon Bay, eastern Indonesia

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Abstract. Secondary estuarine circulation at the sill of Ambon Bay during wet season (July 2019) was investigated to add important insights into the existing knowledge on primary estuarine circulation done by a recent study. The datasets from the previous study were employed to calculate tidal-mean vertical advection as secondary estuarine circulation at the sill. Vertical mixing at the sill was also quantified using the continuity equation. The vertical profiles of vertical advection at the sill of Ambon Bay formed bow-like shapes with zero value at the surface that increased to reach maximum at the mid-depth of the sill (~6 m depth), subsequently decreasing to zero at the seabed. Vertical advection at the sill was found to be larger during spring tide (~2.5×10^{-3} m/s) than during neap tide (~1×10^{-3} m/s). Vertical diffusivity, indicating the magnitude of vertical mixing at the sill of Ambon Bay, showed similar characteristics to vertical advection in terms of vertical profiles (bow-like shapes) and spring/neap tidal variation (spring tide value: 8.5×10^{-3} m^2/s; neap tide value: ~5×10^{-3} m^2/s). The intense vertical mixing at the sill of Ambon Bay has the potential to create turbid water linked to resuspension of seabed sediment in the location.

1. Introduction

Ambon Bay in eastern Indonesia is a shallow-silled tropical fjord due to the inner basin called inner Ambon Bay (IAB) that is separated from outer Ambon Bay (OAB, its outer waters connected to Banda Sea) by a shallow sill (i.e. 12 m; see Figure 1a) [1, 2, 3, 4]. Due to its unique geomorphologic-topographic aspect, Ambon Bay has been of great general interest to oceanographic studies [1, 2, 3, 4, 5, 6, 7, 8]. In particular to the sill of Ambon Bay, the location has attracted many researchers regarding its narrow, shallow aspect, behaving as a constriction of IAB and thus, the sill can create energetic hydrodynamics [6, 9] and a two-layer circulation system, called estuarine circulation similarly found in partly-mixed estuaries [1, 10, 11]. While the former is common in marine systems, the latter shed light on the important of estuarine circulation, the flood/ebb-mean flow, in flushing the surface layer of IAB [1]. Furthermore, [1] indicated that the magnitude of estuarine circulation at the sill is affected by buoyant fronts established during spring flood tide.

A relevant question regarding the achievements of [1] on estuarine circulation is “is there any secondary estuarine circulation as the residual two-layer circulation prevails?”. Such a question has attracted some studies in other estuaries [12, 13,14]. In the system with long, narrow, shallow channel like the sill of Ambon Bay (see Figure 1a) [1], few studies have shown that there is a flood/ebb-mean vertical advection as secondary estuarine circulation besides primary estuarine circulation represented by the two-layer transport [13, 14]. The combination of primary (the two-layer horizontal flow) and secondary (vertical advection) estuarine circulations in this estuarine system is likely to determine vertical mixing in the system via the salt conservation equation [13]. The understanding of vertical mixing in such a system is of interest to water quality management in the location since the process can affect the water turbidity (via resuspension process) [15, 16]. Despite the importance of the knowledge on secondary estuarine circulation at the sill of Ambon Bay, there is no information of the process at the sill built upon the work of [1].

This current study aims to investigate vertical advection as secondary estuarine circulation at the sill of Ambon Bay to expand the work of [1]. The study also sought to quantify the vertical mixing mechanism in the location resulting from the combination of primary and secondary estuarine circulations.

