AMBIENT CURRENT EFFECTS ON VERTICAL SELECTIVE WITHDRAWAL IN A TWO LAYER SYSTEM

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Ambient Current Effects on Vertical Selective Withdrawal in a Two Layer System

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ABSTRACT

The study examined the way in which the selectivity of flow withdrawal into a vertically suspended, upper strata point sink is affected by an ambient current in a two layer system. The results of this study show that an ambient current will influence the selectivity of a withdrawal flow, though the magnitude of the influence is small and is partially masked by the generation of interfacial gravity waves. If such waves can be excluded, then an ambient current would be expected to enhance the phenomenon of selective withdrawal. The generation of interfacial waves may be a more important consequence of an ambient current than its influence on the degree of selectivity; especially as the interfacial waves relate to the subsequent structure of the flow field.

The results also show that within a range of separating heights of the intake from the interface, the degree of selectivity is a quasi-linear function of the separating height. Of special interest is the observation that the defined degree of selectivity approaches unity slowly after passing a critical value of the separating height. The influence of the density difference across the interfacial region is negligible when the intake is close to the density-interface, but increases in importance as the separating height is increased.

Introduction

This study examined the way in which the selectivity of flow withdrawal into a vertically suspended, upper strata point sink is affected by an ambient current in a two-layer system. The goals were:

1. to determine whether the presence of an ambient current inhibits the possibility of significant selective withdrawal, and

2. to determine the magnitude of the bias of the withdrawal flow for conditions other than those of complete selectivity.

The experimental design is shown in Figure 1.

Withdrawal from a stratified flow field is of practical interest and has been seriously studied since 1949 (Craya). Selective withdrawal applications are primarily found in the practice of reservoir management and in the maintenance of recirculating water for thermal energy plants and industrial users. Selectivity refers to the ability of the impressed flow to draw water in of desired quality, in preference to water from regions not having desired quality. The parameters most often controlled through selective withdrawal are temperature and dissolved oxygen; though properties such as turbidity, taste and odor caused by reservoir plant growth, salinity concentrations, and fertilizer and pesticide residues may also be considered.

Literature concerning selective withdrawal has been reviewed by Harleman 1961, and Yih 1965, in which critical conditions for fully-selective withdrawal are given for various flow regimes and withdrawal structures. The published theoretical and laboratory studies of Craya 1949, Gariel 1949, Harleman, et al 1959, Yih 1958, Debler 1959, Huber 1960, Kao 1965, and Koh 1966, are often cited as references for design of withdrawal structures (King 1969). However, these studies give consideration to only the fluid motion induced by the sink demand - i.e. an ambient current is not considered as a parameter. In marine environments and along the shores of streams and estuaries, ambient currents almost always exist, which might significantly influence the withdrawal phenomenon. Questions have been raised concerning the possiblity of selective flow being significantly altered from the presence of an ambient current.

Investigation

The experimental design (shown in Figure 1) used in this study is similar to that of Davidian and Glover (subsequently reported by Rouse 1956). They examined the critical conditions at which withdrawal from the lower layer of a two-layer system was initiated. In one set of experiments an air-water interface was used, while in a second set, conditions at a tap water-salt water interface were investigated. Their experimental results were presented in terms of densimetric Froude number measuring the relative inertial to gravitational forces in the flow. The expression for critical conditions given by Rouse is:

$$\frac{V}{\sqrt{g \frac{\Delta\rho}{\rho} D}} = 5.67\ (Z_c/D)^2$$

where V is the average flow velocity at the intake mouth, g is the gravitational acceleration, $\Delta\rho$ is the change in density measured across the interfacial region,

