TECHNICAL COMPLETION REPORT

OWRT Project Number A-050-Oklahoma

The Oklahoma Water Resources Research Institute

HYDRAULIC MODELING OF MIXING PHENOMENA IN STRATIFIED LAKES

Period: July 1973 to June 1975

by

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"The work upon which this report is based was supported in part by funds provided by the U. S. Department of the Interior, Office of Water Research and Technology, as authorized by the Water Resources Research Act of 1964."

Abstract

The objective of this research was to provide criteria for laboratory modeling of stratified lake flows. Consideration has been given to fluid inflows and to flows generated by a mechanical destratification device.

The inflow experiments were designed to investigate the effects of scale distortion since vertical scale exaggeration is necessary in laboratory size models, to offset the increased viscous forces that accompany the size reduction. Experiments were performed in two inflow lake models which are identical in horizontal dimensions but differ by a factor of two in the vertical dimensions. Density profiles and dye front flow visualization records were made of inflows over a range of flow parameters.

It was established that a vertically exaggerated model of a stratified lake flow cannot replicate all the details of the mixing process. However, vertical dispersion alone can be accurately modeled in a distorted model of an inflow in a stratified basin if the overall Richardson number $J_1 = \frac{g\Delta\rho H}{\rho U^2}$ is used as the modeling parameter. Similarly horizontal dispersion can be accurately modeled if $J_2 = \frac{g\Delta\rho w^2}{\rho U^2 H}$ is used as the basic modeling parameter.

A vertically exaggerated model of Ham's lake was constructed and experiments were run of the mechanical destratification of the model. Surprisingly accurate modeling of the prototype destratification experiments of Garton (2) has been achieved with our model. The appropriate non-dimensional parameter is the overall Richardson number $J = \frac{g\Delta\rho H}{\rho U^2}$ and the characteristic time used to non-dimensionalize the mixing times was the volume of the lake divided by the volume flow rate of the pump.

Nomenclature

F Froude number = $U/\sqrt{gL}$

Fd Densimetric Froude number = $U/\sqrt{g'L}$

FR Froude-Richardson number = $\frac{g^{1/2} L^{3/2}}{\nu}$

g Gravitational constant

g' Effective gravitational constant = $\frac{g \Delta \rho}{\rho}$

h Height of center of gravity of lake/model from the bottom

H Maximum depth of lake or basin

J Basic definition of overall Richardson number = $\frac{g \Delta \rho L}{\rho U^2}$

J_1 First Richardson number = $\frac{g \Delta \rho H}{\rho U^2}$

J_2 Second Richardson number = $\frac{g \Delta \rho w^2}{\rho U^2 H}$

L A characteristic length

Q Volume flow rate of pump

Re Reynolds number = UL/ν

Ri Gradient Richardson number = $\frac{-g \, \partial \rho / \partial z}{\rho \, (\partial u / \partial z)^2}$

S Scale factor = L model/L prototype

SI Non-dimensional Stability index = $\frac{\rho g \, (h_h - h)}{\rho g \, (h_h - h_s)}$

t Time

t_c Characteristic time of mechanical destratification = $\frac{V}{Q}$

t* Non-dimensional time = $\frac{t}{t_c}$

u Local velocity in the x direction

U	Characteristic velocity
V	Volume of lake or model basin
w	Width of inlet
x	Streamwise coordinate
y	Lateral coordinate
z	Vertical coordinate

Subscripts

$( )_h$	Homogeneous
$( )_s$	Fully stratified

Greek Letters

ν	Kinematic viscosity
ρ	Fluid density
ρ_t	Initial density at surface of water

INTRODUCTION

Members of the Oklahoma Water Resources Research Institute (OWRRI) are concerned with the advancement of the state-of-the-art of artificial destratification of lakes and reservoirs. Quintero and Garton (1) have reported the temperature and dissolved oxygen distributions in Ham's lake* which they mechanically destratify with a large pump. (See Figure 1.) Garton (2) and his students (e. g., Steichen (3)) have continued this work each year on Ham's lake as well as on the much larger Lake Arbuckle (8, 900 hectare meters). Toetz, Wilhm, and Summerfelt (4) have analysed the general aspects of the biological effects of artificial destratification (and aeration) in lakes and reservoirs. They have continued to monitor important biological information, including fish growth, on the lakes that Garton has been destratifying.

Since one destratification experiment on a prototype lake takes at least one summer, the advantages of a laboratory model, with the capability to run several mixing experiments in a much shorter time are obvious. We have adopted the goal of developing the modeling technique in stratified lake flows to the state where reliable prediction of prototype lake mixing phenomena is possible. We have the advantage of observing first hand, the prototype experiments of Garton and the other members of the OWRRI.

We have constructed a model of Ham's lake using a 1 to 360 horizontal scale factor and a 1 to 34 vertical scale factor. From the simple cost consideration, scale distortion is necessary in lake modeling in

* 115 hectare-meters in volume.

all but the most abundantly endowed laboratories. The destratification experiment which we model is the situation in which the prototype lake is initially strongly stratified. (In the Oklahoma lakes this is primarily a seasonal thermal stratification.) The experiment begins with turning on of the mechanical pump which destratifies the prototype lake in from 1 to 3 weeks. It is this experiment which we are most interested in modeling in the laboratory.

The major features of our model experiment are:

1) The lake is initially strongly stratified;

2) The destratification pump is a model of the one used by Steichen (3) and Garton (2);

3) The lake model has vertical scale exaggeration.

Although there is considerable experience in the literature with modeling with vertical scale exaggeration (5, 6) and with stratified waterways (7, 8), we have found no reports of hydraulic model studies which involve all three of the major features of our experiment listed above. As a result, much of our effort has concentrated on developing modeling criteria which fit the particular prototype situation we encounter in the OWRRI lake destratification program.

BACKGROUND

The two non-dimensional parameters which govern the flow phenomena of a homogeneous lake are the Reynolds number $Re = \frac{UL}{\nu}$ and the Froude number $F = U/\sqrt{gL}$. Simple analysis of the non-dimensional governing equations of fluid mechanics reveals that if a model lake is constructed exactly to scale, the flow in the model will duplicate that in the prototype if the Reynolds number and the Froude number characteristic of the model flow are exactly equal to the Reynolds and Froude numbers of the prototype.

When we are dealing with models which are of the order of 100 times smaller than the prototype lakes however, it is impossible to match both the Reynolds number and the Froude number of the model situations with the prototype. As a result, exact similitude is not possible. (Even exotic fluids cannot produce the necessary change in kinematic viscosity ν to offset the large change in the characteristic length L). Fortunately, in the turbulent flow regime most commonly found in lake flows, the characteristics of the fluid motion are not strongly dependent on Reynolds number, provided the Reynolds number of the model is large enough to preserve the turbulent flow. Consequently, reasonably good modeling can normally be achieved by matching the Froude number exactly and allowing the Reynolds number of the model to be considerably lower than the Re of the prototype. As pointed out by Fischer and Holley (5) sufficient care must be taken to add roughness to the model basin in places where the flow is not likely to be fully turbulent.

When the prototype lake is of such a large size or the model is so small that the scale factor S is about 1/100 or smaller the model lake becomes so shallow that turbulent flow cannot be preserved. The solution to this has normally been to exaggerate the vertical dimensions of the model which increases the scale factor in the vertical direction. Hence the model Reynolds number based upon a vertical characteristic length is closer to the prototype Re and the turbulent flow can be preserved.

The practice of scale distortion can be subjected to much criticism. Fischer and Holley (5) have stated that distorted models should not be used to model dispersion since "a distorted hydraulic model magnifies the dispersive effects of vertical velocity gradients and diminishes the effects of transverse gradients." However, Keulegan (8) and Barr and Hassan (9) have reported moderately good success in modeling exchange flows in rectangular channels with distorted hydraulic models. They have been able to take account of the distortion by determining the dependence of the flow on the Froude-Reynolds number FR. The flow geometry of the rectangular channel is enough different from our flow condition that the results of their work are not directly applicable. However, our approach to the modeling problem is somewhat similar to theirs. One of the major questions we are trying to answer is what experimental data can we obtain, in direct or corrected form, which will be useful for our predictive purposes, and what data will be unreliable, no matter how the scale distortion effects are accounted for?

If there is density stratification in the model, another dimensionless parameter is important to the hydraulic modeling: the overall Richardson number $J = \frac{g(\Delta\rho)L}{\rho U^2}$. This is derived from the gradient Richardson number $Ri = \frac{-g\, \partial\rho/\partial z}{\rho(\partial u/\partial z)^2}$ by assuming that the density gradient $\partial\rho/\partial z$ scales with a characteristic density difference $-\Delta\rho$ divided by a characteristic length L, and the velocity gradient scales with a characteristic velocity U divided by L (10). If we define an effective gravitational constant $g' = g\,\Delta\rho/\rho$ then J becomes $J = \frac{g'L}{U^2}$. In the Civil Engineering community it is more common to refer to this grouping as the inverse square root of the internal or densimetric Froude number $F_d = U/(g'L)^{1/2}$.