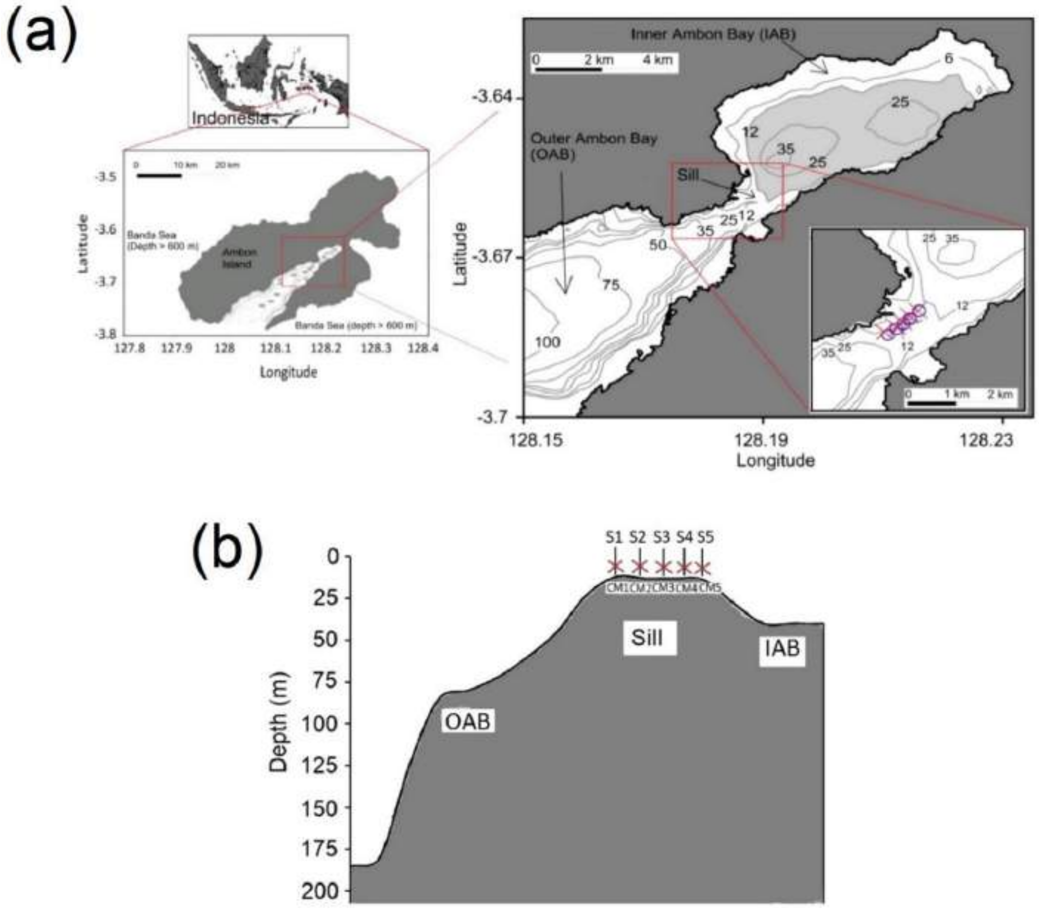

Figure 1. (a) Geography of Ambon Bay of Ambon Island in eastern Indonesia containing inner Ambon Bay (IAB) separated from outer Ambon Bay by a shallow sill (12 m). Blue circles and red crosses in the inset show the CTD stations and bottom-mounted current meter, respectively of [1] whose datasets are used in this current study. (b) The longitudinal section of Ambon Bay from OAB to IAB with the sill showing CTD (S1-S5) and current meter (CM1-CM5) stations.

2. Materials and method

2.1. *Chatwin's analytical model of estuarine circulation at the sill of Ambon Bay*

Chatwin's analytical model of estuarine circulation [14] has been recently applied to the sill of Ambon Bay by [1] due to the geomorphology of the sill suitable for the model (i.e. rectangular, long narrow channel with insignificant lateral flow due to homogenous lateral water mass). [1] sought to quantify primary estuarine circulation, *u*, that is the residual two-layer transport along the sill: surface low-saline water moving offshore the sill coupled with bottom high salinity inflow entering the sill. Mathematically, u, derived from Chatwin's model that was used by [1] is:

$$u(x,z) = -\frac{\beta g}{48\nu}\left(\frac{\partial S}{\partial x}\right)(8z^3 - 15Hz^2 + 6H^2 z) + \frac{1.5u_o}{H^2}(z^2 - 2Hz) \quad (1)$$