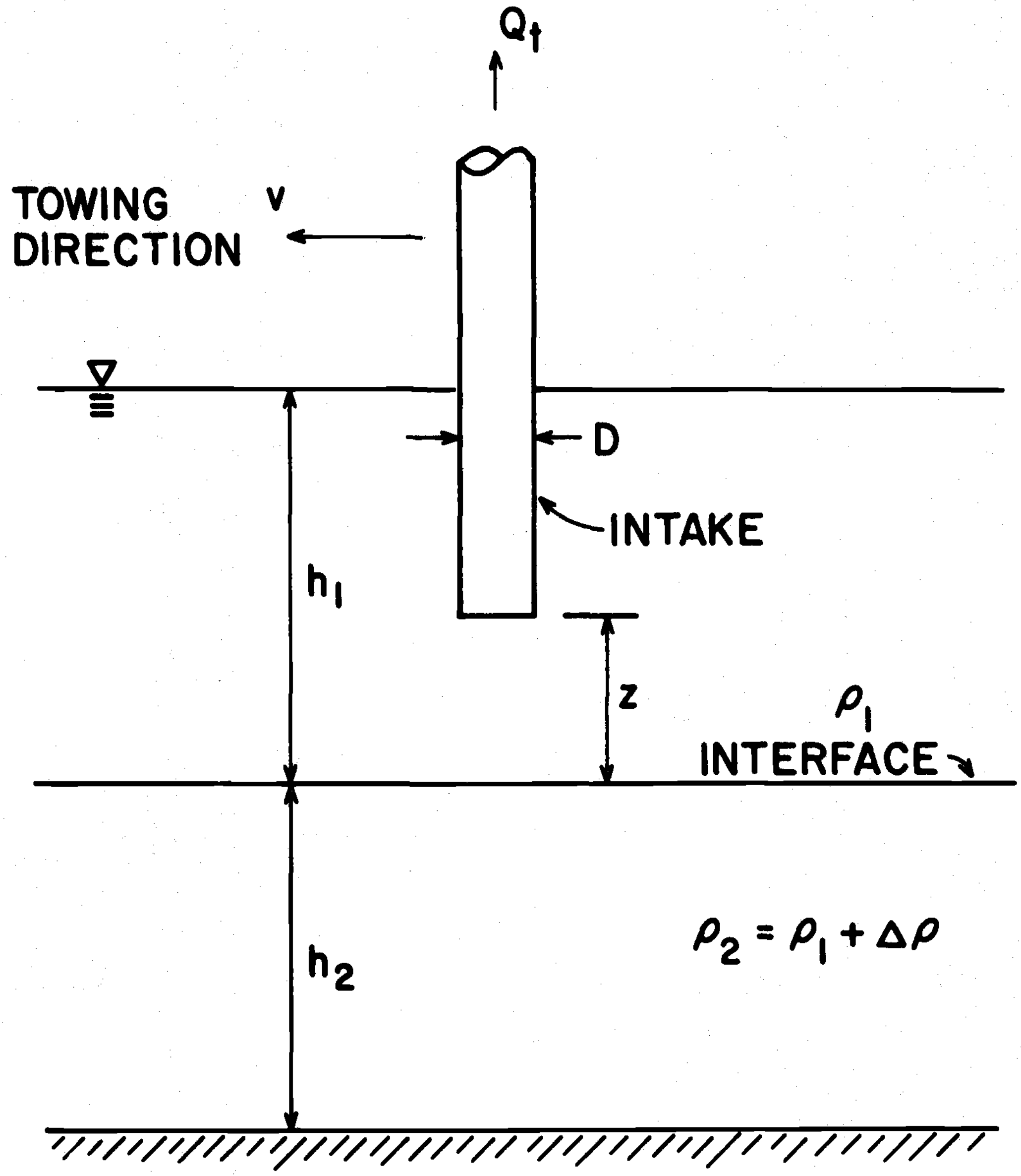

Figure 1. Experimental Design.

ρ is the density of one of the layers (or their average density), D is the diameter of the intake, and z_c is the critical separating height between the density-interface and the intake. For a specified set of conditions, when the separating height, z, is greater than z_c the withdrawal flow is fully-selective. When z is less than z_c the withdrawal flow occurs from both layers and the magnitude of the bias depends mainly on the value of z.

Method of Analysis

A withdrawal flow is defined as selective if it shows a bias in favor of one layer or region over another. Further, the magnitude of the bias is defined as the degree of selectivity. An estimator of the relative magnitude of the flow from each layer is needed. If conditions are such that each layer may be considered homogeneous; the density of a withdrawal sample will serve as an estimator of the selectivity of the flow. Letting Q_t represent the withdrawal rate and Q_1 and Q_2 represent the discharge from the upper and lower layers, respectively; then the continuity relation can be expressed as:

$$Q_t \rho_s = Q_1 \rho_1 + Q_2 \rho_2$$

and

$$\frac{Q_1}{Q_t} = \frac{\rho_2 - \rho_s}{\rho_2 - \rho_1}, \quad \frac{Q_2}{Q_t} = \frac{\rho_s - \rho_1}{\rho_2 - \rho_1}; \qquad (2)$$

where, ρ_1, ρ_2, ρ_s are the densities of the upper and lower layers, and the withdrawal sample, respectively. Knowledge of the ρ_1, ρ_2 and the average density of the withdrawal flow allows comparison of the bias with selected withdrawal conditions.

Flow visualization: Various techniques of flow visualization were utilized. For many stratified flow tests the lower layer was dyed using Erioglaucine A Supra; and in these cases the interface remained distinct and easily observable throughout the run. Wave motion was easily recorded, along with the motion associated with the intake cone. During a number of tests a dyed, immiscible solution of carbon tetrachloride and benzene was used and adjusted to a density between that of the upper and lower layers. If the solution was introduced beneath the surface with a syringe, spheres formed which fell to the level of the density discontinuity to remain on the level at which they were neutrally buoyant. During their subsequent transit by flow disturbances, time-lapse photography could be used to attain an instantaneous indication of the streamlines of the flow field. Also, if dye droplet solutions of slightly differing densities were used, interfacial shear could be observed. Another technique for showing interfacial shear was to drop crystals of potassium permanganate through the horizontal stratified layers. Dye streaks were left and the subsequent flow distorition of the vertical dye streaks would give representation of the velocity profile.

Experiment and Procedure

The experimental equipment consisted primarily of a cylindrical intake structure mounted on a towing bar located over the surface of an open tank. The withdrawal conditions used for analysis had intake diameters, D, of 3.175 and 2.54 centimeters and discharges, Q_t, of 1300 and 1220 cubic centimeters per second, respectively, The intake hose connected with a pump and regulatory valve, and finally to a drain (or second tank). The ambient current was simulated relatively by towing the intake structure over the surface of the water. The set-up is shown in Figure 2. In all cases, the upper fluid was tap water and the lower fluid a saline solution.

A two-layer system was obtained by introducing the heavier fluid beneath the one of less density. The saline solution was mixed in a separate tank and introduced into the flume through two standpipes. The salt solution, being of greater density than tap water already in the flume, spread beneath the upper fluid. As long as a very low flow rate was maintained, little mixing of the interfacial region would be experienced.

For each run, tests were made in a series of approximately equal separating heights, z. The intake structure allowed adjustment of z, which was set and a test performed with the intake held stationary. Tests were repeated at increasing speeds of towing, z being checked and recorded between each test. Adjustments were made when necessary. The observations taken during each test were:

1. determination of the interfacial height and intake elevation by a point-elevation caliper attached to the flume;
2. the surface elevation was read and recorded;
3. movies were taken of the impressed flow (on most tests); and
4. a sample of the withdrawal flow was taken for density determination.

Results and Discussion

1. Proximity and Density-differential Parameters - Zero Current

As would be expected under conditions with zero ambient current, the degree of selectivity was found to be greatly dependent on the proximity of the intake to the density-interface; measured by the variable z. See Figure 1. The correlation between the degree of selectivity and the intake-interface proximity may be examined in terms of a dimensionless relationship if z is divided by the critical value for identical conditions, z_c, as given by Rouse.

$$\frac{z}{z_c} = \frac{z}{0.474\left[\dfrac{Q_t}{\sqrt{g\,\dfrac{\Delta\rho}{\rho_1}}\,D}\right]^{1/2}} \qquad (3)$$

Values of z/z_c less than unity imply the density-interface is drawn to the intake; while values greater than unity suggest the interface does not reach the intake. Different mechanisms are expected to dominate the selectivity withdrawal flow, depending on the value of z/z_c relative to unity.

Figure 3 shows the experimental results of the degree of selectivity for values of the dimensionless proximity parameter, z/z_c. The data points differ in values of the density differential $(\Delta\rho/\rho)$, discharge (Q_t) and intake diameter (D); and were taken from tests with zero ambient current.