In flow situations, such as one we have been studying, where the open surface waves are negligible and the entire surface of the lake is at the same level, the densimetric Froude number actually replaces the conventional Froude number.* Hence in our situation there are two important nondimensional parameters. We use the overall Richardson number $J = g\,\Delta\rho\,L/\rho\,U^2$ and the Reynolds number $Re = UL/\nu$.

In forming the values of the nondimensional parameters there is a major dilemma caused by the scale distortion; namely what do we use for a characteristic length, a vertical or a horizontal dimension, or both? It is more common (5, 7) to use a characteristic lake depth but as Fischer and Holley (5) point out this has not been entirely successful. As one objective, our experiments have attempted to examine this problem in some detail.

*Such would not be the case if there were substantial mean current due to a throughflow in the lake.

EXPERIMENTAL PROCEDURES AND RESULTS

Inflow Experiments

In order to learn more about the effects of scale distortion on the mixing phenomena in stratified lakes we constructed two simple basins that are identical, except that one is twice as deep as the other. These basins consist of simple inlet models where the contour is modeled after a real lake. A sketch of the flowfield is shown in Figure 2. The basins are long and narrow with transparent sides which allow the inflow to be carefully visualized. (See Figure 3.)

In matching the flow conditions in the two basins for any inflow experiment, several combinations of characteristic lengths were used in the Richardson and Reynolds numbers (11). For example, one combination is $J_1 = \frac{g\Delta\rho H}{\rho U^2}$, $Re_1 = \frac{UH}{\nu}$ where H is the maximum depth of the water in the basin, and differed by a factor of two for the two basins. If the velocity gradient $\partial U/\partial z$ is assumed to scale with the characteristic velocity divided by the horizontal characteristic length (the inlet width w) then the overall Richardson number becomes $J_2 = \frac{g\Delta\rho w^2}{\rho U^2 H}$. Several other combinations were attempted, but in our flow situation the two shown here are all that are needed to effectively describe similitude (11). An attempt was made to determine which combination produced the most similar results between the two models in the dispersion pattern of the inflow.

In general, to match the Richardson number J between the model and the prototype, the density differences in the model must be greater than in the prototype lake. The density differences in the prototype may be due to temperature differences; in the model, thermal stratification is impractical -- the required temperature differences are too great and the boundary conditions of conduction from the bottom of the lake or radiation, convection, and mass transfer from the surface are not the same in the model and the prototype. However, if the fluid has similar thermal and molecular diffusivity (i. e., if the Lewis number is near 1) or if the major mechanism of mixing is turbulence rather than diffusion -- which is true in our case -- density differences due to temperature may be modeled by density differences due to dissolved salts.

There are a number of salts which can increase the density of water by about 80%: common table salt can give only about a 5% increase -- less if the solution has to be clear -- but it is convenient and inexpensive, and a few percent weight density increase is adequate for our studies. Stratified conditions are obtained by filling the basin slowly from the bottom with increasingly dense salt solutions. The local density is measured at various depths with a conductivity probe (See Figure 4). From the conductivity and calibration curves we develop, the local density is deduced. A sample calibration curve for one of our conductivity probes is shown in Figure 5.

A large number of tests was run with these models. They consisted of establishing a strongly stratified initial condition and then starting a steady inlet flow of an intermediate density. After the initial transient settled out dye was injected into the inflow fluid as a marker. As this dye pattern passed through the observation region of the inlet several side and top view photographs were taken of the dye front until it passed through. After the photographing was completed a final density profile was measured with the conductivity probe.

Results of Inflow Experiments

Figure 6 is a sketch of a top view of the dye fronts photographed in the shallow and deep models during typical experiments. In this situation both models were run with overall Richardson number J_1 values of $J_1 = \frac{g \Delta \rho H}{\rho U^2} = 0.3$. (The Reynolds numbers were $Re_1 = UH/\nu = 2624$ and 5313 for the shallow and deep models respectively.) As we see the lateral dispersion in the deep model is much greater than in the shallow model. Several experiments of this type for a moderate range of Reynolds numbers (from $Re_1 = 2200$ to 7000) yielded essentially the same results. The conclusion is obvious: using the scale distortion of 2 and the Richardson number combination of $J_1 = \frac{g \Delta \rho H}{\rho U^2}$, similitude between two models of simple lateral dispersion cannot be achieved.

The results depicted in Figure 6 led to the study of the same dispersion pattern with the flow conditions readjusted to give a matching of the other Richardson number combination $J_2 = \frac{g \Delta \rho w^2}{\rho U^2 H}$ at $J_2 = 0.08$. In this case, the dye front patterns, sketched in Figure 7, show very good agreement.

Perhaps of more importance to the program of the OWRRI is the vertical dispersion of the inflows into the model basins. Figure 8 shows a sketch of the dye front profiles in the shallow and deep models, plotted in non-dimensional coordinates. These are the side views of the same flows whose top views were shown in Figure 6. (i.e., $J_1 = 0.3$ for both flows). In this case the vertical dispersion rates were approximately equal (non-dimensionally) for the shallow and deep model while the lateral dispersion rates were not even close. As with many of the experiments we ran, the intermediate density of the inflows were not exactly matched nor were the initial non-dimensional density profiles so the equilibrium level that the inflows sought were not exactly the same. Numerous experiments with similar flow conditions demonstrated that the final equilibrium level of the inflow and its dispersion rates were not strongly related.

The final density profiles measured with the conductivity probe clearly confirmed the lens of intermediate density fluid that the flow visualization indicated. Figure 9 shows an example of one of the final measured density profiles along with a measured initial density profile typical of all our experiments.

Experiments on the vertical dispersion rates of the two models with matched values of $J_2 = \frac{g \Delta \rho w^2}{\rho U^2 H}$ yielded results typically like those of Figure 10. In this case, the vertical dispersion is significantly less for the deep model than for the shallow model. (The lateral dispersion rates for these two experiments were very similar as shown in Figure 7.)

These experiments and many more just like them have convinced us that in this type of stratified lake mixing, complete similarity cannot be obtained if vertically exaggerated models are used. On the other hand, selective analysis of the data can produce useful results. For example, if the first Richardson number grouping $J_1 = \frac{g \Delta \rho H}{\rho U^2}$ is used as the primary non-dimensional parameter then the model will provide good similarity with the prototype in the vertical dispersion. If $J_2 = \frac{g \Delta \rho w^2}{\rho U^2 H}$ is used as the primary non-dimensional parameter there will be good similarity in the lateral dispersion. The results discussed here are specifically for the inflow configuration we have used. However, it is reasonable to generalize these results to similar destratification flows such as that found with the mechanical pump.

Mechanical Destratification Experiments

After some expertise had been developed in the experimental and modeling technique, a model of Ham's lake was constructed. As mentioned earlier the horizontal scale of the model is about 1:360 and the vertical about 1:34. This gives us what appears to be a reasonable balance between compactness, vertical distortion, and feasible Reynolds number. This lake has a number of tortuous limbs, which we wanted to include in the model, without making the model smaller in scale. As a compromise, the limbs were modeled accurately as to depth, width, etc., but bent around so as to keep the overall dimensions down.

As mentioned in the Introduction, the destratification pump is a model of the one used by Quintero and Garton (1). This pump consists of a large propellor pointed downward in the water enclosed in a simple shroud. For the present experiments the model does not have the large conical skirt which can be seen in Figure 1. The reason we have left it off is because the major prototype data used for comparison was taken with no diffuser on the pump. (Ref. Steichen (3))

Our plan is to evaluate with the model, several configurations of the basic mechanical destratification device used by Garton. However, as a first step we are attempting to devise, impliment, and test modeling criteria which we can use in the mechanical destratification situation described in the Introduction.

Steichen's (3) experience is that during the mechanical destratification of a lake temperature (and hence density) profiles taken at different locations in the lake are not substantially different. Because of this it appears that the vertical mixing is the important physical process in the destratification. Based upon the results of our inflow experiments this leads us to using the original Richardson number grouping $J_1 = \frac{g \Delta \rho H}{\rho U^2}$ as the primary non-dimensional parameter in the modeling.

On July 16, 1973, Steichen (3) began continuous operation of the destratification pump (without the conical shroud) in Ham's lake. Figure 11 is a reproduction of the average temperature profile he measured on that day and density profile deduced from the temperatures. Table 1 lists the pertinent information about the lake and the pump for this operation. Based upon the initial density difference and using the pump average outlet velocity as the characteristic velocity, the Richardson number for this flow calculates to be $J = \frac{g \Delta \rho H}{\rho U^2} = 0.40$. The pertinent fluid dynamic data from this experiment can be summarized in Figures 12 and 13. Figure 12 shows a record of the density profiles measured

TABLE 1

Parameters of Prototype and Model Lakes for Destratification Experiments

	Prototype Experiment	Model Experiment A	Units
Lake Volume V	1.15×10^6	.348	meters^3
Maximum Depth H	9.0	.263	meters
Stratification $\frac{\Delta\rho}{\rho}$	.0025	.026	
Propellor diameter	107	3.76	centimeters
Pump flow rate Q	0.67	4.5×10^{-4}	meters^3/sec
Average pump Outlet velocity U	0.74	0.41	meters/sec
Richardson Number J_1	0.40	0.40	
Characteristic Time t_c	1.72×10^6	767	sec.
Reynolds Number $Re = \frac{UH}{\nu}$	6.56×10^6	1.06×10^5	

(from temperature readings) throughout the prototype destratification experiment.