Here, $\beta = 7.8 \times 10^{-4}$ ‰$^{-1}$, H, $\partial S/\partial x$ and u_o are respectively the expansion coefficient of salt, the total depth of sill (12 m), horizontal salinity gradient and seaward velocity of brackish water from IAB. Horizontal and vertical coordinates are represented by x and z. g and ν are gravity acceleration and vertical eddy viscosity, respectively. [1] converted the vertical coordinate originally used in [14] (i.e. $z = 0$ at the seabed) to fit the CTD deployment (i.e. z = 0 at the surface layer) and hence, u became:

$$u(x,z) = -\frac{\beta g}{48\nu}\left(\frac{\partial S}{\partial x}\right)\left(8(H-z)^3 - 15H(H-z)^2 + 6H^2(H-z)\right) + \frac{1.5u_o}{H^2}\left((H-z)^2 - 2H(H-z)\right) \quad (2)$$

This current study seeks to unveil secondary estuarine circulation at the sill of Ambon Bay. Based on Chatwin's model [14], for rectangular, long narrow channel with estuarine water mass that is laterally homogenous, vertical advection, w, behaves as secondary circulation due to the prevailing u, and thus, w can be estimated using the continuity equation [14]:

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \quad (3)$$

Chatwin's model [14] indicated that w is estimated by integrating Equation (3) using u in Equation (1) with boundary conditions:

$$w = 0 \text{ at } z = 0 \text{ and } z = H \quad (4)$$

Thus, w is:

$$w(x,z) = \frac{\beta g}{48\nu}\left(\frac{\partial^2 S}{\partial x^2}\right)(2z^4 - 5Hz^3 + 3H^2 z^2) \quad (5)$$

To synchronize w with the coordinate of the CTD deployment as previously done by [1], w becomes:

$$w(x,z) = \frac{\beta g}{48\nu}\left(\frac{\partial^2 S}{\partial x^2}\right)\left(2(H-z)^4 - 5H(H-z)^3 + 3H^2(H-z)^2\right) \quad (6)$$

Note that $\partial S/\partial x$ and $\partial^2 S/\partial x^2$ in here were numerically calculated using centred-difference approaches based on [17].

2.2. *Vertical diffusion at the sill of Ambon Bay*

In the system of Chatwin model (i.e. laterally homogenous water mass and in steady-state condition that is the mean two-layer transport over tidal cycles) including at the sill of Ambon Bay [1, 14], the most important components of hydrodynamics in the salt conservation equation are the horizontal advection flow (u; see Equation 2), the vertical advection flow (w; see Equation 6) and the vertical diffusion (representing vertical mixing), K_v, [13], written as:

$$u\,\frac{\partial S}{\partial x} + w\frac{\partial S}{\partial z} = K_v\frac{\partial^2 S}{\partial z^2} \quad (7)$$

Hence, the vertical diffusion (or mixing), K_v, can be estimated when u and w are known by using Equations 2 and 6, respectively. Here, K_v at the sill was estimated using Equation 7 with $\partial S/\partial x$ and $\partial^2 S/\partial x^2$ in here numerically calculated using centre-difference approach based on [17]

2.3. Datasets in the study

This study employed oceanographic datasets from measurements conducted by [1] using the CTD casts along the sill (stations S1-S5) measuring water density (given by salinity S) with the related bottom-mounted current meters (CM1-CM5) (see Figure 1b). The measurements were conducted during high freshwater input condition during wet season in July 2019 and during spring/neap tidal cycles in the season that is between 17-25 July 2019 [1]. The datasets allowed this study to provide u (Equation 2), w (Equation 6), the associated vertical salinity at the sill and K_v (Equation 7). This current study only calculated the values of w and K_v while the values of u were simply obtained from [1].

3. Results and discussion

3.1. Overview of water stratification and primary estuarine circulation at the sill of Ambon Bay: insights from Salamena et al. [1]

Water stratification (given by along sill-averaged vertical salinity; color contour in Figure 2a) at the sill of Ambon Bay during high freshwater inputs in wet season (July 2019) was comprehensively observed by [1] regarding its variations within spring and neap tidal cycles. The previous study [1] found that water stratification was stronger during spring tide (i.e. 17-21 July 2019) than during neap tide (24-25 July 2019) (see Figures. 2a and b).