Linear regression techniques were applied to the data shown in Figure 3 and the corresponding results summarized in Table 1. The coefficient of correlation, R^2, a measure of the proportion of variation in the dependent variable (Q_l/Q_t) accounted for by the fitted equation, is given in the table. Expressions 1 and 7 from Table 1 are shown as curves A and B in Figure 3.

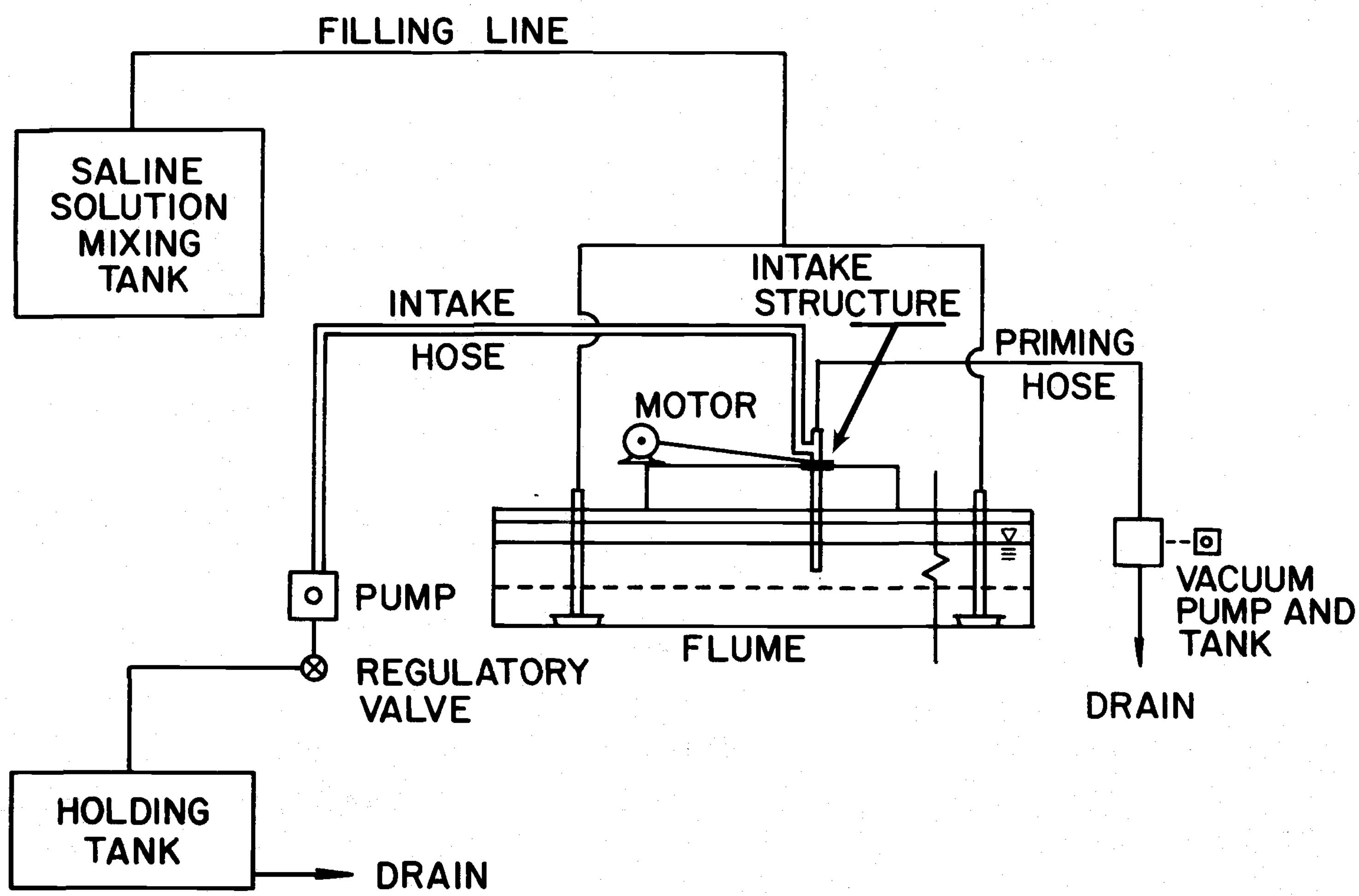

Figure 2. Experimental Set-up.