Conventional analysis of this type of data includes a calculation of the progress of the stability index with time. In non-dimensional form this stability index is $SI = \frac{\rho g (h_h - h)}{\rho g (h_h - h_s)}$ where h is the height from the bottom of the center of gravity of the lake, ρ is the average lake density, and the subscripts h and s stand for homogeneous and fully stratified respectively. The stability index is the gravitational potential energy of the lake referenced to the lake in its homogeneous condition and non-dimensionalized with the potential energy of the fully stratified lake (with the same reference). This index is computed from the density profiles and the elevation contours of the lake which provide the volume of the lake in every increment of elevation.

The progress of the stability index with time during the prototype destratification experiment is plotted in Figure 13. The time variable t has been non-dimensionalized with the characteristic time t_c for this phenomenon defined as the ratio of the total volume of the lake divided by the volume flow rate of the pump, i. e., $t_c = \frac{V}{Q}$ and $t^* = \frac{t}{t_c}$. A fourth order polynomial least squares regression curve fit has been made to this data and yields the curve in the figure. Now using a criterion that the lake is destratified when the stability index falls below 10% of its initial value, we see that for the prototype experiment $t_d^* = .76$ ($t_d = 15.1$ days). This non-dimensional destratification time is one of the most important parameters of the physical process which we hope to be able to predict with the use of the hydraulic model.

Several destratification experiments were performed in our model lake with different density and velocity conditions. In each case the density profile was as similar (in shape) as we could make it to the prototype experiments' initial profile, however the difference between the surface and bottom densities was adjusted to different values to suit the experiment.

The experiment of most interest to us was the one in which the pump output velocity* and the stratification were adjusted so that the Richardson number $J_1 = \frac{g \Delta \rho H}{\rho U^2}$ equaled 0.40 to match the prototype experiment. The important properties of the lake and of the pump are found in Table 1 (listed as Experiment A) along with the prototype data.

The density profiles which were measured in the model during destratification are shown in Figure 14. For these conditions the whole experiment took less than an hour so our time resolution is not as good as some other runs (at higher Richardson number) which took several hours. Although it is not obvious in Figure 14, most model density profiles taken during destratification had a stairstep shape characteristic of the lens of intermediate density moving through the lake. Time sequence photographs of flow visualization of this lensing is seen in Figure 15. (Here the fluid entering the pump is marked with dye beginning with the start up of the pump.)

The stairstep shape of the density profiles is not as readily apparent in the prototype lake. There are probably two reasons for this. First,

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*The average output velocity of the pump was obtained in two ways. First motion pictures were taken of dye tracer flowing through the pump as a function of pump RPM. The second way (which agreed substantially with the first) was to measure the mean output velocity with a pitot tube, and correct the calibration for swirling flow.

the Reynolds number of the model flow is much smaller than in the prototype lake. As a result, there is probably some decrease in the turbulent mixing of the lens flow. Second, there are complicated climatological effects such as sun radiation, surface evaporation and heat transfer, and surface wave induced mixing which increase the amount of mixing and diffusion of the mass and energy in the lake. We expect that our model can replicate only the most important mixing phenomenon, namely the convection set up by the mechanical pump.

In overall behavior the model does quite a good job of replicating the destratification phenomenon. The progress of the stability index with non-dimensional time of the model experiment compares favorably with the prototype as seen in Figure 16. The non-dimensional destratification time (using the 10% SI criterion) of $t_d^* = .88$ is within 15% of the destratification time for the prototype. This agreement is actually much better than we should expect (the ratio of characteristic times of the prototype to the models is over 2000 and the Reynolds numbers ratio by a factor of 62). In fact, another experiment at close to this value of Richardson number had a non-dimensional destratification time twice that of the prototype. We are presently rerunning several experiments to establish consistency in our data. However, we are strongly encouraged that the model results are in the same range as the prototype experimental results. This has provided us with the confidence that the modeling can produce useful results if one is careful with the application and the analysis.

CONCLUSIONS

There appears to be no way in which a vertically exaggerated model of a stratified lake flow can replicate all the details of the mixing processes. However, vertical dispersion alone can be accurately modeled in a distorted model of an inflow in a stratified basin if the overall Richardson number $J_1 = \frac{g \Delta \rho H}{\rho U^2}$ is used as the modeling parameter. Similarly horizontal dispersion can be accurately modeled if $J_2 = \frac{g \Delta \rho w^2}{\rho U^2 H}$ is used as the basic modeling parameter.

The use of varying salinity to obtain the density stratification works well and is convenient. Measurement of local density with the conductivity probe we have developed is very repeatable and accurate.

A vertically exaggerated model of Harn's lake was constructed and experiments were run of the mechanical destratification of the model. Surprisingly accurate modeling of the prototype destratification experiments of Steichen (3) has been achieved with our model. The appropriate non-dimensional parameter is the overall Richardson number $J = \frac{g \Delta \rho H}{\rho U^2}$ and the characteristic time used to non-dimensionalize the mixing times is the volume of the lake divided by the volume flow rate of the pump.

Acknowledgement

The experiments upon which this paper is based were run by G. E. Kouba, T. A. Gibson, and N. Sharabianlou. Their assistance is gratefully acknowledged. The coordination of the lake destratification research by Mr. H. R. Jarrell and the help of Prof. J. E. Garton is also appreciated.

References

(1) Quintero, J. E. and Garton, J. E., "A Low Energy Lake Destratifier," ASAE Paper No. 72-599, 1972.

(2) Garton, J. E., private communication.

(3) Steichen, J. M., "The Effect of Lake Destratification on Water Quality Parameters," Ph. D. Thesis, Oklahoma State University, 1974.

(4) Toetz, D., Wilhm, J., and Summerfelt, R., "Biological Effects of Artificial Destratification and Aeration in Lakes and Reservoirs - Analysis and Bibliography," Bureau of Reclamation Report REC-ERC-72-33, U. S. Department of Interior, Denver, Colo., 1972.

(5) Fischer, H. B., and Holley, E. R., "Analysis of the Use of Distorted Hydraulic Models for Dispersion Studies," Water Resources Research, Vol. 7, No. 1 (February, 1971), 46-51.

(6) Francis, J. R. D., "Scaling of River and Estuary Models," Engineering (London), Vol. 190 (1960), pp. 329-331.

(7) Barr, D. I. H., "Model Simulation of Vertical Mixing in Stratified Flowing Water," The Engineer (London), Vol. 215 (1963), pp. 345-352.

(8) Keulegan, G. H., "The Mechanism of an Arrested Saline Wedge," Estuary and Coastline Hydrodynamics, New York: McGraw-Hill, 1966.

(9) Barr, D. I. H., and Hassan, A. M. M., "Densimetric Exchange Flow in Rectangular Channels," La Houille Blanche, Vol. 18, No. 7, (1963), pp. 757-766.

(10) Turner, J. S., Buoyancy Effects in Fluids, Cambridge, 1973.

(11) Kouba, G. E., "Modeling Inflows into Stratified Lakes with Vertical Scale Distortion," M.S. Thesis, Oklahoma State University, 1974.