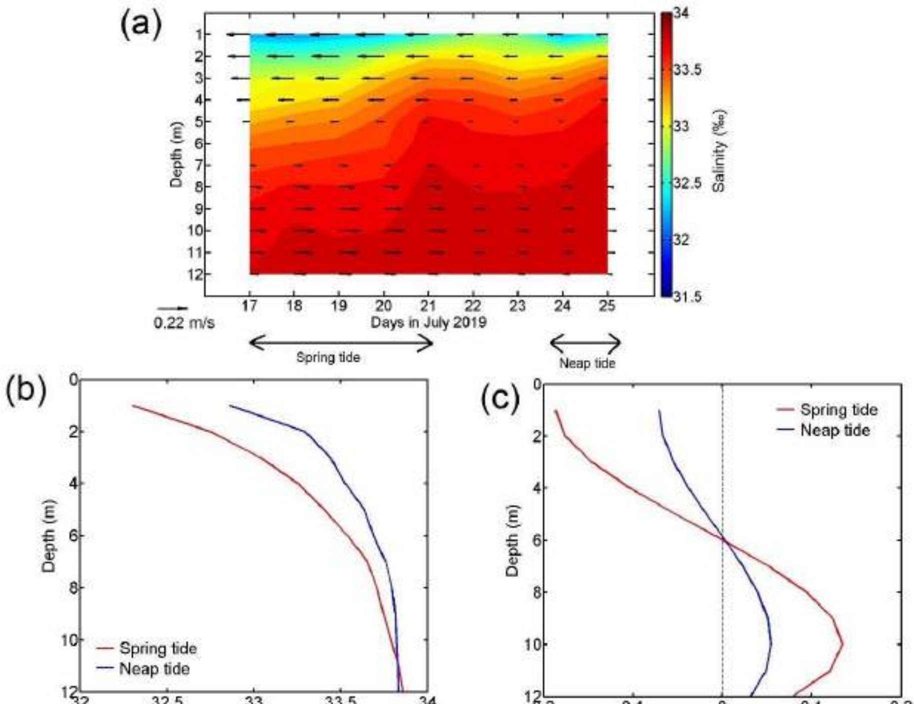

Figure 2. (a) Temporal evolutions of along sill-averaged observed salinity at the sill of Ambon Bay (from S1-S5 in Figure 1b) with modelled primary estuarine circulation using Equation 2 (arrows). The profile is obtained from Figure 3a of [1]. (b) Vertical profiles of along sill-averaged observed salinity at the sill of Ambon Bay for spring tide (red line) and neap tide (blue line). (c) similar to (b) but for primary estuarine circulation.

Applying Equation 2 to quantify primary estuarine circulation, *u*, [1] showed that primary estuarine circulation at the sill of Ambon Bay is characterized by surface outflow moving towards OAB (current arrow moving to the left) coupled with bottom inflow towards IAB (current arrow moving to the right) (see Figure 2a). *u* (the size of arrow in Figure 2a and also see Figure 2c) was found to be faster during spring tide (i.e. maximum values for surface outflow and bottom inflow of 0.22 m/s and 0.15 m/s, respectively within 17-21 July 2019) than during neap tide (i.e. 0.08 m/s and 0.05 m/s for the respective flows within 24-25 July 2019). This corresponds to stronger water stratification during spring tide that results in larger $\partial S/\partial x$ in for the formula of *u* (Equation 2) than during neap tide (Figure 2b) [1, 14, 18, 19].