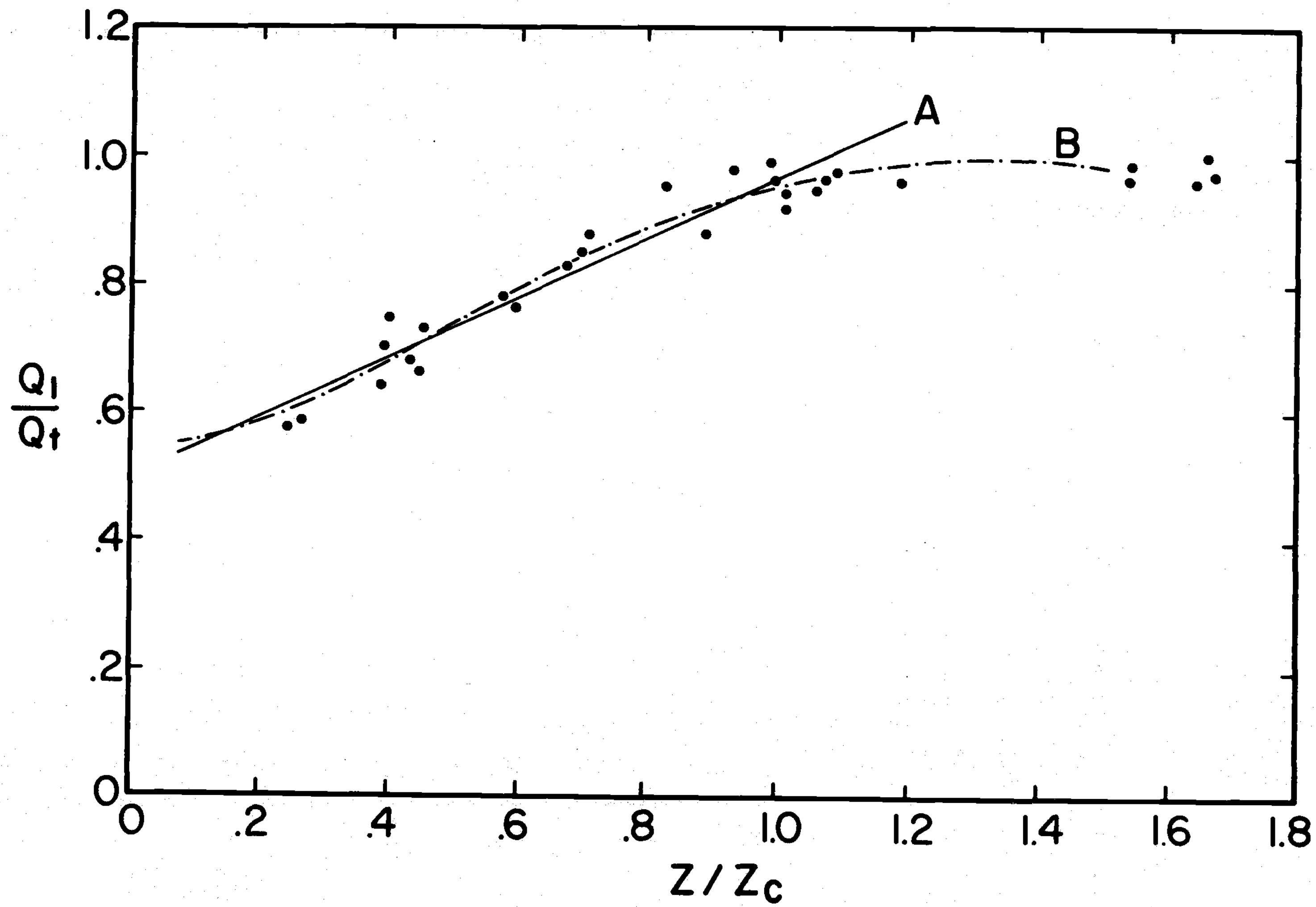

Figure 3. Relation of the degree of selectivity to the proximity parameter.

TABLE I

	DEPENDENT VARIABLE	INDEPENDENT VARIABLE(S)	DATA RANGE	REGRESSION EQUATION	R^2
1.	Q_1/Q_t	Z/Z_c	$0 \le \frac{Z}{Z_c} \le 1.0$	$Q_1/Q_t = .496 + .468\,(Z/Z_c)$	0.920
2.	Q_1/Q_t	$Z/Z_c, \Delta\rho/\rho_1$	$0 \le \frac{Z}{Z_c} \le 1.0$	$Q_1/Q_t = .468 + .472\,Z/Z_c + .605\,\Delta\rho/\rho_1$	0.932
3.	Q_1/Q_t	Z	$0 \le \frac{Z}{Z_c} \le 1.0$	$Q_1/Q_t = .549 + .0720\,Z$	0.742
4.	Q_1/Q_t	$Z/Z_c, \Delta\rho/\rho_1$	$0 \le \frac{Z}{Z_c} \le 1.0$	$Q_1/Q_t = .415 + .0840\,Z + 2.204\,\Delta\rho/\rho_1$	0.875
5.	Q_1/Q_t	Z/Z_c	$0 \le \frac{Z}{Z_c} \le 1.0$	$Q_1/Q_t = 0.41 + .723\,\tanh(Z/Z_c)$	0.945
6.	Q_1/Q_t	$Z/Z_c, \Delta\rho/\rho_1$	$0 \le \frac{Z}{Z_c} \le 1.0$	$Q_1/Q_t = .352 + .729\,\tanh(Z/Z_c) + .265\,(\Delta\rho/\rho_1)^{1/2}$	0.956
7.	Q_1/Q_t	Z/Z_c	$0 \le \frac{Z}{Z_c} \le 1.7$	$Q_1/Q_t = 0.639\,\mathrm{EXP}\left[1.93\tanh(Z/Z_c) - 1.07\,(Z/Z_c)^{1/2}\right]$	0.941
8.	Q_1/Q_t	Z/Z_c	$0 \le \frac{Z}{Z_c} \le 1.7$	$Q_1/Q_t = 0.916 + 0.038\,Z/Z_c$	0.252
9.	Q_1/Q_t	$\Delta\rho/\rho_1$	$0 \le \frac{Z}{Z_c} \le 1.7$	$Q_1/Q_t = 0.934 + .781\,\Delta\rho/\rho_1$	0.377
10.	Q_1/Q_t	$Z/Z_c, \Delta\rho/\rho_1$	$0 \le \frac{Z}{Z_c} \le 1.7$	$Q_1/Q_t = 0.882 + .818\,\Delta\rho/\rho_1 + .040\,Z/Z_c$	0.664
11.	$\Delta\rho/\rho_1$	$Q_1/Q_t, \Delta\rho/\rho_1$	$0 \le \frac{Z}{Z_c} \le 1.1$	$\Delta\rho/\rho_1 = -0.089 + .335\,Q_1/Q_t - .253\,\tanh Z/Z_c$	0.205

The regression analysis shows that within a range of separating heights of the intake from the interface ($0<z/z_c \leq 1.0$), the degree of selectivity is a quasi-linear function of the separating height. The product-moment correlation coefficients for Q_1/Q_t, z/z_c and Q_1/Q_t, z are .959 and .944 respectively. These high values of the correlation coefficients were obtained from data with values of the density differential parameter, $\Delta\rho/\rho_1$, ranging from 0.0160 to 0.0811. It is apparent that within this range of the proximity parameter ($0\leq z/z_c \leq 1.0$) the magnitude of the difference in densities between the layers is not important. Its influence is negligible when the intake is close to the density-interface, but increases in importance as the separating height is increased. Of special interest is the observation that the selectivity approaches unity slowly after passing a critical value of the proximity parameter.

Figure 4 shows the relation between the degree of selectivity of the withdrawal flow and the ratio of the cross-sectional area at the vena contracta of the withdrawal jet from the lower layer (A_c^*, the cross section where the withdrawal jet contraction is greatest) to the cross-sectional area of the intake, $\pi D^2/4$. This relationship is linear and the mentioned ratio might have been used as an estimator of the selectivity in place of the defined degree of selectivity; provided that z is less than critical.

