INTERNATIONAL JOURNAL OF R&D IN ENGINEERING SCIENCE AND MANAGEMENT

Effect of seawater intrusion on the nutrient dynamics of the Melen Estuary

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ABSTRACT

Melen watershed of Turkey provides water to İstanbul and it is geographically located in the Western Black Sea region. The research goal is to conduct a preliminary research to observe the effects of the seawater intrusion on the nutrient dynamics of the Melen Estuary. It is planned to investigate what it is needed to be done to preserve the estuarine habitat that is now adapted to fresh water environment. Since the ecological component of the work, the environmental conditions that constrain the habitat of key biological entities that are most interested in (based on a survey of the literature) can be assessed. Salinity ranges will be focused because of its impact as a main driver for species distribution.

1. Aims and Background

An estuary is located where the river dumps into the sea. There are some differences between the river and the sea. Although they both contain water and have an aquatic habitat, there are some significant differences exist. River is the body of running water and there is no retention for the water and a sea mainly stores water. An estuary consists of the characteristics of both a sea and a river. Estuaries have a fertile soil, a flat land, and a fresh water. The limits of estuarine habitats can differ temporally and spatially due to the tidal cycles, river discharge variations, temperature, and changes in bedform [1]. An estuary has mixed and funnel type tidal waves and a briny environment [2].

Melen watershed of Turkey from the West Black Sea region is shown in Figure 1. It has the 2437 km^2 area [3]. At the mid of the Watershed 360 km^2 wide Duzce Plain exists. Melen Watershed is bounded by Bolu Mountains in the east, Sakarya (Adapazari) Province in the west, Orhan Mountains in the north, and Abant Mountains in the south. According to Erturk et al. [4] Buyuk Melen River will supply more than fifty percent water demand of Istanbul. In 2039, 35 m^3/s water is planned to be withdrawn from Buyuk Melen Watershed for Istanbul [4]. For this purpose a reservoir system is being constructed on the Buyuk Melen River. Melen Watershed is regarded as a sensitive area, since Buyuk Melen River is used as a potable water source for Istanbul [5]. Melen Estuary, which has the approximate coordinates of 41º 04' 22'' N and 30º 58' 02'' E, is selected as the research area for this study (See Figure 2).

Melen River is 30 km long. It flows into the Black Sea at the Melen Estuary that is located on the border which separates Kocaali District of Sakarya Province and Akcakoca District of Duzce Province (See Figures 3-8). Buyuk Melen River is currently under the threat of land based pollution. According to Sumer et al. [7] its water can be classified as water class number 2. Since 2001 settlements and the population in the watershed has been increased. As far as it is known there is no best management practices applied in the region. Therefore a significant decrease in the water quality of the river is expected.

The Melen watershed provides fresh drinking water to most of Istanbul. There are a few rivers in Melen watershed and government constructed a water regulator at the end of the river junction (See Figure 9). There is a water purveyor that pumps this fresh water all over the city, but in the past, the water was discharged into the estuary connected to the Black Sea. Now they pump the water with a 150 km long pipe. Still a little amount of remaining water is released for the estuary. There is also a drawndown of fresh water from agriculture. There are agricultural areas on both sides of estuary and the farmers use the water in estuary. There is also fish catchment in the estuary. The main objective of this research is to research the effect of the seawater intrusion on the nutrient dynamics of the Melen Estuary. For this purpose first hydrodynamic then the water quality analysis is aimed to be performed.

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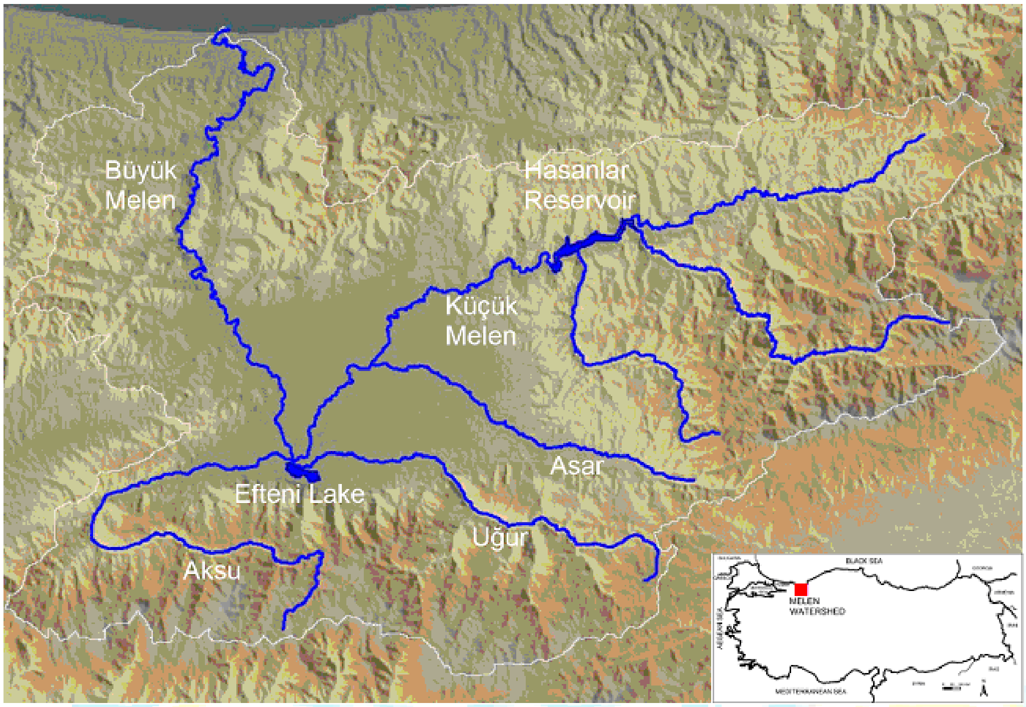

Figure 1. Melen Watershed and its Rivers [6].

Figure 2. Sakarya ,and Duzce Provinces are shown highlighted on Turkey Map [8].

Figure 3. Borders of Sakarya (Adapazari) and Duzce Provinces [8].