3.2. Vertical advection as secondary estuarine circulation at the sill of Ambon Bay

Building upon the work of [1] as highlighted in the previous section, this current study seeks to unveil secondary estuarine circulation at the sill of Ambon Bay. Here, secondary estuarine circulation at the location was represented by vertical advection, *w*, (Figure 3) as a result of the prevailing *u* at the horizontal axis along the sill channel; *w* was estimated using Equation 6. In general, *w* (Figure 3a) had positive values indicating the prevailing upward transport at the sill of Ambon Bay due to primary estuarine circulation, *u*. The vertical velocity, *w*, was found to be larger during spring tide (i.e. w = ~2.5×10^{-3} m/s, especially on 18 July 2019) than during neap tide (i.e. w = ~1×10^{-3} m/s especially on 24 July 2019; see Figure 3a), similar to the patterns of *u* (see Figures 2a and c). From vertical profiles in Figure 3b, the maximum values of *w* were concentrated around the mid-depth of the sill (i.e. around 6 m depth) and thus, the vertical profiles formed bow-like shapes, consistent with previous studies such as [13, 14].

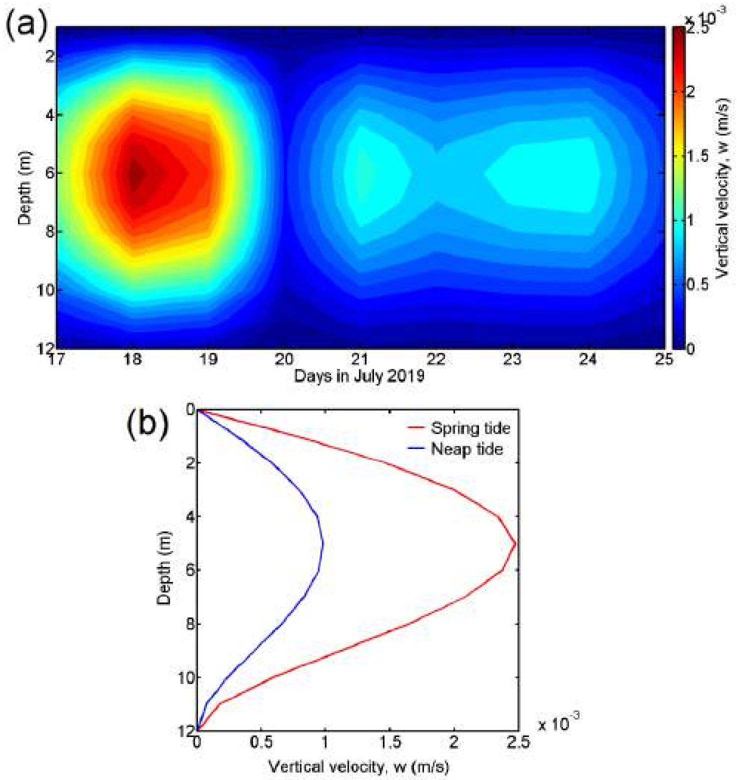

Figure 3. (a) Similar to Figure 2a but for vertical velocity as secondary estuarine circulation calculated using Equation 6. (b) similar to Figure 2c but for secondary estuarine circulation.

Secondary estuarine circulation, *w*, was approximately one to two orders of magnitude lower than primary estuarine circulation, *u*. For instance, the maximum values of *w* within spring/neap tidal cycles (Figure 3a) were around 1-2.5 × 10^{-3} m/s. In contrast, *u* has a range of 5×10^{-2} to 2×10^{-1} m/s (Figure 2c). The considerably smaller values of *w* than that of *u* are consistent with the work of [13]; see their Figures 11.2b and 11.9b.

3.3. *Vertical diffusivity at the sill of Ambon Bay*

Vertical mixing magnitude, represented by vertical diffusivity, K_v, at the sill of Ambon Bay, resulting from the primary (*u*) and secondary (*w*) estuarine circulations at the location (see Equation 7), varied within spring-neap tidal cycles (Figure 4a). For instance, vertical mixing was found to be more intense during spring tide (K_v = up to 8.5 × 10^{-3} m^2/s) than during neap tide (K_v = up to ~5 × 10^{-3} m^2/s). This is similar to the patterns of *u* (Figure 2a) and *w* (Figure 3a).