The nature of the observed withdrawal flow is dependent on the value of z/z_c. When this parameter is less than unity the flow resembles potential flow into the intake and occurs from both layers. Typical withdrawal cones are shown in Figure 5. On the other hand, when the proximity parameter is greater than unity the region of then density-interface immediately beneath the intake is essentially a zone of stagnation with no appreciable fluid motion relative to the intake. The mechanism of withdrawal of the lower layer is similar to that discussed by Keulegan 1941 concerning the shear region between two fluids of varying degrees of dissimilarity with the upper layer flowing over a stationary lower layer. A number of mechanisms of density transport are associated with the various conditions of shear. Keulegan mentions the existence of a weak current in the lower layer flowing upward toward the interface. "In a sense, the boundary layer of the upper liquid acts as a pump, raising the small portions of the lower liquid to the level of the interface, then causing these portions to move horizontally." The vertical current is responsible for the decrease in the selectivity of the withdrawal flow when conditions suggest that the withdrawal should be completely selective. Although the density-interface never reaches the intake, part of the fluid from the lower region moves vertically upward into the flowing region of the upper layer and into the intake. Figure 6 shows the radial velocity as a function of the distance from the intake, measured just below and above the interface, and at an elevation half-way between the intake and the density-interface. It is of interest that the radial velocity just below the interface drops off rapidly near the intake.

2. Ambient Current

Series of tests with various speeds of towing of the intake were performed as part of the experiment to simulate ambient currents relative to the selective withdrawal intake. All tests in a series were made with approximately the same value of the proximity parameter. On most of these, the discharge through the pump was sampled to obtain a specimen for determining the degree of selectivity; also movies were taken of the flow field. Thus the observable motion could be determined and subsequently correlated with the degree of selectivity. The results of the analysis show that the presence of ambient currents significantly influence the selectivity of stratified flow withdrawal, though the influence is complex.

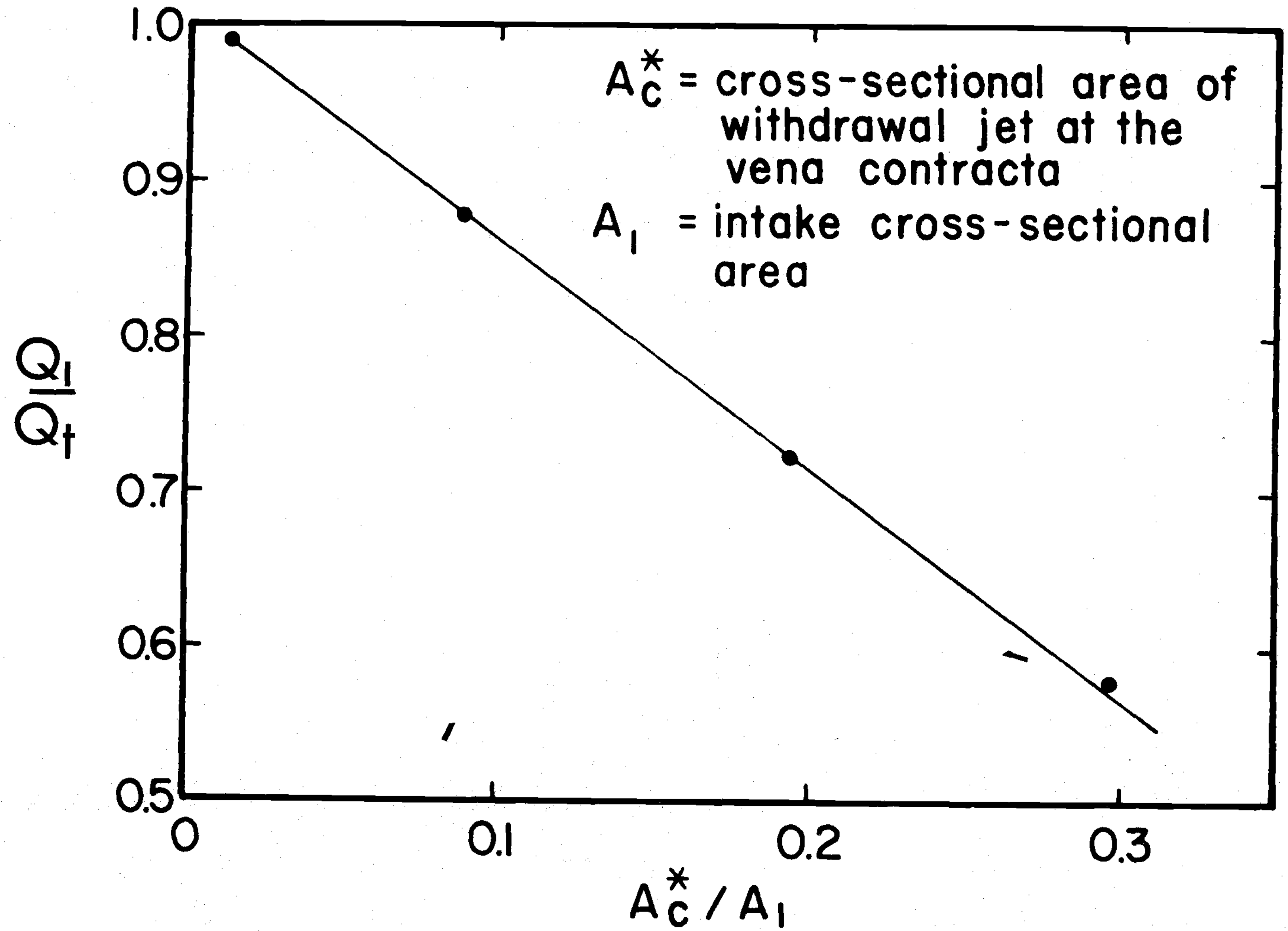

Figure 4. Relation of the degree of selectivity to the contraction coefficient.