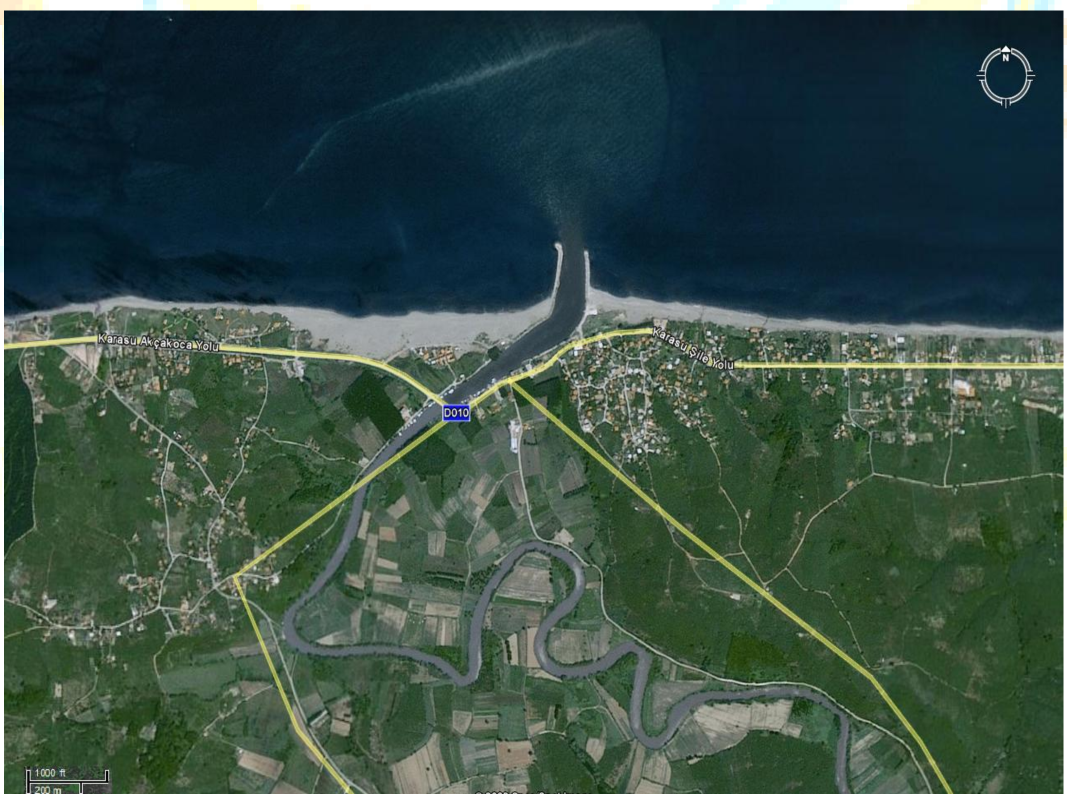

Figure 4. Melen Estuary [8].

Figure 5. Where Melen River meets The Black Sea.

Figure 6. Melen Estuary photo taken from inland.

Figure 7. Melen Estuary to headwater.

Figure 8. Construction around Melen Estuary.

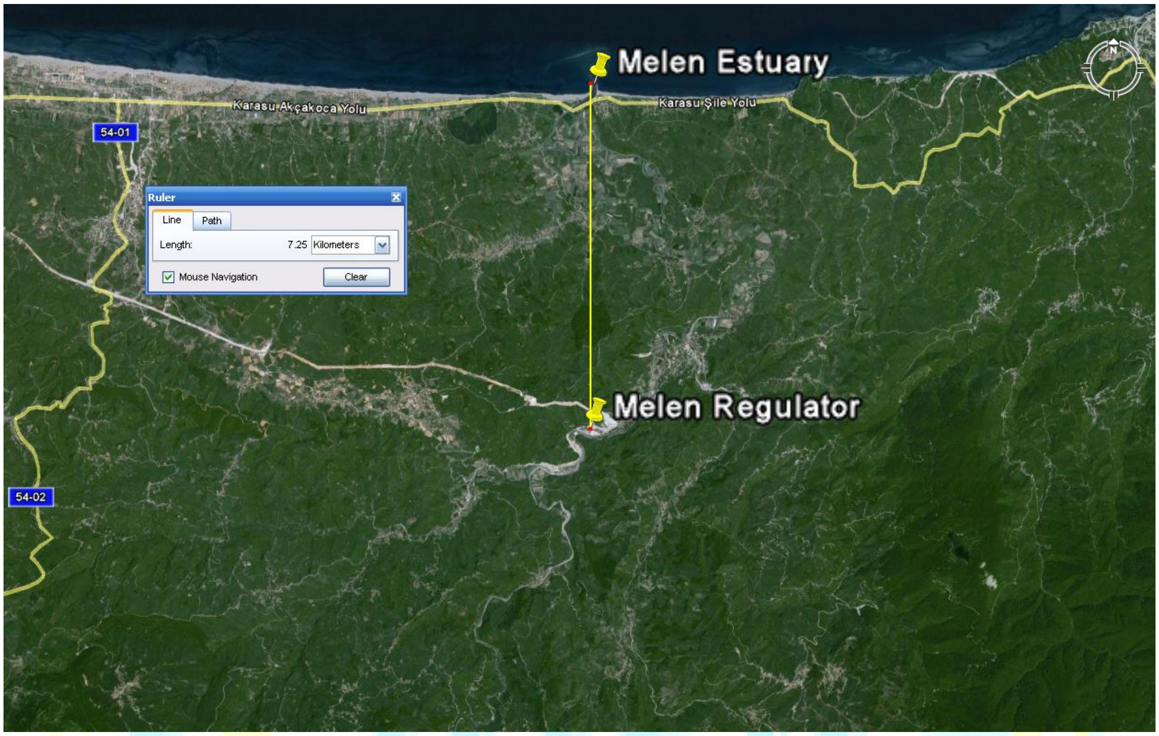

Figure 9. Location of Melen Regulator [8].

2. Research Methodology

Pollutants of the research area are mostly diffused or nonpoint sources. The pollutants are generally carried off by storm water. Non-point sources (NPS) are agriculture, urban, forestry, construction, mining, dams, channels, saltwater intrusion, land disposal, and urban streets [9]. Diffuse sources can be converted into point sources using watershed models and the geographical information system (GIS) [10]. In the absence of local data, the runoff models and water quality data reported in the literature can be used to estimate the likely range of diffuse pollution load generated from a catchment [11]. The most effective solution against diffused pollution is the treatment train concept based on the combination of a series of complimentary treatment techniques to achieve enhanced water quality, Best Management Practices (BMPs). Some BMPs are; stabilizing stream banks, avoiding livestock access to the water body, reconstructing stream channels, creating in stream habitat, creating forested wetlands and restoring vegetated buffers [12]. Implementing BMPs such as manure storage and silage leachate control helps to use the nutrients on the farm more efficiently and reduces field runoff potential.

The leaching of nutrients and other chemicals from the agricultural fields, effluents disposed by different types of industrial activities and improper domestic waste management practices are often the reasons stated for the deterioration in water quality of lakes, reservoirs, rivers and estuaries so on. The water quality investigations undertaken can be classified as qualitative and quantitative types. The qualitative studies are based on the questionnaire surveys, discussions or any other techniques chosen to obtain relevant information on user perception on prevailing water quality. The quantitative nature of assessment refers to the precise information on different pollutant parameters, usually undertaken based on detailed sampling followed by laboratory analysis. The quantitative investigations on water quality are assessed on the physical, biological and chemical characteristics of water. The physical parameters refer to those assessed by physical means like visual appeal, odor and taste. The high turbidity, mixing with colored wastewater, high water temperature, odor generated from the dead and decayed matter are some of the changes that are noticed through physical means. But chemical parameters are those that require detailed chemical analysis to understand the characteristics. The dissolved oxygen that measures the amount of oxygen molecules present in the dissolved state, biochemical oxygen demand to give the measure of organic impurities in water, nutrients like nitrates and phosphates are the major chemical parameters that must be monitored continuously. The bacteriological quality refers to the various biological organisms that are present in water like phytoplankton, bacteria, protozoa and a variety of small plants. In the case of lakes and reservoirs, the high influx of nutrients into the water body results in the indiscriminate growth of green plants like phytoplankton and small sized floating weeds termed as eutrophication. In order to estimate the long term impact of the current pollution trends on the water quality, model and simulation studies become very essential. The models usually proposed are theoretical models, empirical models or statistical models. They are very essential to understand the changes in the water quality of streams and hence to propose appropriate means for the restoration methods. The mechanisms behind the fate and transport of contaminants/pollutants are mostly based on mass balance calculations that incorporate different processes like dispersion, adsorption/desorption, accumulation, biodegradation and precipitation. Erturk et al. [4] developed a water quality model for the Melen Reservoir using QUAL2K software package that is distributed for free from United States Environmental Protection Agency (USEPA). Same model can be used for the water quality analysis of the Melen Estuary.