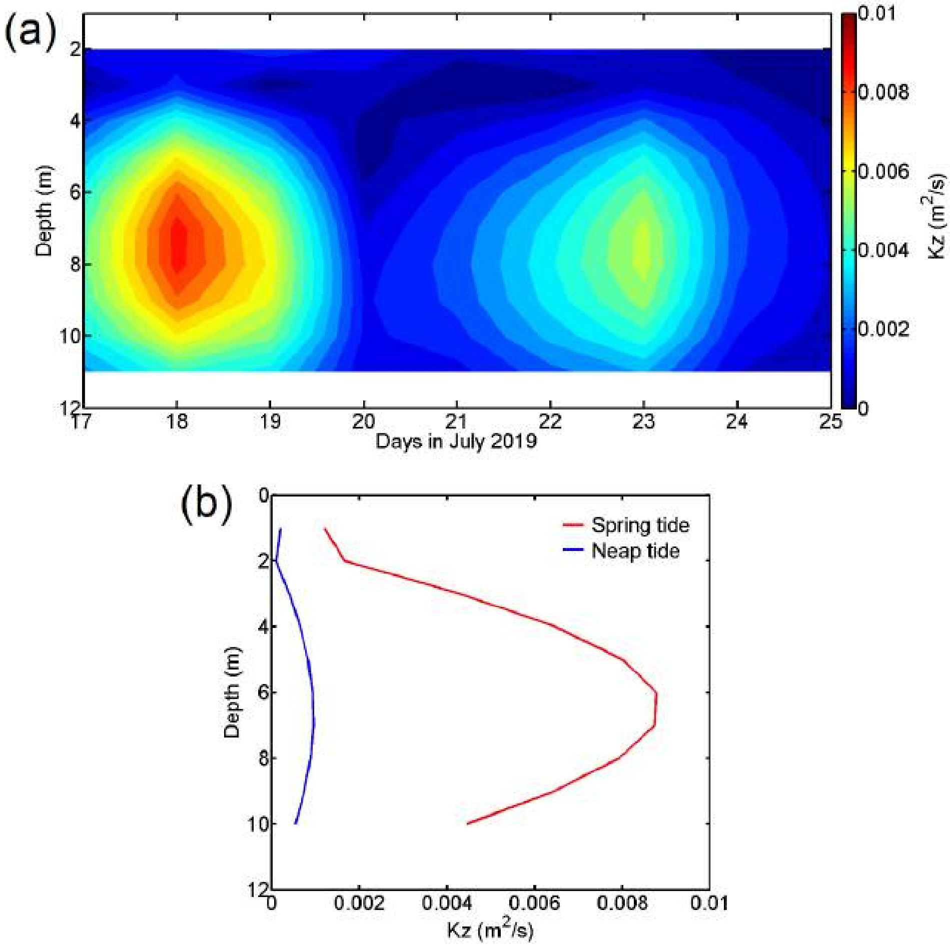

Figure 4. (a) Similar to Figure 3a but for vertical diffusivity calculated using Equation 7. (b) Similar to Figure 3b but for vertical diffusivity.

Regarding vertical mixing process in Ambon Bay fjord system that is the IAB basin with the sill as its only shallow entrance, vertical mixing at the sill is more intense than that inside the IAB basin particularly at the deep layer of the basin (i.e. depths below the sill at IAB; Figure 5). For instance, vertical diffusivity at the sill was found to be up to 8.5×10^{-3} m^2/s, one order larger than that in the interior IAB basin ($3.3\text{-}3.7 \times 10^{-4}$ m^2/s) [3]. This difference is likely to be due to the shallower depth of the sill (12 m) than the IAB basin (average depth: 25 m; maximum depth 40 m) that allows the sill to be highly subject to tidal-induced mixing (as the shallow sill creates faster barotropic tidal flow) compared to the IAB basin [20].