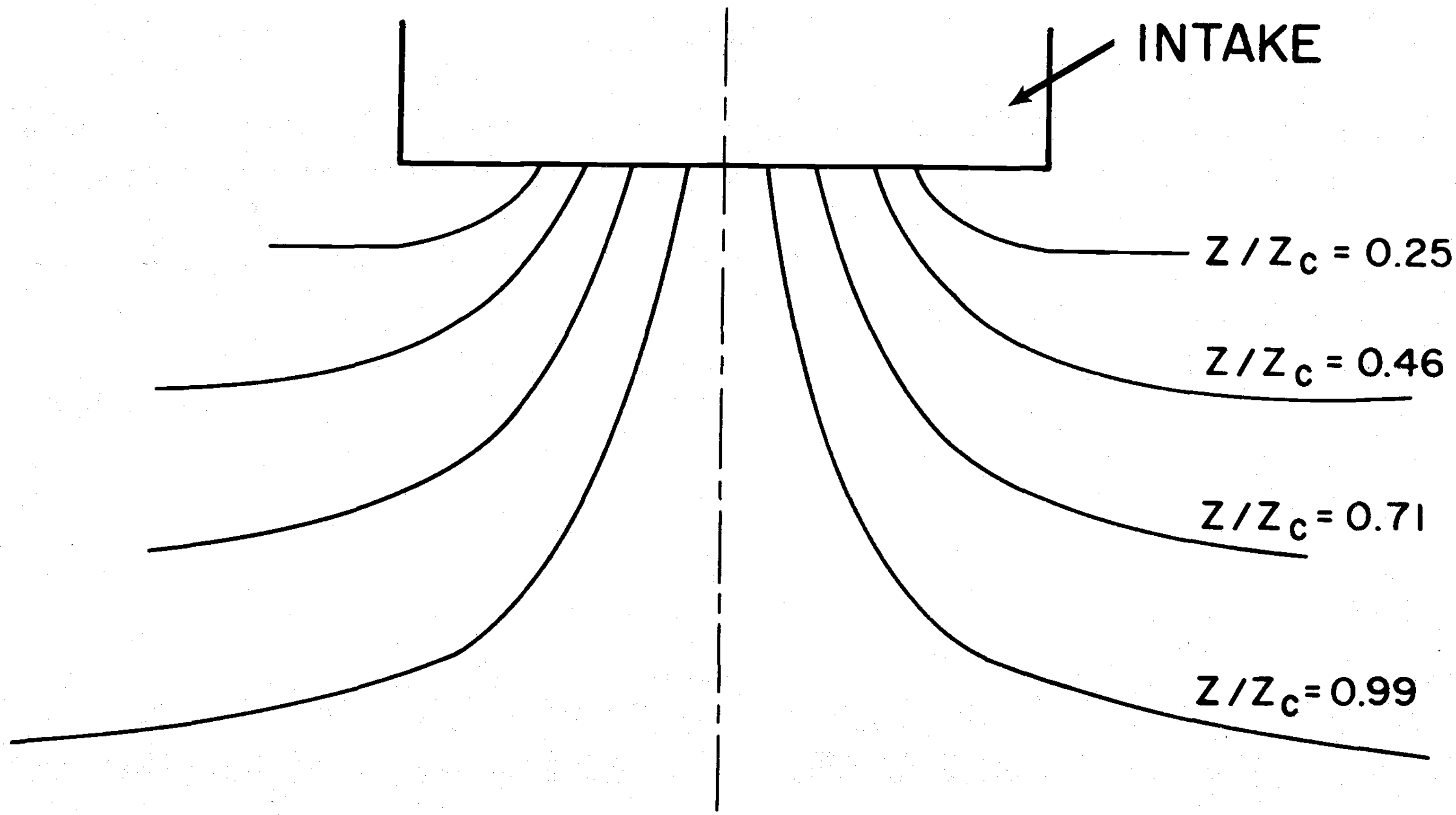

Figure 5. Typical withdrawal cones.