Some terms defined by Nguyen [13] will be used in this study:

- Advection refers to the transport by a current in a river.
- Dispersion is the movement of the particles by diffusion.
- Molecular diffusion represents the distribution by molecular motions regarding the Fick's law and diffusion equation.
- Turbulent diffusion means the random distribution of particles by turbulent motion.

According to [2] estuaries can be classified based on their salinity, shape, geology, tidal and river influence. Shape of the Melen can be defined as funnel or trumpet shape. As it is seen from the Figure 4, the banks converge in upstream direction. It is not easy to comment on the tidal influence in the Melen Estuary at once, long time research is needed to define Melen Estuary in terms of the tidal influence. After the construction of Melen Regulator (See Figure 9) significant reduction in discharge is observed. Water is still considered as fresh and the bottom is sandy. But due to the reduction in flow rate of the river, salt water intrusion is generated. The tide is mainly responsible this situation since high tide correlates with reduced flow. Depending on its geology Melen Estuary can be classified as the alluvial in a coastal plain. Water in the estuary can deposit the sediments and also it can erode the estuary bed. Shape of the alluvial estuaries is strongly dependent on the discharge in other words rainfall that has been received from the catchment area of the watershed.

There is a salt water intrusion situation in the Melen Estuary. Black sea water is salty; however neither Melen River water nor Melen Estuary is not salty that much. Melen rivers are considered as fresh water, previously also estuary water was completely fresh, but now there is a suspension regarding the salty water intrusion from Black Sea since the flow rate of water comes from melen rivers is decreased, which threatens the habitat in estuary. Based on the salinity Melen Estuary can be classified as positive or normal estuary. Because in this kind of estuaries salinity decreases gradually in upstream [2]. This is what we expect for the Melen Estuary. Figure 10 shows the salt intrusion mechanisms.

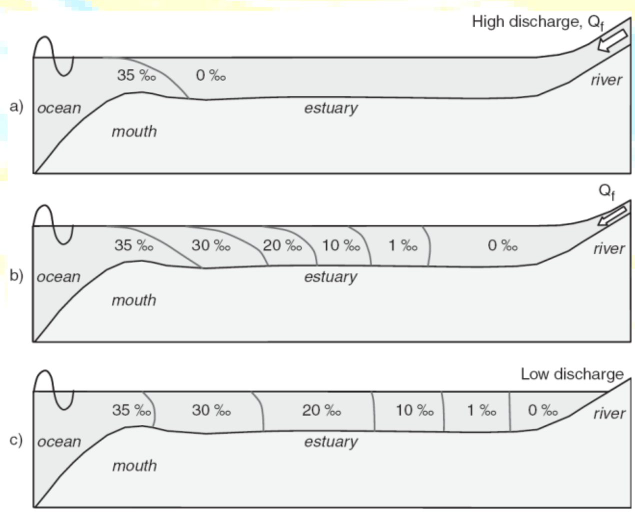

Figure 10. Salinity for (a) a stratified, (b) a partially mixed, and (c) a well-mixed estuary [2].

Stratification in estuaries is occurred due to the intrusion of more dense saline sea water. In case of any Salt wedge, three layers are formed. These layers are lower saline sea water layer, interface layer at the middle and the fresh river water layer at the top (See Figure 11). Model developed by Ibanez et al. [14] determines advective fluxes of water and salt in three layer. In Figure 11 salt wedge estuaries are shown under steady river discharge. In that model, river discharge is assumed as steady. In Figure 11; q represents the flux, ij refers to the vertical flux in the layer i and the layer j.

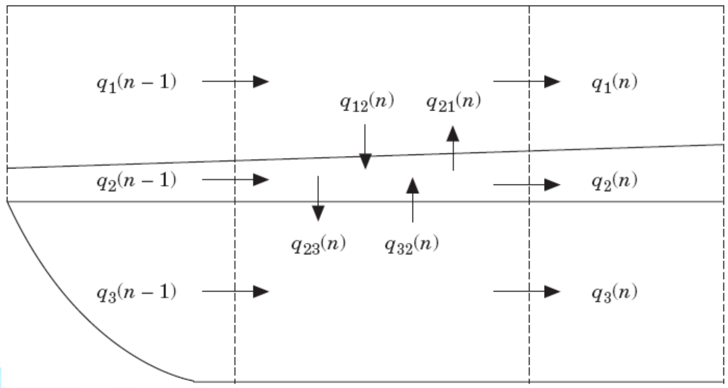

Figure 11. Three layers and some compartments of the Estuary [14].

The accurate determination of salinity and other hydrologic information involves incorporation of large volume of information which also carries huge uncertainty. The tidal pumping, which is caused by flood-ebb channel re-circulation, is reported to influence the salinity distribution in the estuarine region significantly [15]. The authors have developed a three-dimensional model (DELFT3D) as virtual laboratory, which could generate necessary data on hydrodynamics and hence estimate the salinity distribution. This model was adapted most from already available model called, KUSTZUID, which was developed and calibrated by Dutch Ministry of Transport and Public Works. The results obtained using the model includes the measure of water level, discharge and salinity level. These have shown good agreement with the observed results. Also, a direct relationship between longitudinal salt dispersion with flood-ebb loop length and tidal efficiency is also confirmed in this study [15]. The prediction of the salinity distribution in the complex situations like multi-channel estuaries like Mekong delta has also been reported in the literature [16].

Mekong delta is unique in its character. It has large number of branches and transports huge quantity of water (2000 m^3 per second) even during summer. The prediction model is framed on the principle that the multi-channel estuarine system would function as single entity and the paired branches could be appropriately combined to one. The results obtained from the analysis show that steady state models could predict the salinity levels very well. They could also explain the equilibrium conditions established in the estuaries during variable flow period especially during the dry seasons. Also, authors have computed the system response time for Mekong also. The data used in the paper was collected during the period 1991 to 1998. As Mekong delta is a very active morphologically, its topography too is undergoing continuous change due to the transport of sediments through the river. Hence, the model would require continuous improvement by incorporating the recent topographical details. Further, the model also has parameters like mean estuary depth and river discharge that have high degree of uncertainty [16].

Determination of fresh water discharge is essential for quantification of salinity distribution. In the case of very low flows the salinity distribution is observed to be maximal. But the low fresh water flows coupled with high tidal flows make the accurate estimate of fresh water discharges very difficult. And in the case of Mekong delta, the multi channel characteristics make the accurate direct determination of discharge computation very cumbersome. A reliable model has been proposed to estimate the river discharge under the above situations [13]. The principle applied in this process is the reverse calculation; from the known values of salinity distribution the authors have developed equations to determine the river discharge. In this connection, two separate approaches have been attempted for different clusters of rivers in this basin. In the first approach, based on the information on the salinity distribution and estuarine shape of each branch the discharge in the individual branches is computed. And in the other approach, from the combined shape of estuarine branches and the salinity distribution, the combined discharge is estimated. These analytical models could be used to compute the river discharges in multi channel estuarine regions by collecting the salinity distributions [13].

Gu and Lawrence [17] analyzed the frictional exchange flow using a constant width rectangular channel (See Figure 12). Results of their study shows that density interface is both asymmetric and nonlinear. In Figure 13, density interface points are depicted for varying frictional effects (α=0.01, 0.1, 1.0 and 10).