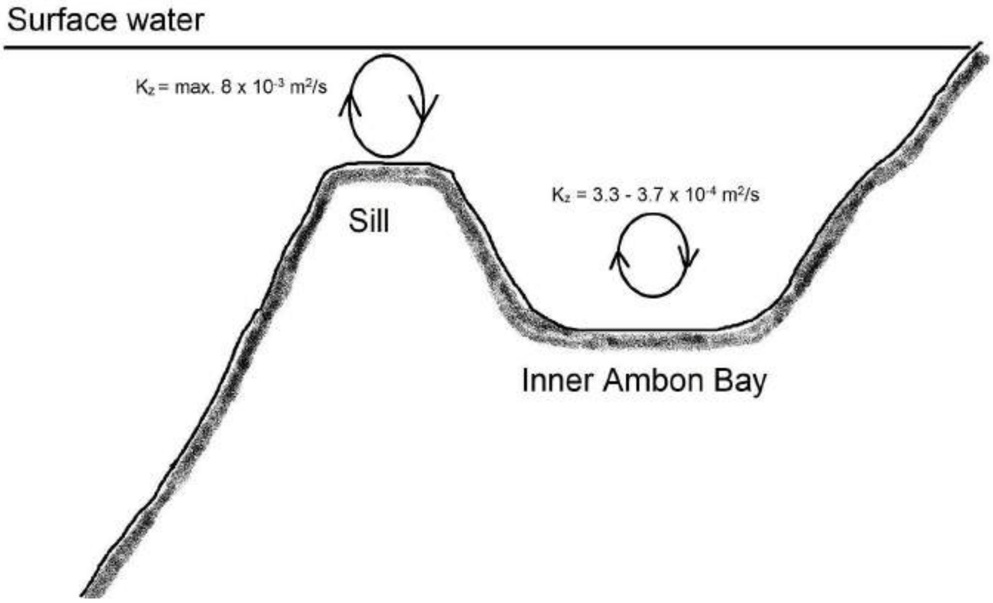

Figure 5. The longitudinal section of Ambon Bay fjord with sill as a shallow entrance of inner Ambon Bay that is combined with the magnitude of vertical diffusivity at the sill and in the interior inner Ambon Bay. The schematic loops indicate vertical mixing in these locations.

3.4. A driver of turbid water at the sill of Ambon Bay

The sill of Ambon Bay is characterized by marine waters with high turbidity. The water visibility at the sill can be as much as 3 m horizontally and vertically, e.g., visual observations during the deployment of bottom current meters at the sill (Figure 6) whose data were used to predict *u* in [1].

Turbid water established at the sill of Ambon Bay is likely to be contributed by the prevailing energetic hydrodynamics in the location. The narrow, shallow sill of Ambon Bay (400 m wide, 12 m deep) is subject to energetic tidal force as barotropic tidal current accelerates in such a geomorphology [21, 22]; i.e. the maximum barotropic tidal current crossing the sill of Ambon Bay can reach ~1 m/s [6]. This fast barotropic tidal current can stir up the seabed of the sill via the increase of bottom shear stress, hence, eroding the seabed sediment [16]. The eroded sediment from seabed of the sill enters the water column and is then transferred further vertically due to the prevailing intense vertical mixing in the location (Figure 4). As such, this is likely to establish turbid water at the sill [15, 16, 23], supported by the visual observation (Figure 6).

Figure 6. Visibility of water column at the sill of Ambon Bay

4. Conclusions

Secondary estuarine circulation at the sill of Ambon Bay is represented by tidal-mean vertical advection obtained from Chatwin model. The vertical profiles of the vertical advection formed bow-like shapes with zero value at the surface that increased to reach maximum at the mid-depth of the sill (~6 m depth), subsequently decreasing to zero at the seabed. Vertical advection at the sill was found to be larger during spring tide (~2.5 $\times 10^{-3}$ m/s) than during neap tide (~1 $\times 10^{-3}$ m/s). Vertical diffusivity, indicating the magnitude of vertical mixing at the sill of Ambon Bay, showed similar characteristics to vertical advection in terms of vertical profiles (bow-like shapes) and spring/neap tidal variation (spring tide value: 8.5 $\times 10^{-3}$ m^2/s; neap tide value: ~5 $\times 10^{-3}$ m^2/s). The intense vertical mixing at the sill of Ambon Bay has the potential to create turbid water linked to resuspension of seabed sediment in the location.

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