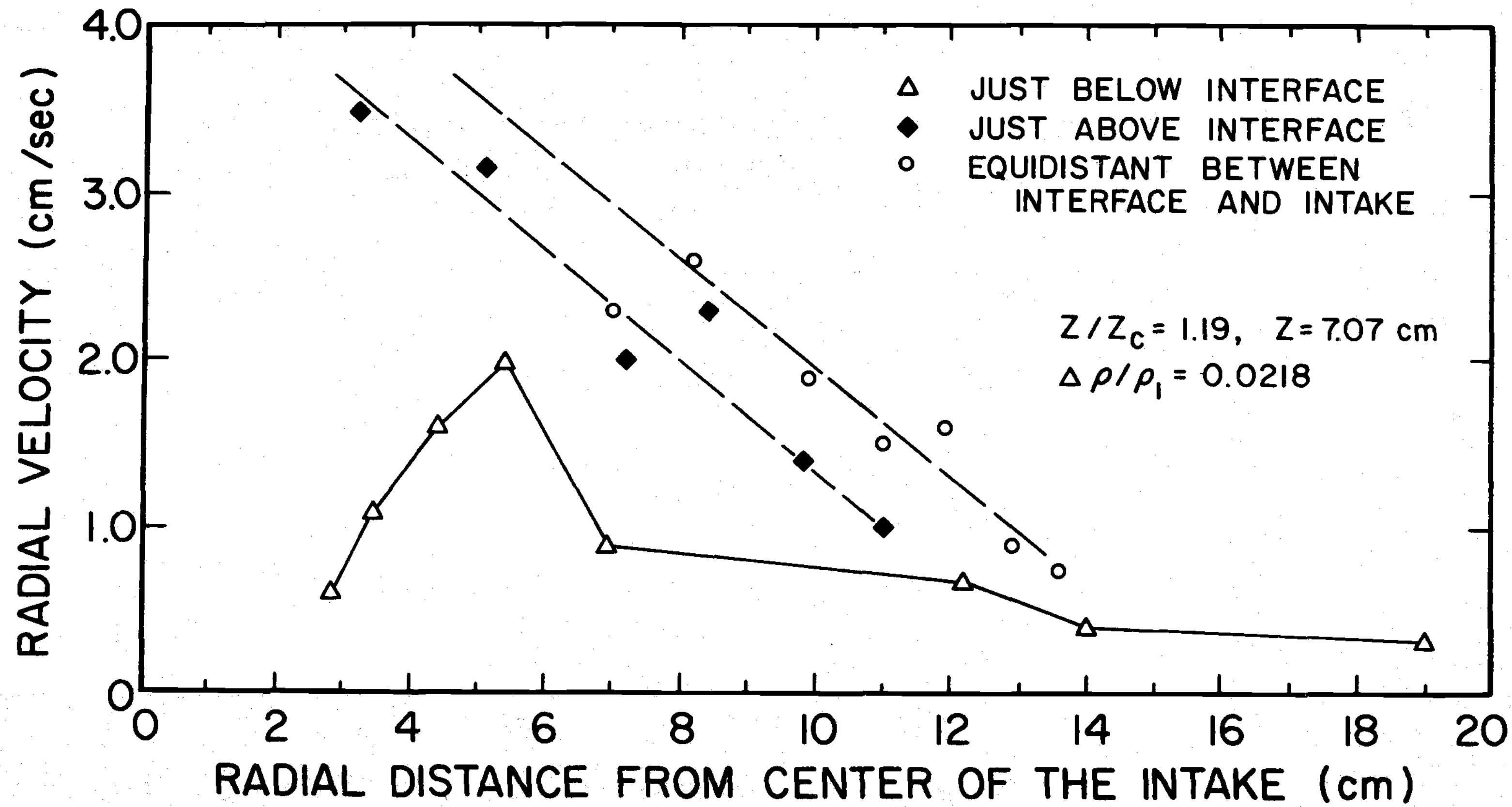

Figure 6. Relation of the radial velocity to the radial distance from the intake.

Generation of interfacial waves caused by moving intake (which acts as a moving low-pressure area) can both increase and decrease the selectivity of withdrawal. Generation of surface gravity waves by a moving low-pressure area has been discussed by Lamb 1945, and subsequently examined in the laboratory by Wiegel, Snyder and Williams, 1958. Wiegel, et al. observed that when the low-pressure area moved over the surface at a low velocity no waves were formed. Waves were generated when the velocity of the pressure area was increased: the amplitude of these waves increased with increases in the pressure area velocity as the shallow water wave velocity, $\sqrt{gh}$, is approached (h is the depth). Further increases in velocity resulted in decreases in the wave amplitude. The main feature of these water gravity waves was that they were essentially of constant period. The generated wave crests moved at the same speed as the low-pressure area. A wave train would trail the pressure area because the group velocity of gravity waves would be less than that of individual waves. The same type of characteristics were observed for the generated interfacial waves considered in the present study.

When the generated interfacial wave crest remains in the immediate vicinity of the intake the withdrawal selectivity decreases. As the current increases and the wave crest falls further behind the intake, the selectivity increases. For high velocity ambient currents the selectivity of the withdrawal flow is expected to be greatly enhanced, though the interfacial region behind the intake will be greatly disturbed. If such interfacial waves can be excluded, then an ambient current would be expected to allow the intake to draw more strongly from its own level of immersion.

The relationship between selectivity and the magnitude of the ambient current may be examined in terms of increases and decreases in the measured degree of selectivity relative to that expected under identical withdrawal conditions but with no ambient current. Figure 7-A shows such a relationship for a series having values for the density differential ($\frac{\Delta\rho}{\rho_1}$) and proximity ($\frac{z}{z_c}$) parameters of about 0.045 and 0.6, respectively. The range of the relative selectivity falls between 0.92 and 1.12, which corresponds to a measured degree of selectivity falling between 0.73 and 0.88. If this is broken down further, the range of the ratio of the discharge from the upper and lower layers (Q_1:Q_2) is 950:350 at a towing speed of 8.3 cm/sec. and 1150:150 at 21.5 cm/sec. (with Q_t equal to 1300 cc/sec.). The magnitude of the change in discharge ratio for changes in the velocity of towing increases for smaller values of the proximity parameter and decreases for larger values.

Figure 7-B shows the averaged response for various ranges of z/z_c, taken over all series of all runs. The regions showing decreased selectivity corresponded with observed large amplitude waves in the immediate viciinty of the intake, as seen in films of the tests. Increases in intake velocity resulted in having these waves located further behind the intake, and thus having less of an effect on the withdrawal flow. This corresponds to the increased selectivity at high velocities. It was interesting to note that when z/z_c was less than unity and a withdrawal cone was present, wave generation was damped. At high velocities the withdrawal cone became unstable and capillary sheading was observed. The largest waves were formed when z/z_c was slightly greater than unity. Under these conditions, if the velocity of the intake were high the interfacial region behind the intake would be greatly disturbed and mixing would occur.