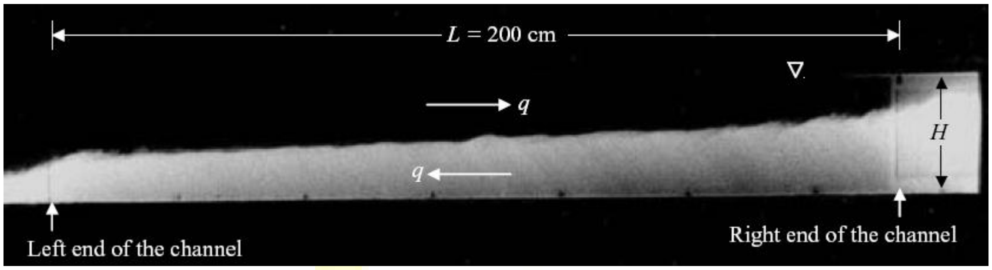

Figure 12. Two-way maximal exchange flow [17].

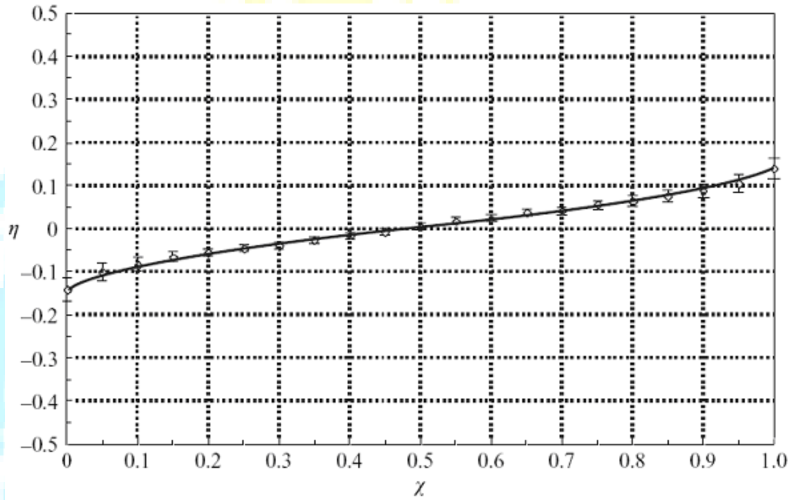

Figure 13. Density interface with changing frictional parameters [17].

Ibanez et al. [14] claimed that the discharge is the key issue for controlling the hydrologic dynamics of the Ebre and Rhone estuaries. For this purpose several field measurements had been conducted. It is found that the topography of the estuary bed affects the extent and retreat of the salt wedge. Ibanez et al. [14] shows the relation between river discharge and the interface depth as seen in Figure 14.

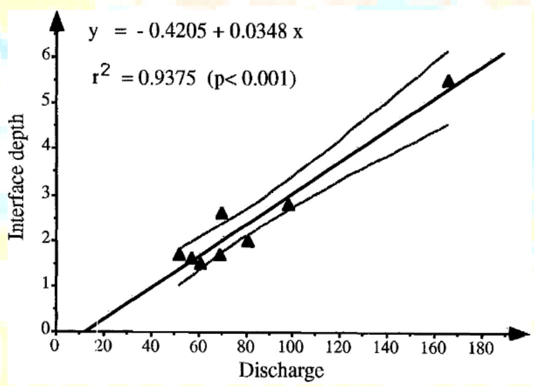

Figure 14. Regression of river discharge (m^3/s) vs. interface depth (m) Ibanez et al. [14].

Suzal et al. [18] selected The Gediz River (İzmir Bay, Turkey) as a research area. In that study, an experimental study was conducted and the relation between the water pollution parameters and the salinity was investigated by measuring the dissolved inorganic nutrients at the river mouth.

Dermissis and Partheniades [19] investigated shear stresses in saline wedges by conducting an experimental study. 20 meters long variable slope flume is used (See Figure 15). For this purpose 4 distinct approaches were used. Firstly velocities were measured using hot film anemometers. Then, equations of motion were integrated using Leibniz Integral Rule. Also, one dimensional model of Schijf-Schoenfeld was applied. Finally equations of motion were integrated considering zero bed stress. The general equations of motion and continuity for steady flow are shown in Equations 1 and 2, respectively.

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-g\frac{dz_0}{dx}+\frac{1}{\rho}\left(\frac{\partial \tau_{zx}}{\partial z}+\frac{\partial \tau_{yx}}{\partial y}\right)-\frac{1}{\rho}\frac{\partial \rho}{\partial x} \quad (1)$$

$$\frac{\partial u}{\partial x}+\frac{\partial u}{\partial y}=0 \quad (2)$$

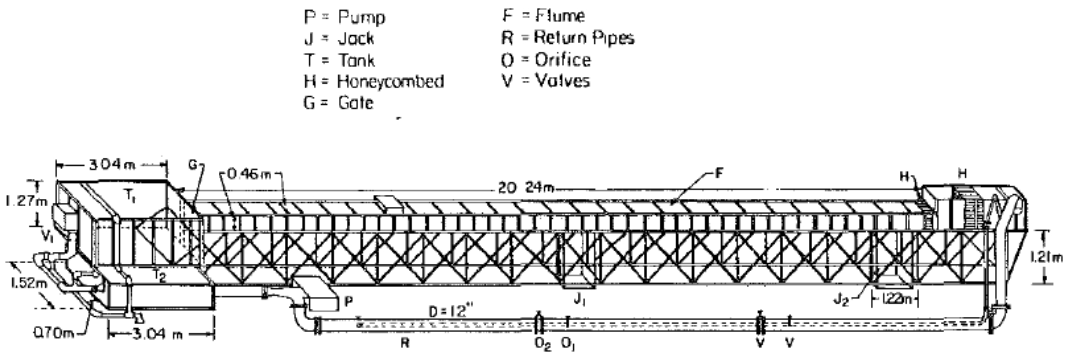

Figure 15. Outline of the flume and the basic experimental systems [19].

Results show that interfacial and bed friction coefficients are related to the multiplication of Reynolds Number (Re) and square of Densimetric Froude Number (Fr), $ReFr^2$. When two layer saline wedge is generated (See Figure 16), the dominated shear stresses are generated in both the interface and the bed.

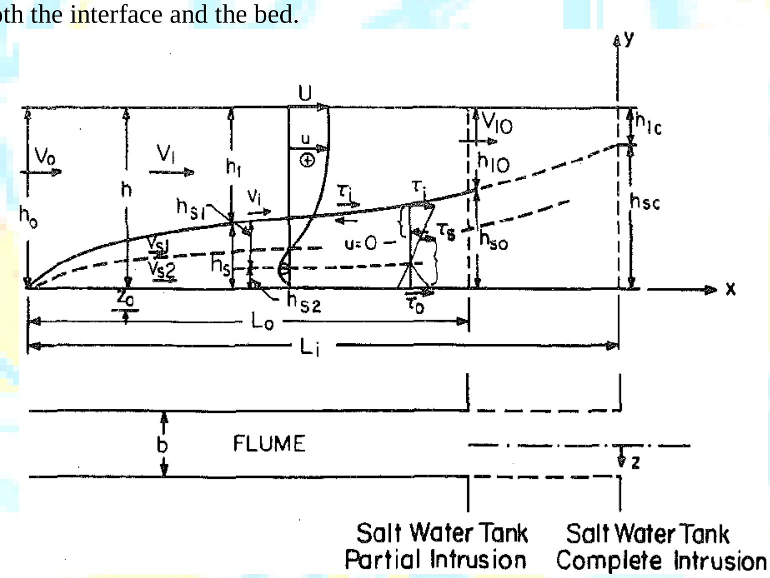

Figure 16. Sketch of the arrested salt wedge [19].