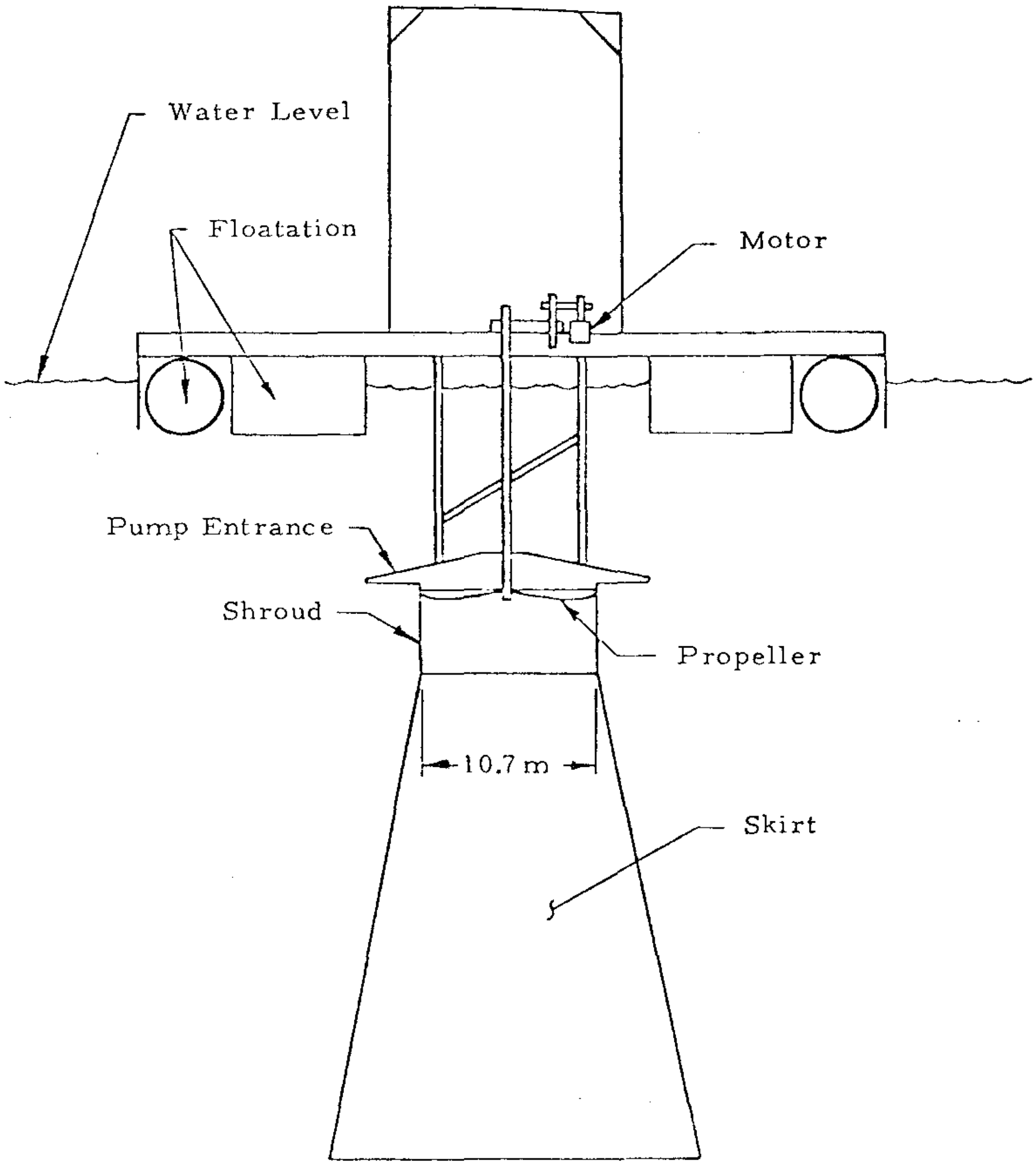


Figure 1 Schematic of the mechanical pump used by Garton.

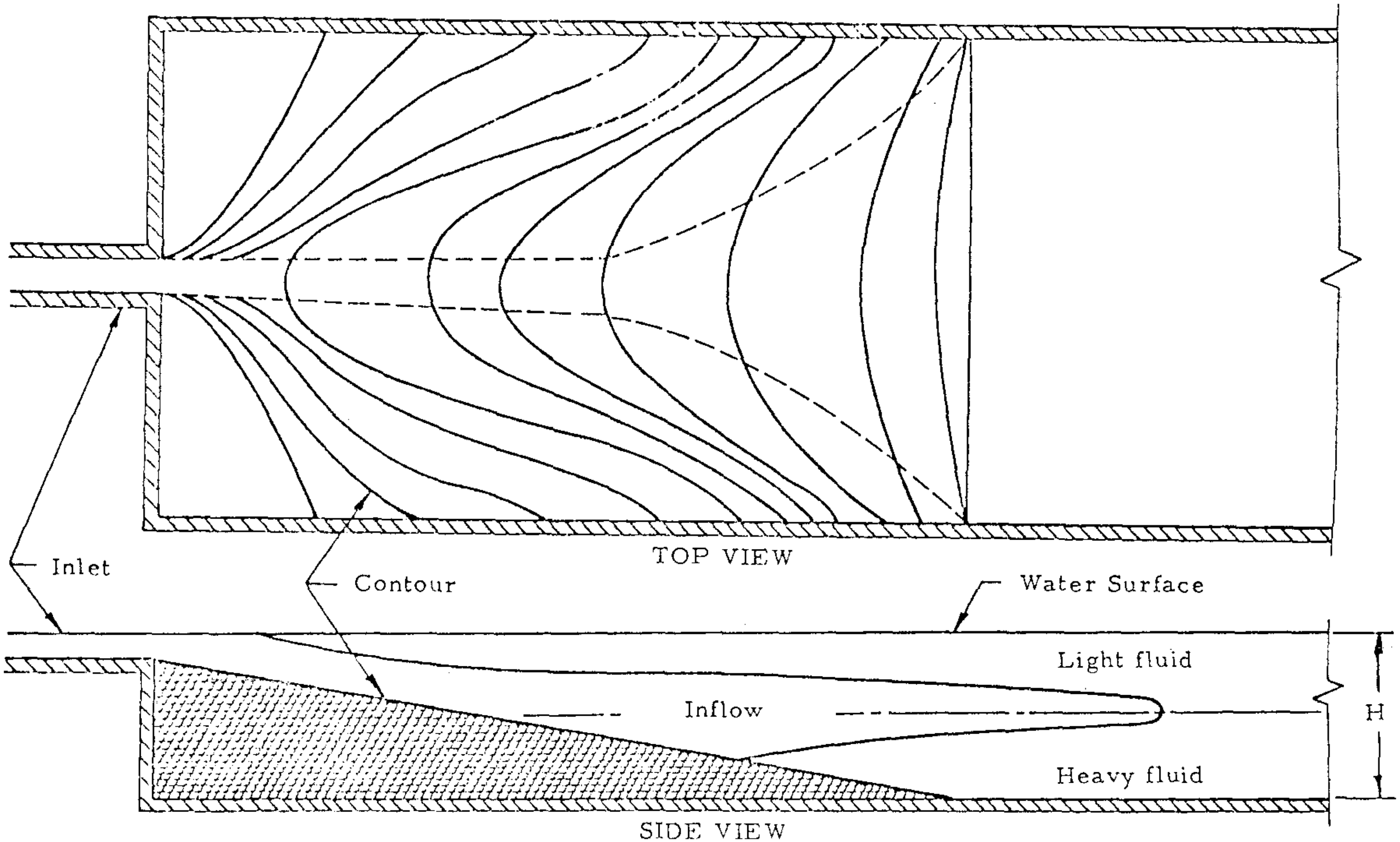


Figure 2 Sketch of the flowfield of the inflow experiments.