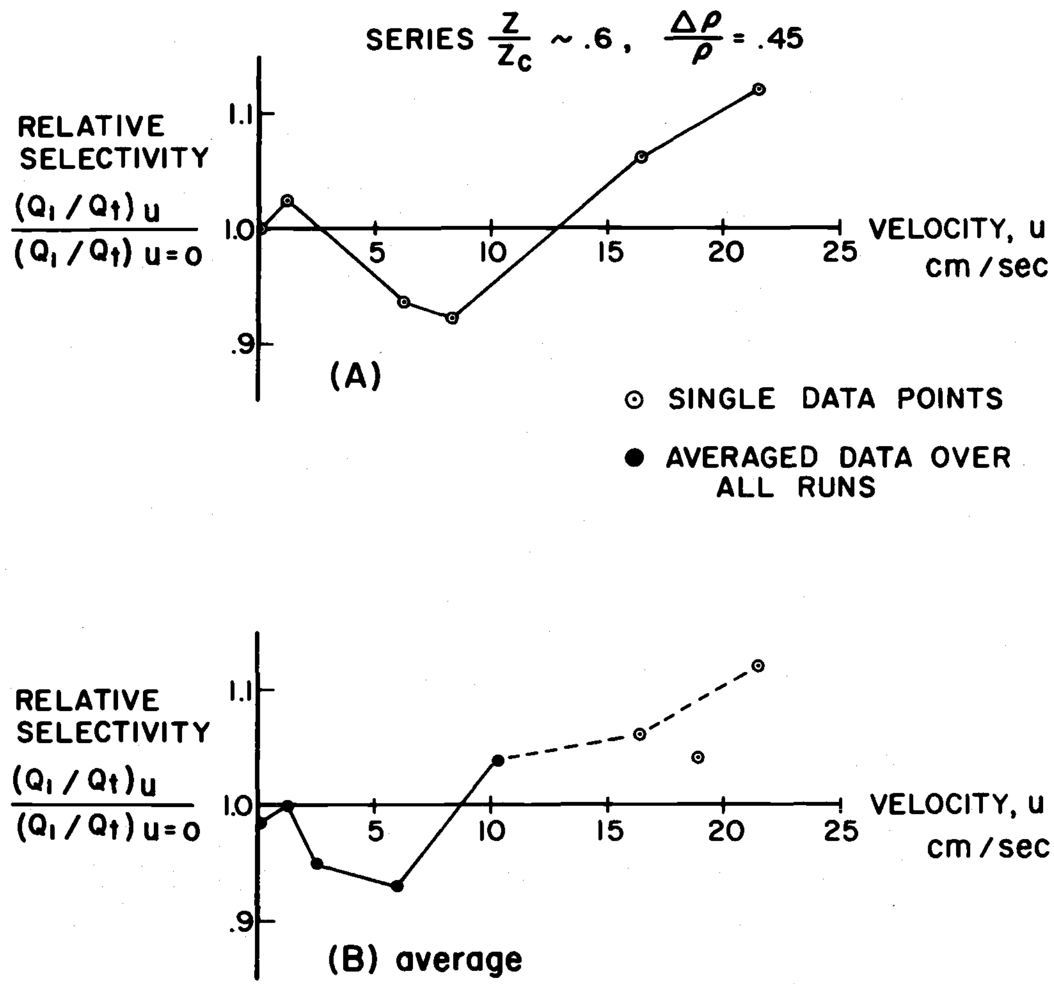

Figure 7. Relation of the <u>relative</u> degree of selectivity to the towing velocity.

Applications: thermocline:

The results of this study may be relevant to discussion on the stability of a thermocline in the vicinity of a withdrawal intake. Woods 1971 and Woods and Fosberry 1966 have discussed the structure of the thermocline in the sea as composed of alternating *sheets* having great temperature or density gradients and strong localized shear, and *layers* having much greater widths and much weaker static stability and shear. A feature of the sheets are long coherent trains of steep internal gravity waves. The strong shear at the crest of these waves has been observed to give Kelvin-Helmholtz instability. Woods has suggested that heat is able to penetrate the sheets spasmodically during the formation and decay of breaking waves (and the short lived patch of turbulence they produce). In this case, the presence of internal waves may influence the temperature differences across a given sheet and the subsequent structure of the thermocline.

In the presence of a withdrawal current, waves may be generated within these sheets as they are advected past the intake structure; and it is expected that the generated waves will have a large amplitude even when the thermocline is not within the boundary of the withdrawal flow. The number of breaking internal waves might increase, allowing for an increase in heat flux and subsequent decrease in stability. Thus, to insure the persistence of the thermocline structure and its stability in the presence of an ambient current, withdrawal intakes must be located at distances further from the thermocline than those suggested by previous investigations of the selective withdrawal phenomenon.

Conclusion:

The behavior of flow withdrawal into a vertically suspended, upper strata point sink was examined experimentally to invesitgate the influence of an ambient current. The results of this study show than an ambient current will influence the selectivity of a withdrawal flow, though the magnitude of the influence is small and is partially masked by the generation of interfacial gravity waves. If such waves can be excluded, then an ambient current would be expected to enhance the phenomenon of selective withdrawal. The generation of interfacial waves may be a more important consequence of an ambient current than its influence on the degree of selectivity; especially as the interfacial waves relate to the subsequent structure of the flow field.

The results also show that within a range of separating heights of the intake from the interface, the degree of selectivity is a quasi-linear function of the separating height. Of special interest is the observation that the degree of selectivity approaches the unity slowly after passing a critical value of the separating height. The influence of the density difference across the interfacial region is negligible when the intake is close to the density-interface, but increases in importance as the separating height is increased.

References

1. Craya, A., Theoretical Research on the Flow of Nonhomogeneous Fluids, La Houille, Blanche, 4, 1949.

2. Debler, W. R., Stratified Flow into a Line Sink, Proceedings, American Society Of Civil Engineers, Vol. 85, No. EM 3, July 1959.

3. Gariel, P., Experimental Research on the Flow of Nonhomogeneous Fluids, La Haouille, Blanche, 4, 1949.

4. Harleman, D. R. F., Stratified Flow, Handbook of Fluid Dynamics (ed. Streeter), Chapter 26, McGraw-Hill, 1961.

5. Harleman, D. R. F., Morgan, R. L., and Purple, R. A., Selective Withdrawal from a Vertically Stratified Fluid, 8th Congress, International Association for Hydraulic Research, August 1959.

6. Huber, D. G., Irrotational Motion of Two Fluid Strata Towards a Line Sink, Journal of Fluid Mechanics, Vol. 21, Part 3, 1965.

7. Kao, T. W., A Free-Streamline Solution for Stratified Flow Into a Line Sink, Journal of Fluid Mechanics, Vol. 21, Part 3, 1965.

8. Keulegan, G. H., Laminar Flow at the Interface of Two Liquids, Journal of Research of the National Bureau of Standards, Vol. 32, Research Paper RP1591, June 1941.

9. King, D. L., Hydraulics of Stratified Flow, Second Progress Report, Selective Withdrawal from Reservoirs, United States Department of the Interior, Bureau of Reclamation, Report No. Hyd-595, September 1969.

10. Koh, R. C. Y., Viscous Stratified Flow Towards a Sink, Journal of Fluid Mechanics, Vol. 24, Part 3, 1966.

11. Lamb, H., Hydrodynamics, 6th Edition, Dover Publications, New York, 1945.

12. Rouse, H., Seven Exploratory Studies in Hydraulics, Proceedings, American Society of Civil Engineers, Vol. 82, No. HY 4, August 1956.

13. Wiegel, R. L., Snyder, C. M., and Williams, J. E., Water Gravity Waves Generated by a Moving Low Pressure Area, Transactions, American Geophysical Unions, Vol. 39, No. 2, April 1958.

14. Woods, J. D., Micro-oceanography, Underwater Science (ed. Woods and Lythgoe), Chapter 9, Oxford University Press, 1971.

15. Woods, J. D. and Fosberry, G. G., The Structure of the Thermocline, Underwater Association Report, 1966-67.

16. Yih, C. S., On the Flow of a Stratified Fluid, Proceedings, 3rd U. S. National Congress on Applied Mechanics, 1958.

17. Yih, C. S., Dynamics of Nonhomogeneous Fluids, Chapter 3, The MacMillan Co., New York, N. Y., 1965.