These stresses are noted by τ_i and τ_0, respectively and they are associated with f_i and f_0. According to Dermissis and Partheniades [19] related studies on stratified flows are focused only on the interface. Interfacial stresses were checked using the Equation 3.

$$\tau_i=\mu\frac{du}{dy}-\overline{\rho u'v'} \quad (3)$$

Where;

u is the temporal mean velocity in x-direction.

y is the vertical distance from the bed.

u' and v' are instantaneous turbulent velocity components in the x and y directions, respectively.

Interfacial friction factor (f_i) can be defined as seen in Equation 4.

$$f_i=\frac{8\tau_i}{\rho V_1^2} \quad (4)$$

Where;
V_1 is the average freshwater velocity.
Using equation of motion f_i can be calculated (See Equation 3).

$$f_i = \frac{T_i}{\rho V_o^2} = \left\{ \frac{\left[\left(\frac{\Delta\rho}{\rho}\right) g\, h_{so} + 2\beta\left(1+\frac{\Delta\rho}{\rho}\right)\varepsilon^2 V_{1o}^2\right] h_{1o}\,\overline{h_1} - 2\alpha\, h_o\,\overline{h_s}\, V_o^2}{2V_o^2\, h_{1o}\,(\lambda\,\overline{h_1} + \overline{h_s})} \right\} \frac{h_{so}}{L_o}$$

$$+ \frac{0.0559}{b^{1.25}} h_o^2 \left(\frac{\nu}{V_o h_o}\right)^{0.25} \left[\frac{\overline{(b+2h_1)^{0.25}}}{h_1}\right] \frac{\overline{h_s}}{(\lambda\,\overline{h_1} + \overline{h_s})} \qquad (5)$$

Where;
b is the channel width.
β is the Monin-Obukov constant.
V_o is the velocity of the fresh water before salt wedge.
h_o is the height of the fresh water layer.
V_{1o} is the average freshwater velocity of the upper layer at the ocean end of channel.
h_{1o} is the height of the fresh water layer at the ocean end of channel.
h_{so} is the height of the saline water layer at the ocean end of channel.
L_o is the critical length.
T_i is the average value of τ_i (interfacial shear stress).
α is the momentum correction coefficient assumed to be constant and independent of x.
$\overline{h_1}$ is the mean fresh water height in partial intrusion zone.
$\overline{h_s}$ is the mean saline water height in partial intrusion zone.
V_1 is the average fresh water velocity.
V_i is the velocity at the interface.
ε is V_i / V_1
Using equation of motion for τ_0=0, fi can be calculated (See Equation 4).

$$f_i = \frac{T_i}{\rho V_o^2} = \left[\frac{\left(\frac{\Delta\rho}{\rho}\right) g\,\overline{h_1}\, h_{so}}{2V_o^2\, h_o} - \frac{\alpha\,\overline{h_s}}{h_{1o}} \right] \frac{h_{so}}{L_o} \qquad (6)$$

Finally, one dimensional energy equation developed by Schijf and Schoenfeld states that the average interfacial friction factor is:

$$\overline{f_i} = \frac{2\,h_o}{L_i} = \left[\frac{1}{5(F_o')^2} - 2 + 3(F_o')^{2/3} - \frac{6}{5}(F_o')^{4/3} \right] \qquad (7)$$

Where;
F_o' is the densimetric Froude number ($V_o / \sqrt{\Delta\rho/\rho\, g\, h_o}$).
L_i is the maximum salinity intrusion length.
In an experimental study, interfacial friction coefficients were determined by direct measurements of Reynolds stresses through a hot film anemometer. The values of f_i that are determined by the integration of the equations of motion (See Equation 5) are closely agreed with the experimental measurements. Interfacial friction factor (f_i) was calculated using mentioned four approaches and the results were plotted in Figure 17.

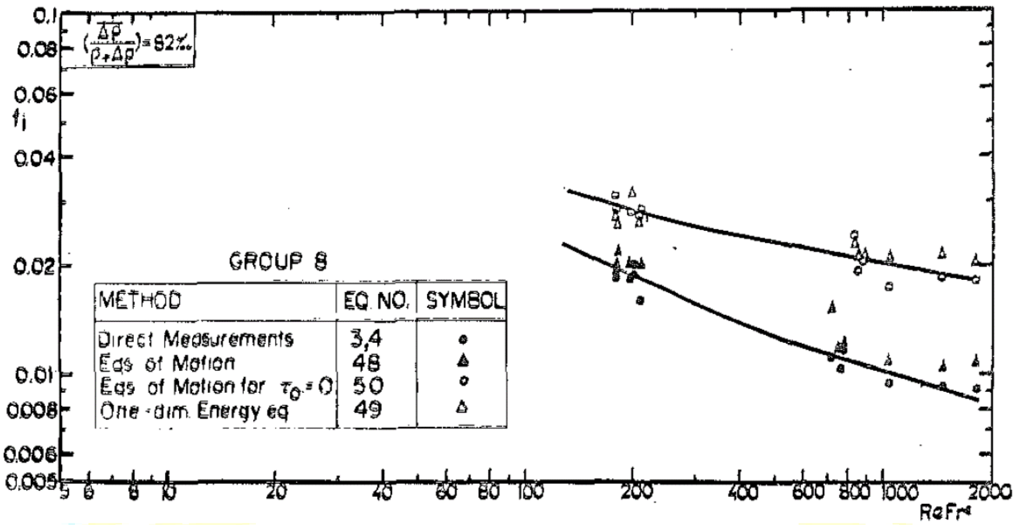

Figure 17. Interfacial friction coefficients, f_i, for $\Delta\rho/(\rho + \Delta\rho) = 0.0820$ [19].

Experimental results shows that the salinity distribution around the interface can be defined using Equation 8. See Figure 18 for the definition of interfacial zone.

$$\frac{\rho_l - \rho}{\Delta\rho} = \frac{1}{2}\left[1 - \tanh\left(\frac{y - h_s}{\frac{\delta}{2}}\right)\right] \qquad (8)$$

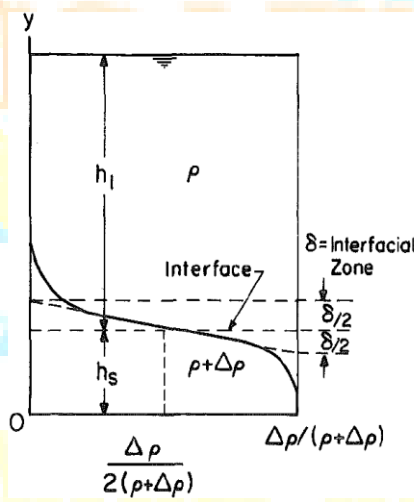

Figure 18. Definition of interfacial zone [19].

Nakai and Arita [20] developed a method for the prevention of saline wedge intrusion. In their experiments the two parameters A/B and A/R were used to define conditions: A represents the buoyancy due to an air curtain, B stands for the intrusion force of a saline wedge. R shows the inertial force of a fresh water flow [20]. They also introduced a new parameter called α that is defined by (A/B)/(A/R). Saline wedge intrusion into rivers causes water intake troubles hence it damages the agriculture in neighboring regions [20]. Similar problem is seen in The Melen Estuary. In order to solve this problem the intrusion length of saline wedges should be shortened. Therefore the oxygen concentration in the river water will increase by dissolving of air bubbles. An air curtain seriously affects the saline wedges in a channel. Behavior of air curtains can be classified into the three types (See Figure 19).