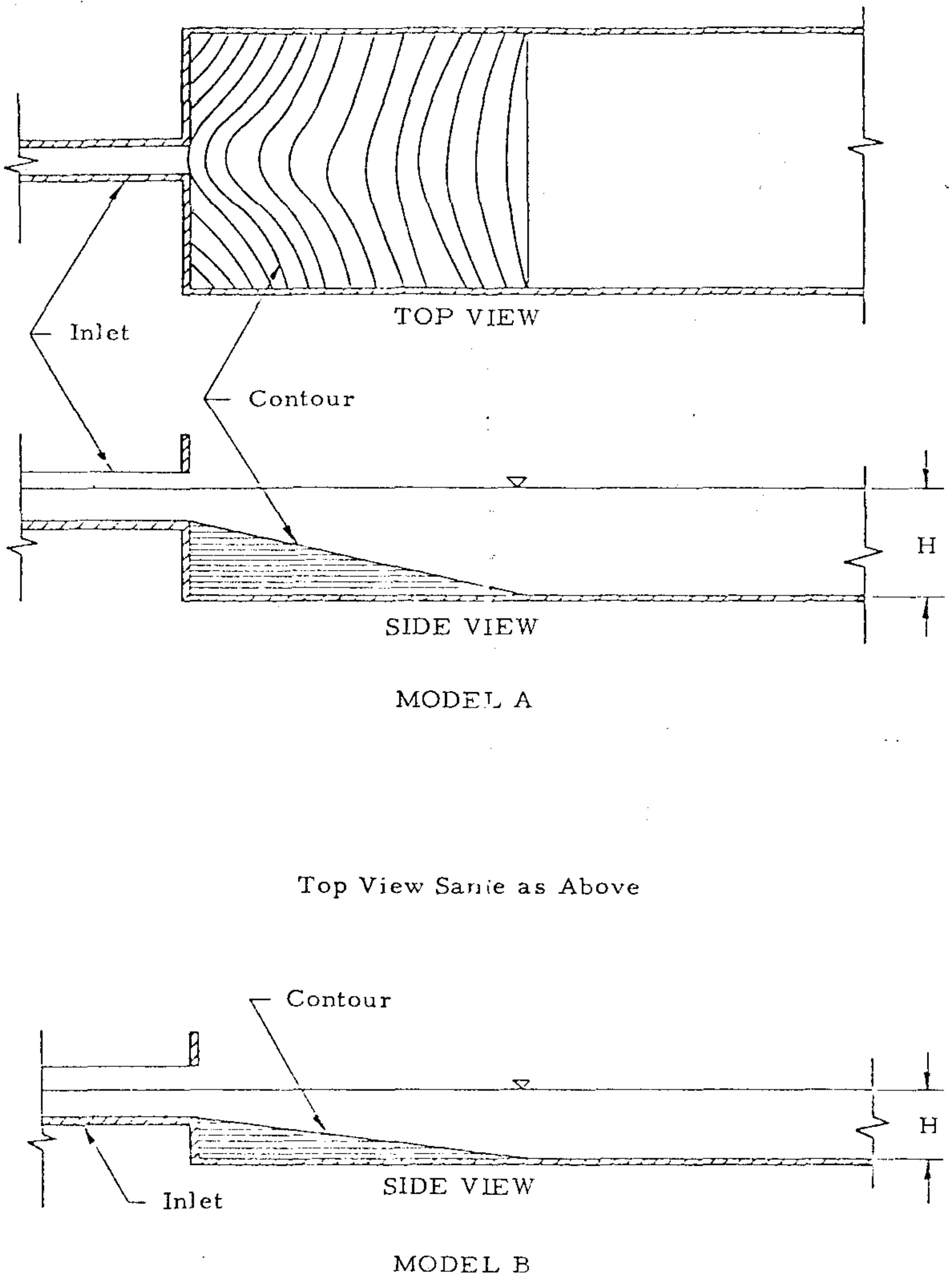


Figure 3 Top view and side views of inlet flow basins.

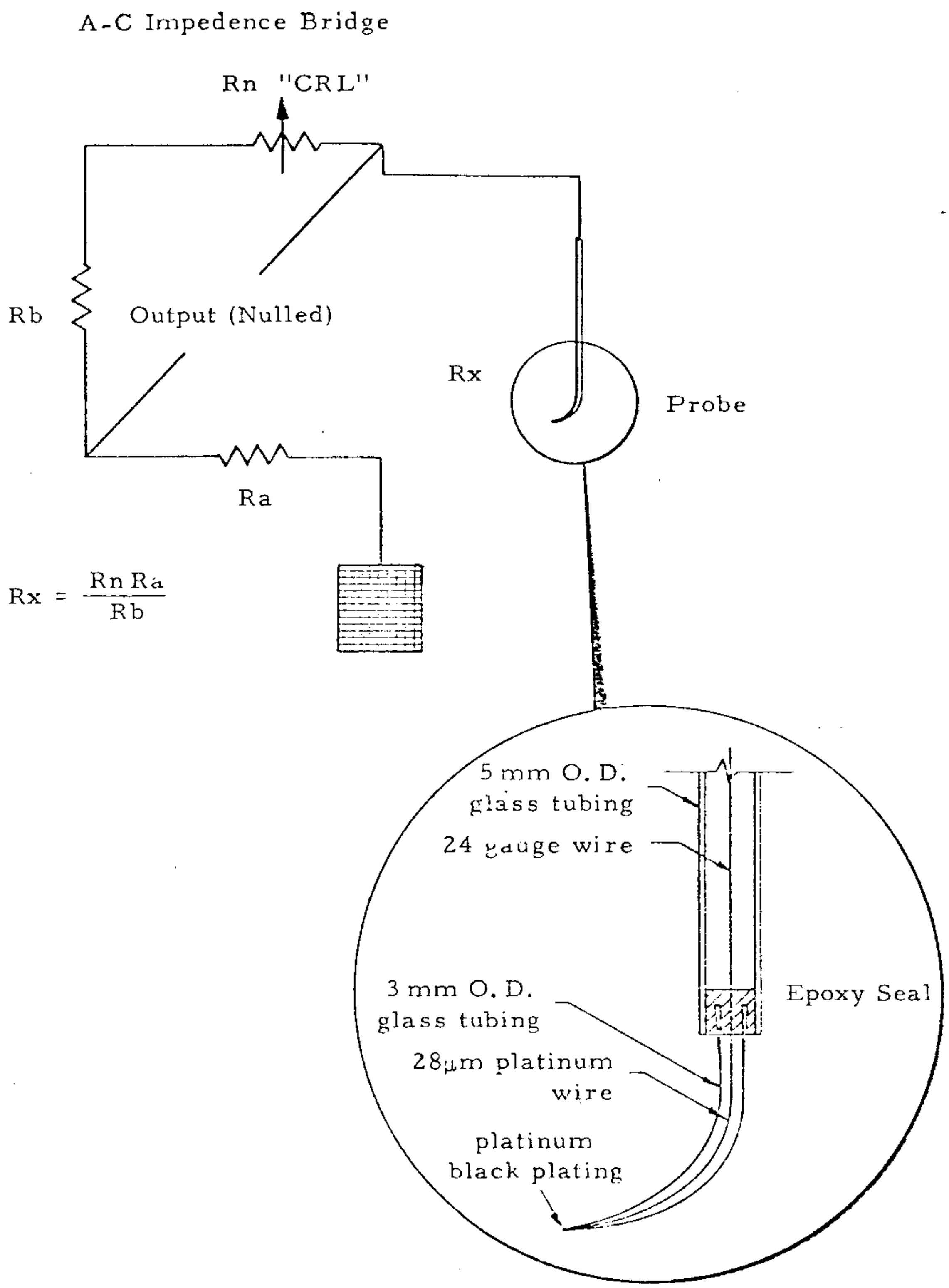


Figure 4 Schematic diagram of conductivity probe.

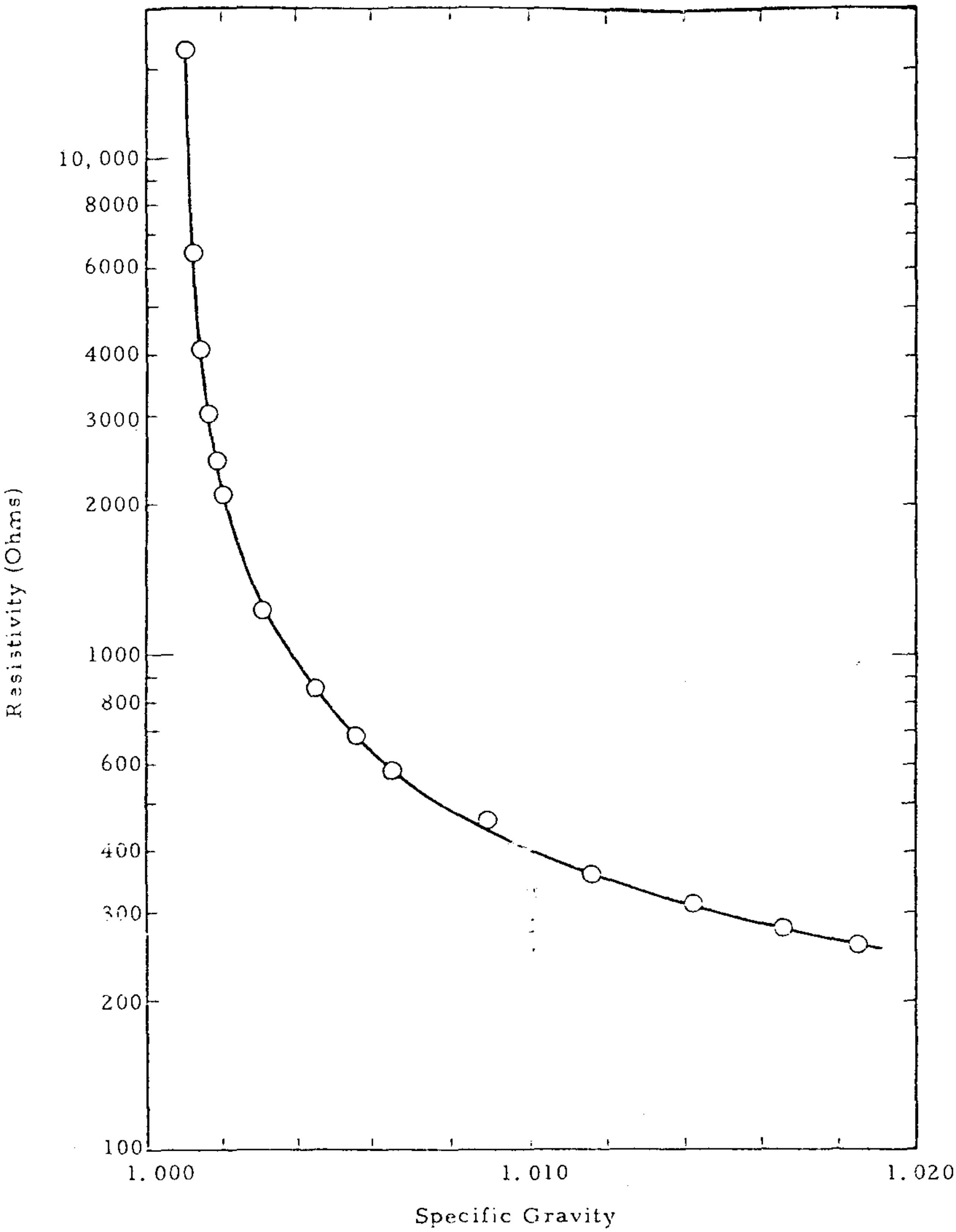


Figure 5 Sample calibration curve for a conductivity probe.