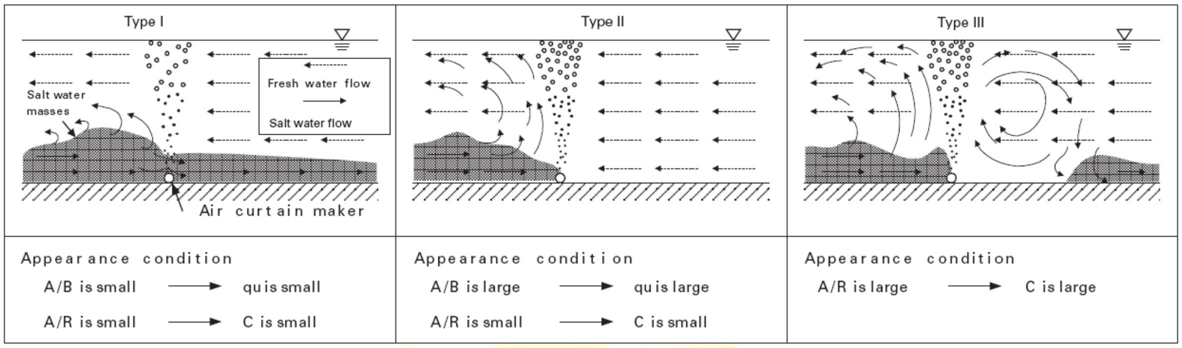

Figure 19. Flow type classification [20].

Another prevention method could be the saltwater barrier sill. A sand sill can arrest the salt wedge intrusion. There are some examples for this method throughout the world. In Mississippi River, US Army Corps of Engineers applied a saltwater barrier sill against salt water intrusion (See Figures 20 and 21).

Figure 20. Mississippi River and the location of the saltwater barrier sill [21].

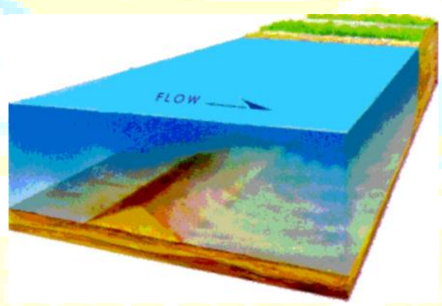

Figure 21. Saltwater sill in the Mississippi River [21].

The density difference between fresh river water and the seawater itself causes the penetration of sea water up to the river in the form of a saline wedge. There are three main factors which cause mixing and dispersion in estuaries. These are the tide, the river and the wind [22, 23].

According to Hettiarachchi [22] prevention of salt water intrusion is possible if the flow control structures are used. These structures should have automatic or manual control systems. Estuary number is another classification for the estuaries [2]. Tide and the river discharge are the most effective factors that have an influence on the estuary character and this influence can be defined using a number called Canter-Cremers. According to Aerts et al. [24] Canter-Cremers number or “mixing parameter” [22] equals to the ratio between the amount of entering fresh and saline water during a tidal period (See Equation 9).

$$N = \frac{Q_f T}{P_t} \quad (9)$$

Where;
N is the Canter-Cremers number (mixing number).
Q_f is the fresh water discharge.
T is the tidal period.
P_t is the saline water volume (Volume of the tidal prism).
0.1 > N > 0 mixed estuary
1.0 > N > 0.1 partially mixed estuary
N > 1.0 stratified estuary.
Another important estuary number is Richardson number. Fischer et al. [25] defined this number as the ratio of the potential energy provided by the river discharge (See Equation 10).

$$N_R = \frac{\Delta\rho}{\rho}\frac{gh}{v^2}\frac{Q_f T}{P_t} \quad (10)$$

Where;
$\Delta\rho$ is the difference in density between fresh and salty water or river and the sea water.
ρ is the density of fresh river water.
g is the acceleration of gravity.
v is the tidal velocity.
h is the channel height.
$\Delta\rho\, g\, Q_f$ is the term for buoyancy.
Equation 10 can also be written as seen in Equation 11.

$$N_R = \frac{\left(\frac{\Delta\rho}{\rho}\right) g\, Q_f}{W v^3} \quad (11)$$

Where;
W is the channel height.

If the Richardson number is low, kinetic energy in tidal currents mix the river and sea waters. Therefore estuary is well mixed. Richardson number incorporates the effect of the relative density difference between fresh water, seawater and the Froude number. Celerity of the wave can be defined as the square root of the gravity force and the height of the wave (See Equation 12).

$$c_0 = \sqrt{(gh)} \quad (12)$$

or according to Blanton et al. [26];

$$c = \sqrt{\left(g\left(\Delta\rho/\rho_0\right)d_1\right)} \quad (13)$$

Where;
d_1 is the depth of the buoyant layer.
$\Delta\rho/\rho_0$ is the density deficit of the buoyant water.
Flood current speed is u, when c=u, seawater plunges below an arrested wedge of the estuary [26]. As seen in Equation 14. Froude number is defined as the ratio between the tidal velocity and the celerity.

$$F = \frac{v}{c_0} \qquad (14)$$

Atkinson [27] stated that buoyant jet with a sloping bottom is very original topicf among the jet studies (See Figures 22 and 23). For instance in Melen Estuary Buyuk Melen River discharges into the Black Sea and buoyancy is occured due to the temperature and the salinity differences. According to the observations a jet attaches when the discharge Froude number, F_0, is greater than about 2.5, and when bottom slope, S, is less than about 15 % [27]. F_0 was defined by Atkinson as seen in Equation 15.

$$F_0 = \frac{U_0}{\left(g_0^{'} h_0\right)^{1/2}} \qquad (15)$$

Where;

$g_0^{'} = \mathrm{g}\left(\rho_\mathrm{a} - \rho_0\right)/\rho_\mathrm{a}$, reduced gravity at the outlet.

g = gravitational acceleration.

$As = h_0 / 2b_0$ is the aspect ratio of the jet discharged (fresh water).

Where;

h_0 is the depth of the buoyant jet (fresh water).

b_0 is the half width.

$$F_0^{'} = \frac{M_{f_0}^{5/4}}{B_0^{1/2} Q_0} \frac{U_0}{\left(g_0^{'} A_0^{1/2}\right)^{1/2}} \qquad (16)$$

Where;

$F_0^{'}$ is modified Froude number ($F_0 \, As^{1/4}$)

As is discharge aspect ratio ($h_0 / 2b_0$)

$A_0 = 2b_0 h_0$ is cross sectional area.

$M_{f_0} = U_0 Q_0$ is three dimensional discharge kinematic momentum flux.

$B_0 = g_0^{'} Q_0$ is three dimensional buoyant flux.

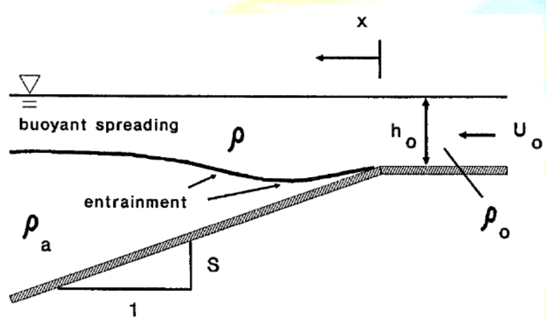

Figure 22. Buoyant surface discharge on a sloping surface.

Ratio between the entrainment flow and the (two dimensional) discharge is defined according to the dimensional analysis (see Equations 9 and 10).

$$\frac{Q_e}{Q_0} = f\left(F_0, F, \theta\right) \qquad (17)$$

or

$$\frac{Q_e}{Q_0} = f\left(\frac{Q_0 B_0^{1/3}}{M_0}, \frac{h}{L_s}, \theta\right) \tag{18}$$

Where;

$B_0 = U_0 g_0^{'} h_0$ is discharge buoyancy flux.

$M_0 = U_0^2 h_0 + 0.5 g_0^{'} h_0^2$ is the flow force.

$\theta = \tan^{-1} S$

$\frac{M_0}{B_0^{1/3}}$ represents the discharge scale.

$L_s = \frac{M_0}{B_0^{2/3}}$ represents a buoyancy length scale for two dimensional flow.

Property of interest (ϕ) is going to be a function of the parameters shown in Equations 19 and 20.

$$\phi = f\left(x, h_o, b_o, U_o, g_o^{'}, S\right) \tag{19}$$

or

$$\phi = f\left(x, M_o, B_o, Q_o, h_0, S\right) \tag{20}$$

If M_o and B_o are selected as repeating variables, and a bottom friction factor f_b is added for generality, for the case $\phi = h_d$ the Equation 20 becomes;

$$\frac{h_d}{L_s} = f\left(\frac{x}{L_s}, \frac{Q_o}{L_s \zeta}, \frac{h_0}{L_s}, S, f_b\right) \tag{21}$$

Where;

S is the bottom slope.

f_b is the friction factor.

$L_s = \frac{M_0^{3/4}}{B_0^{1/2}}$ represents a buoyancy length scale for three dimensional flow.

Since $\frac{Q_o}{L_s}$ and $\frac{h_0}{L_s}$ are the functions of As and F_0 for the three dimensional flow;

$$\frac{h_d}{L_s} = f\left(F_0, As, S, f_b\right) \tag{22}$$

$$\frac{h_d}{L_s} = 0.04 \frac{S^{0.65}}{F_0\, As^{0.15}\, C_D^{0.55}\, \alpha_j} \tag{23}$$

Where;

α_j is the jet entrainment coefficient.

C_D is the drag coefficient.

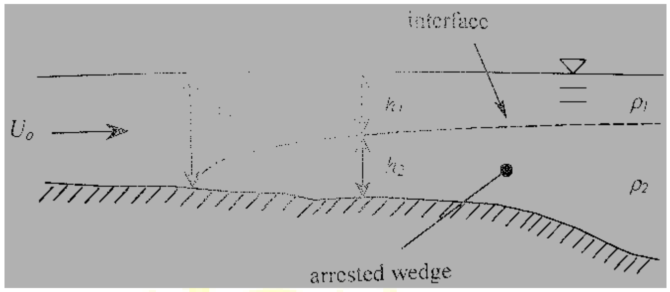

Figure 23. Arrested density wedge [28].

According to Rubin and Atkinson [28] interface position can be defined by the following equation;

$$\frac{dh_1}{dx} = -\frac{\frac{f_i}{8} Fr_1^2 \left(1 + \frac{\rho_1 h_1}{\rho_2 h_2}\right)}{1 - Fr_1^2} \qquad (24)$$

Where;

f_i is the interface friction factor.

From conservation of mass;

$$\rho_d \, Q_d = \rho_0 \, Q_0 + \rho_a \, Q_e \qquad (25)$$

Where;

$Q_d = 2U_b b_d h_d$ is the discharge at the detachment point.

U_d is the corresponding velocity.

b_d is the corresponding half width.

h_d is the height at the detachment point.

Entrainment value for volumetric flow rate (Q_e) is;

$$Q_e = 2\int_0^{(x_d / \cos\theta_b)} (u_e h) dx = 2u_e \frac{x_d}{\cos\theta_b}\left(\frac{h_0 + h_d}{2}\right) \qquad (26)$$

Where;

u_e is the corresponding velocity.

θ_b is the side angle.

Since $x_d = (h_d - h_0)/S$;

$$Q_e = u_e \left(\frac{h_d^2 - h_0^2}{S \cos\theta_b}\right) \qquad (27)$$

The mass conservation statement can be solved for the detachment velocity (U_d) and density at the detachment point (ρ_d);

$$U_d = U_0 \left(\frac{\rho_0 b_0 h_0}{\rho_d b_d h_d}\right) + \left(\frac{\rho_a u_e}{2 \rho_d b_d h_d}\right)\left(\frac{h_d^2 - h_0^2}{S \cos\theta_b}\right) \qquad (28)$$

$$\rho_d = \frac{2\rho_0 b_0 h_0 + \rho_a u_e \left(\frac{h_d^2 - h_0^2}{S \cos\theta_b} \right)}{2U_d b_d h_d} \quad (29)$$

The forces and the momentum fluxes can be seen in Figure 24. If the momentum equation is considered, it can be written as follows;

$$-\tau_0 A\cos\theta = \rho_d M_{fd} - \rho_0 M_{f0} \quad (30)$$

Where;

$\tau_0 = C_D \rho U^2$ is the bottom shear stress (ρ and U^2) are the average values within the attached region.

$A = (h_d - h_0)(b_d + b_0)/S\cos\theta$ is the bottom area.

Then Equation 28 becomes;

$$-\frac{C_D}{4}\left(\frac{h_d - h_0}{S}\right)(\rho_0 - \rho_d)(U_0^2 + U_d^2)(b_0 + b_d) = 2(\rho_d b_d h_d U_d^2 - \rho_0 b_0 h_0 U_0^2) \quad (31)$$

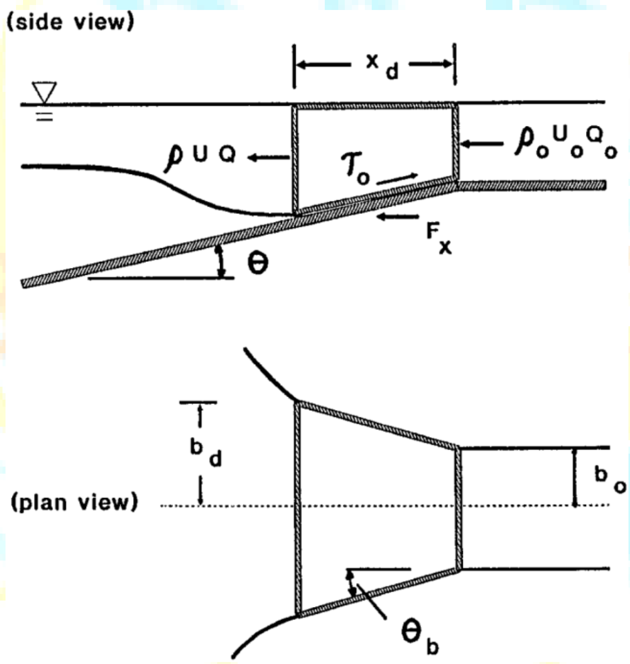

Figure 24. Control volume approach for evaluation of momentum equation [27].