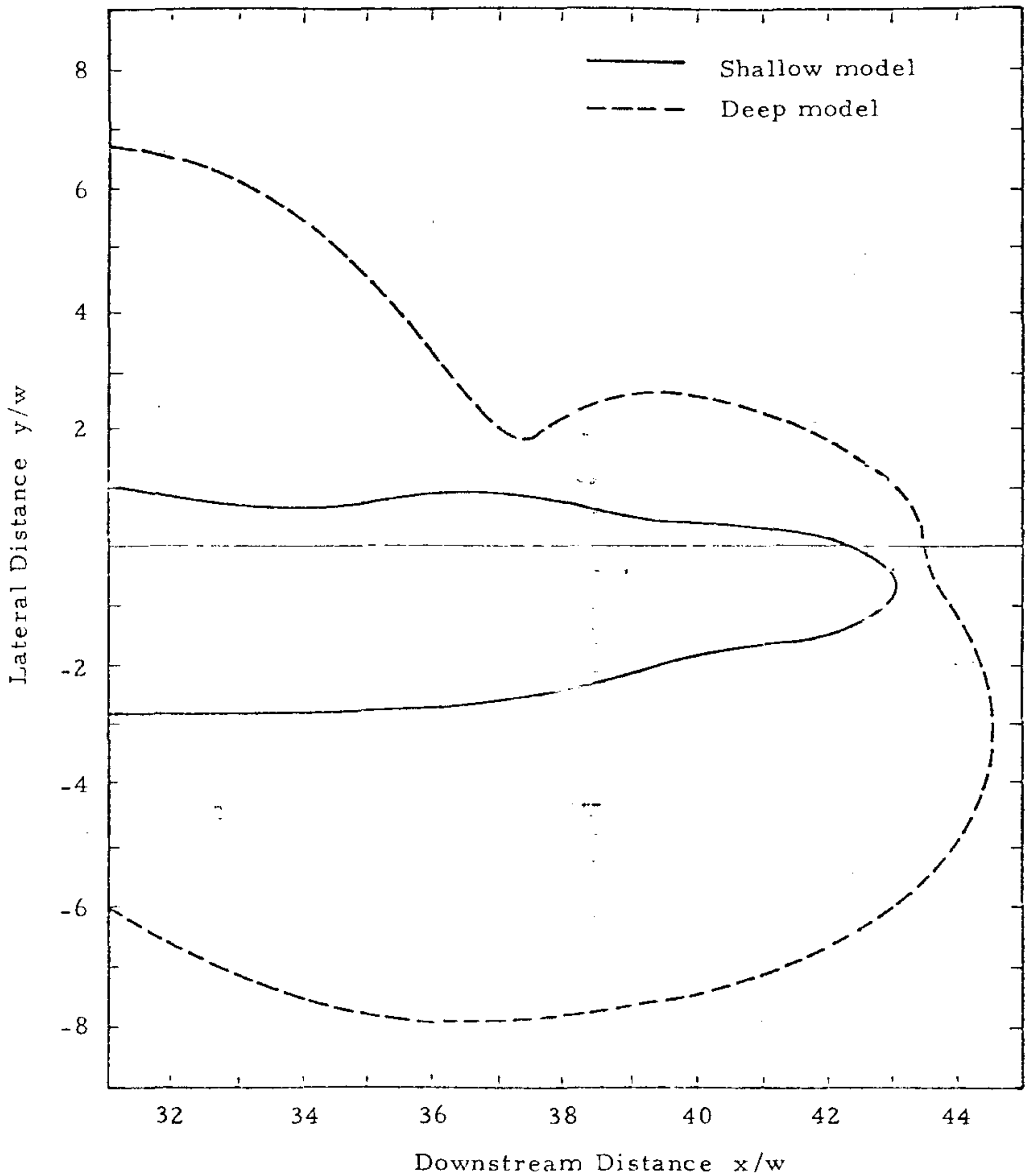


Figure 6 Top view of dye front comparison between shallow and deep model inflows with matching $J_1 = \frac{g \Delta\rho H}{\rho U^2}$

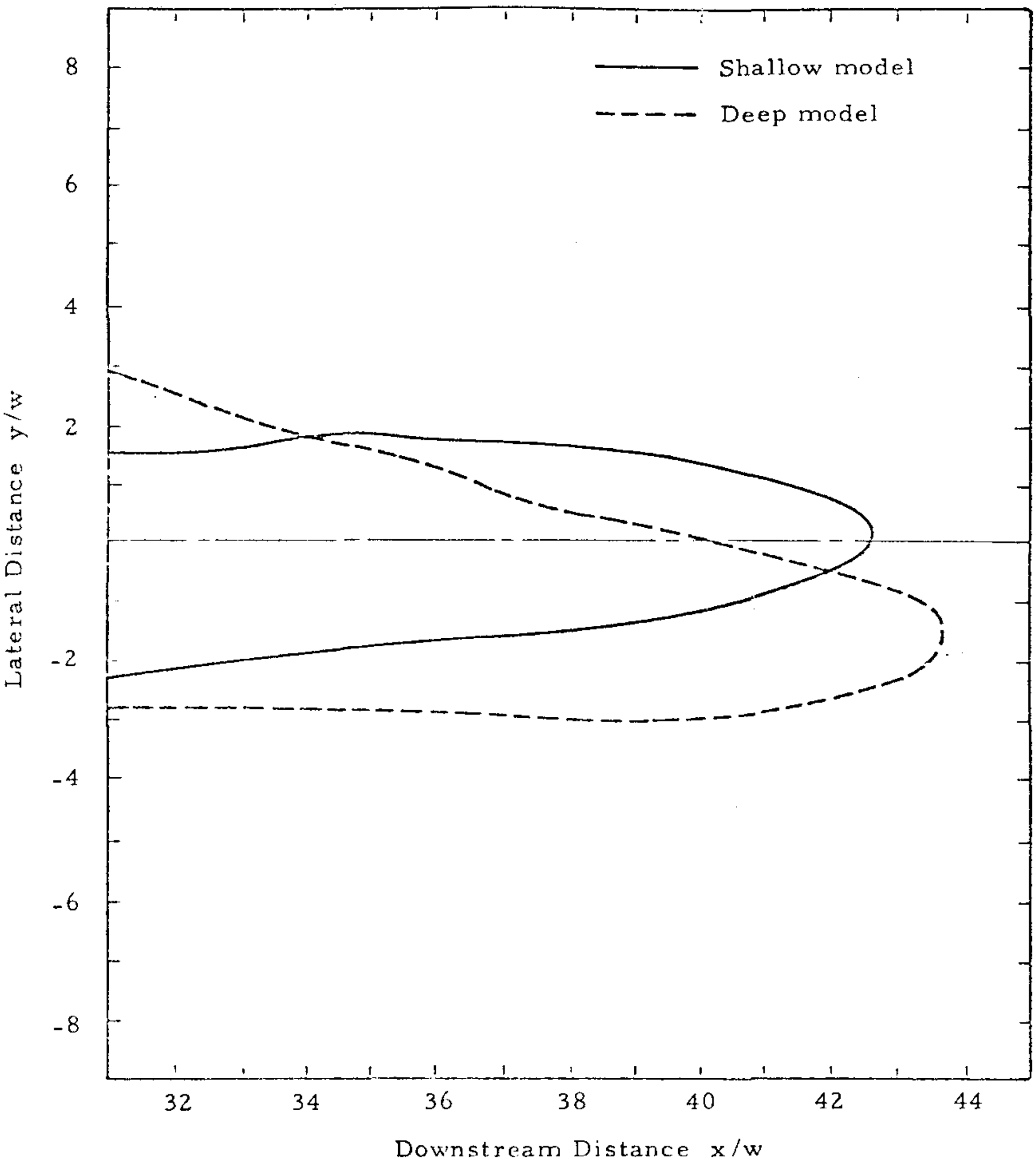


Figure 7 Top view of dye front comparison between shallow and deep model inflows with matching $J_2 = \frac{g \Delta \rho w^2}{\rho U^2 H}$