Fouli and Zhu [29] described the salinity regime of a coastal plain estuary. It connects to the ocean through a flood tide delta that acts as a sill. Fouli and Zhu [29] investigated the transition of two-layer stratified flow from the slope of bottom topography to a horizontal channel (See Figure 25). The flow is modelled in a rectangular channel that has a bottom sill and connects two reservoirs of fluids with slightly different densities [29]. Figure 26 shows the time averaged concentration profiles.

$$G^2 = F_1^2 + F_2^2 \quad (32)$$

Where;

F_1^2 and F_2^2 are the densimetric Froude numbers for each layer (See Equation 15).

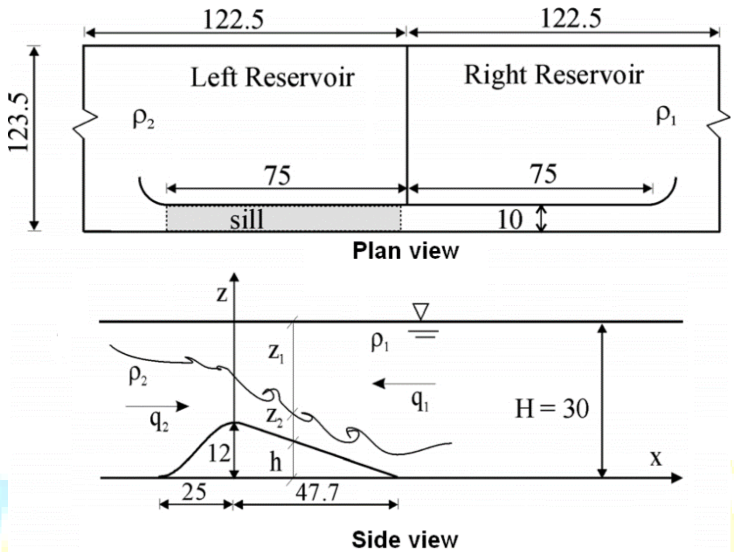

Figure 25. Schematic of the experimental set-up [29].

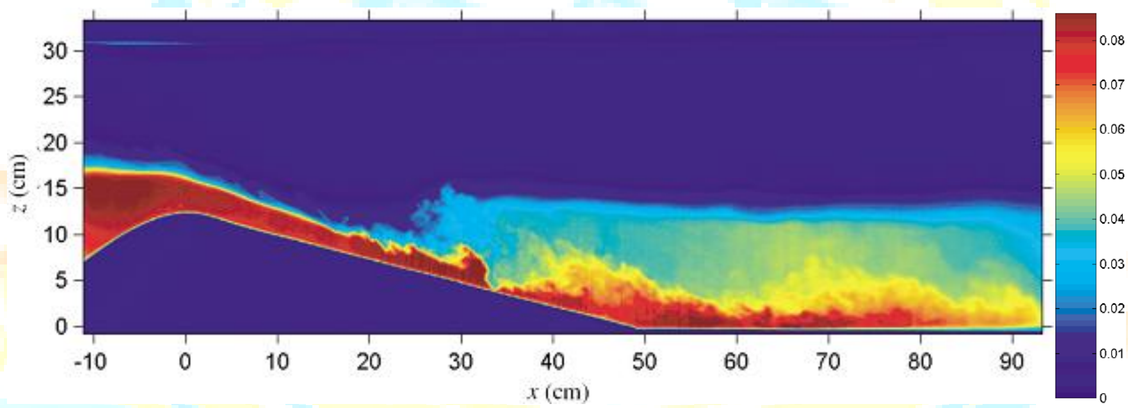

Figure 26. Time-averaged concentration profiles. The scale indicates concentration levels in μg/L [29].

Figure 27 shows the change in the composite Froude number through the channel. According to the experiments of [29], composite Froude number was found to drop gradually from $G^2 \approx 2$ along the slope to $G^2 \approx 0.6$ at $x \approx 75$ cm, beyond which it stayed almost constant. Hence, the flow transitions from super-critical conditions along the slope to sub-critical conditions within the channel in the lee of the topography and it is assumed that interfacial friction causes such a transition [29].

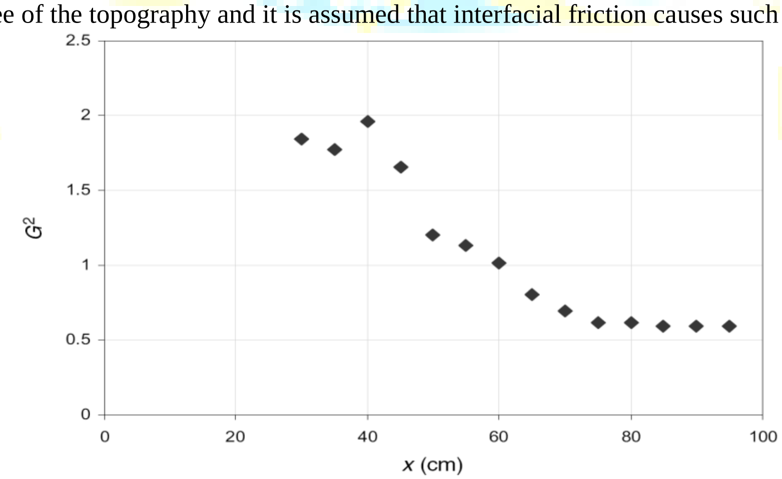

Figure 27. The spatial variation of the composite Froude number [29].

If $0.3 < F^2 < 1$, the seawater plunges on the sill; if $F^2 > 1$, the plunge point is landward of the sill in the case of a flood-tide delta. The withdrawal depth (h_b) in a basin of depth H_b flow going over a sill with depth H_s and velocity U_s is;

$$h_b = \frac{1}{2} H_s + \left[\frac{1}{2} H_s^2 + \frac{U_s^2}{N^2} \right]^{1/2} \qquad (33)$$

Where;

$$N^2 = g\,\Delta\rho / \rho H_b$$

The latter parameter ($\partial S / \partial x$) estimation using the salt balance equation:

$$\frac{\partial S}{\partial t} = -U \frac{\partial S}{\partial x} \qquad (34)$$

According to Nguyen [14] the movements of salt in the estuary can be presented by the advection-dispersion equation:

$$\frac{\partial S}{\partial t} + \bar{u} \frac{\partial S}{\partial x} = \frac{1}{A} \frac{\partial}{\partial x} A D \frac{\partial S}{\partial x} \qquad (35)$$

Where;

D (L^2T^{-1}) is the effective longitudinal dispersion coefficient.

A is the cross section area.

$\bar{u} = \nu \sin(\omega \mathrm{t})$

$\omega = 2\pi / T$

υ (LT^{-1}) is the tidal velocity.

3. Conclusions

A considerable amount of nutrient pollution is observed apparently in the Melen Estuary. Among people this is mainly due to hazelnut agriculture in the catchment area of the watershed. Also, there is a mass settlement area where there is improper or no infrastructure. However, more robust analysis is needed in order to understand the phenomenon occurred in the estuary. This research is planned to be divided into two parts. The first part will be the hydrodynamic analysis of the estuary. In this part changes in the sea water and the fresh water profile in the estuary is going to be predicted. And the second part will be the water quality analysis. At this point the effects of nonpoint sources and the Black Sea on the water quality of the estuary is going to be researched.

In particular, it is planned to concentrate on salinity changes at the freshwater**.** What should be the minimum amount of the water released from the regulator to the estuary in order to let the habitat survive? Hydrodynamic analysis of the estuary will be dealt with to see what could be the position of salty water in different cases. Considerable land base pollution due to diffused sources is expected. Hence, nutrient dynamics will also be investigated. Contribution of sea water intrusion for the nutrient dynamics will be ascertained.

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