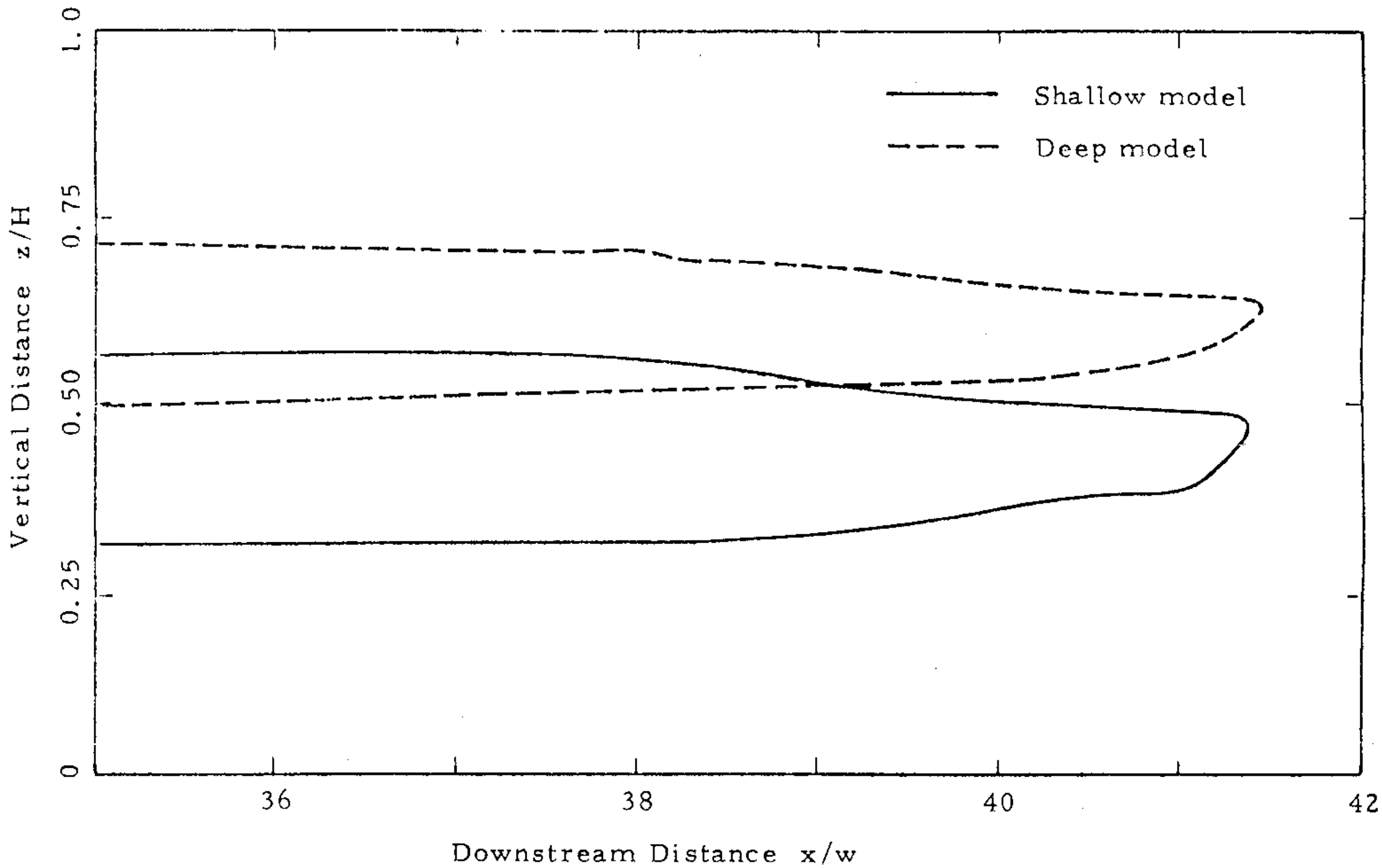


Figure 8 Side view of dye front comparison between shallow and deep model inflows with matching $J_1 = \frac{g\Delta\rho H}{\rho U^2}$

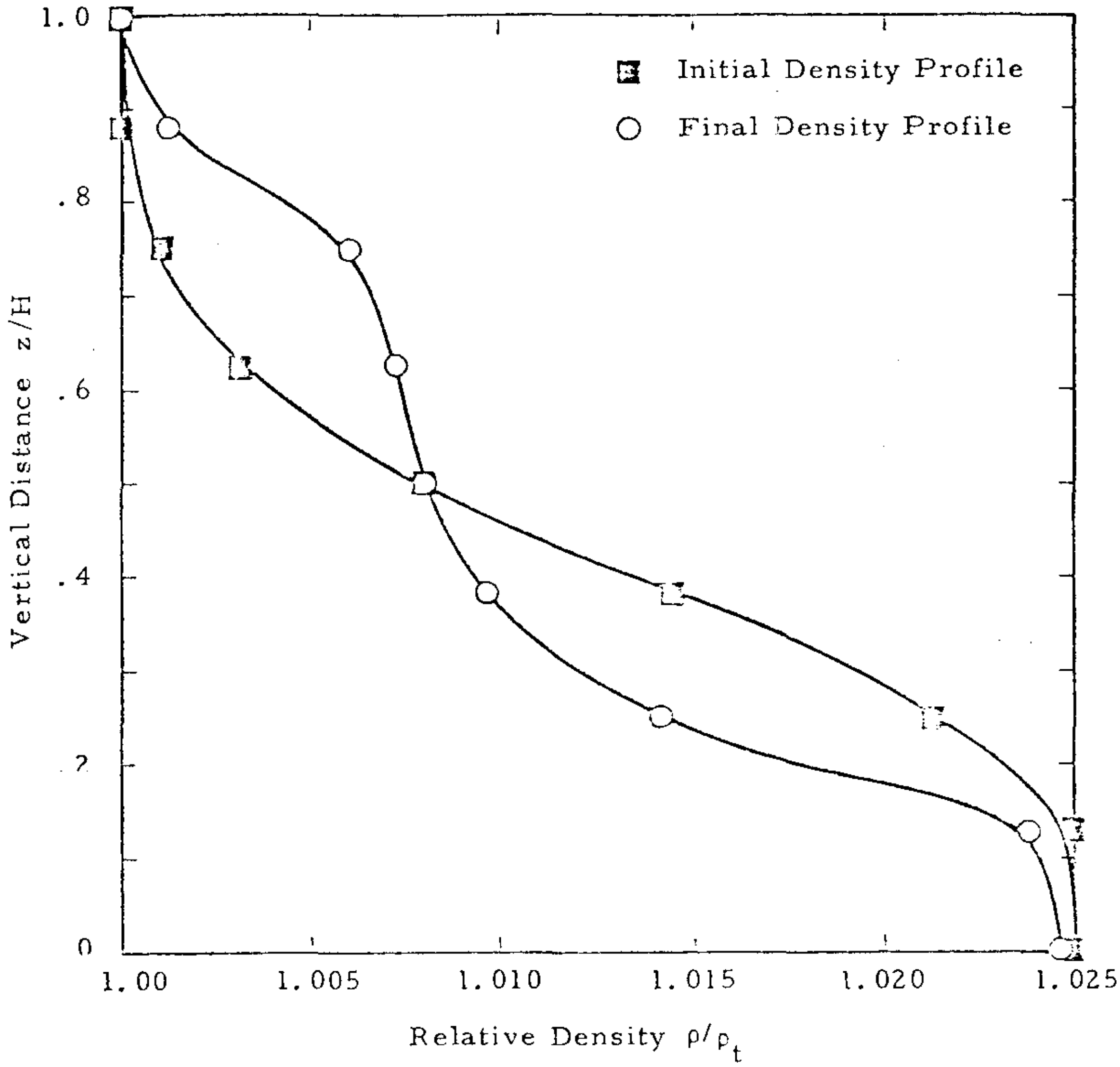


Figure 9 Initial and final density profiles measured with the conductivity probe in one of the inflow basins.

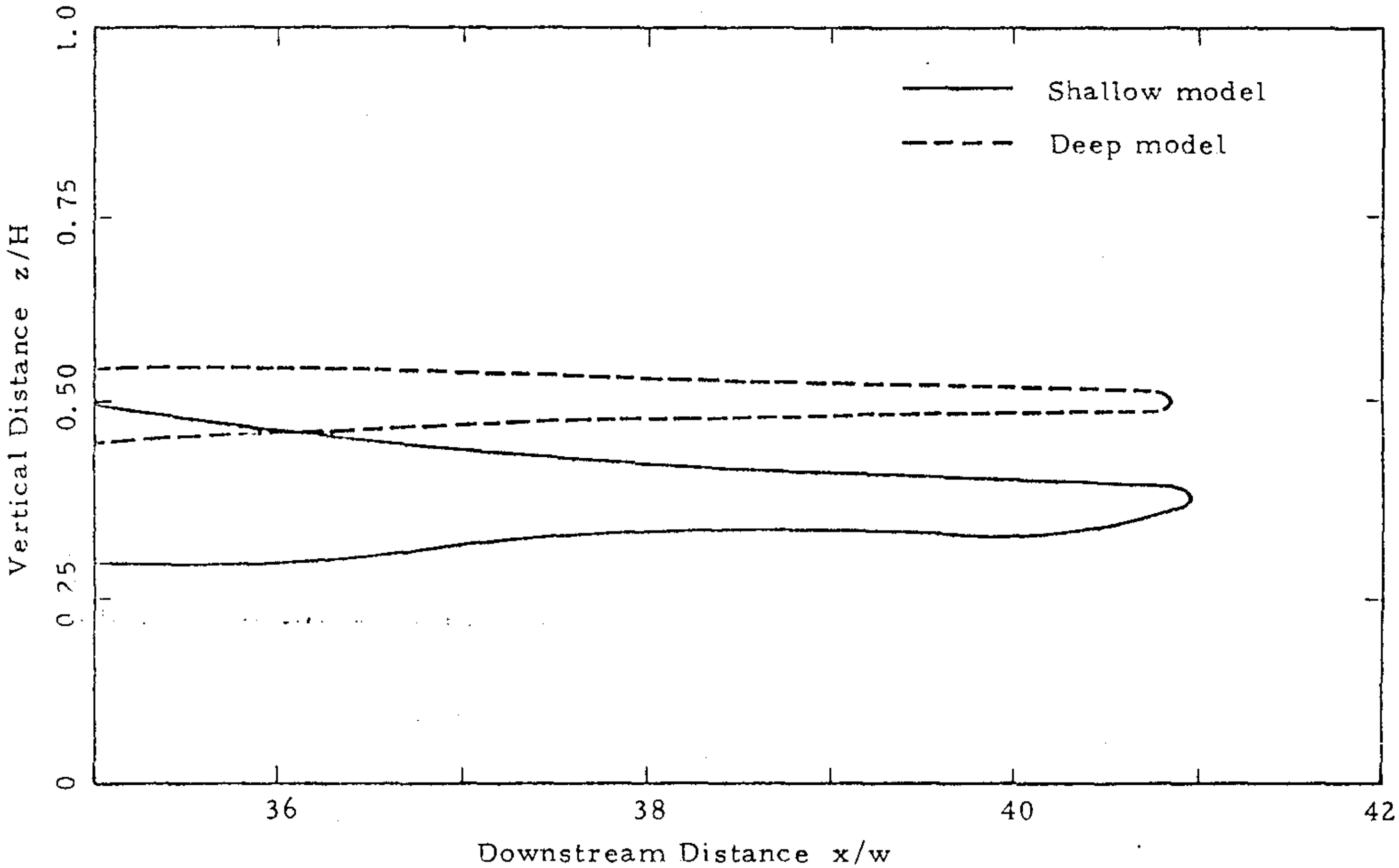


Figure 10 Side view of dye front comparison between shallow and deep model inflows with matching $J_2 = \frac{g \Delta \rho w^2}{\rho U^2 H}$

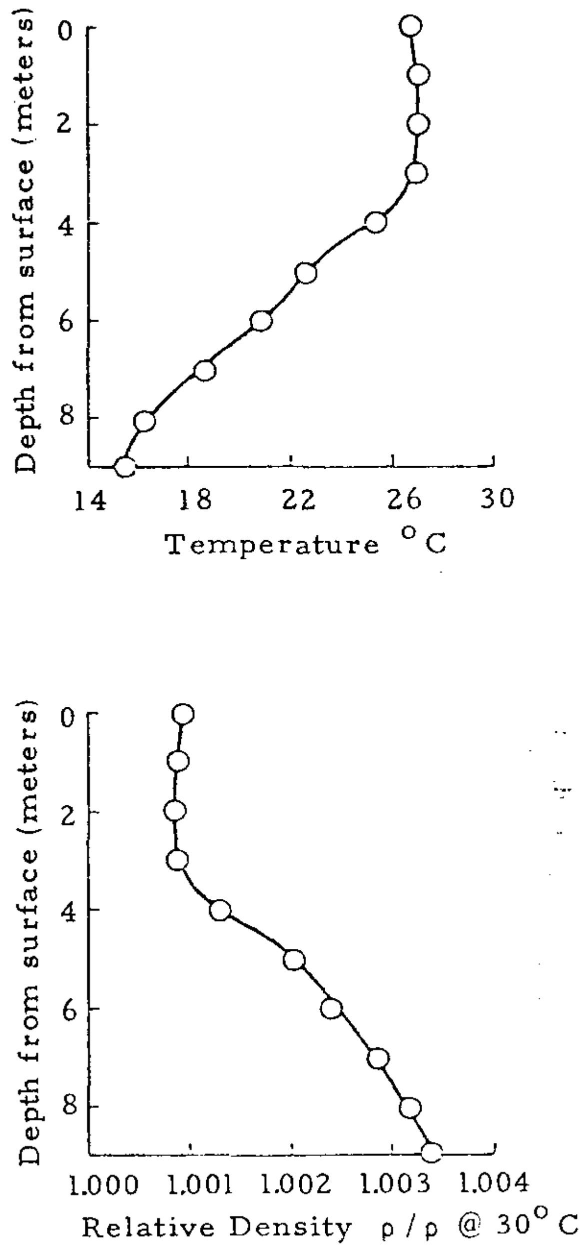


Figure 11 Average temperature and density profiles in Ham's lake just preceeding the prototype experiment.

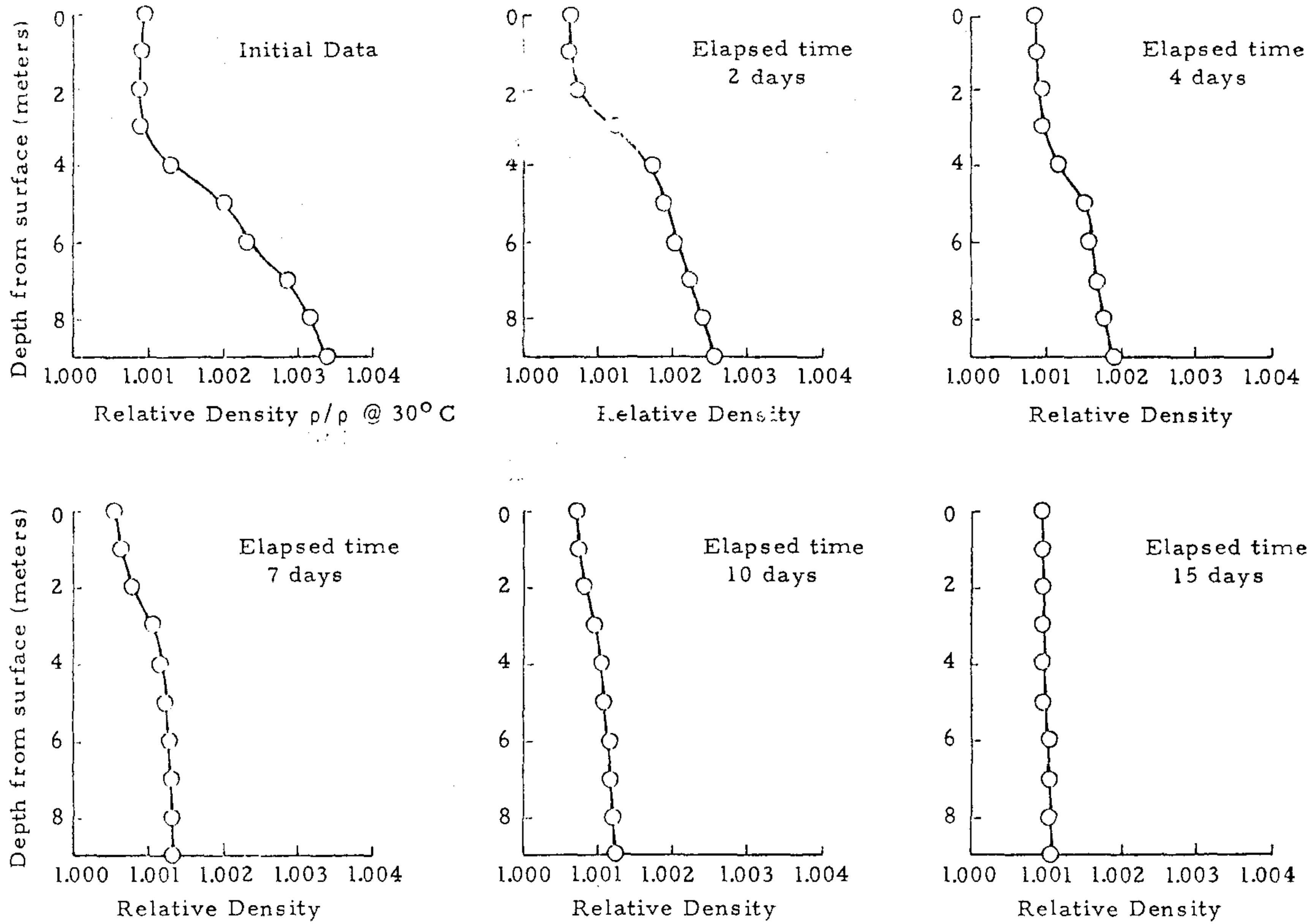


Figure 12 Density profiles recorded throughout the prototype destratifier experiment.

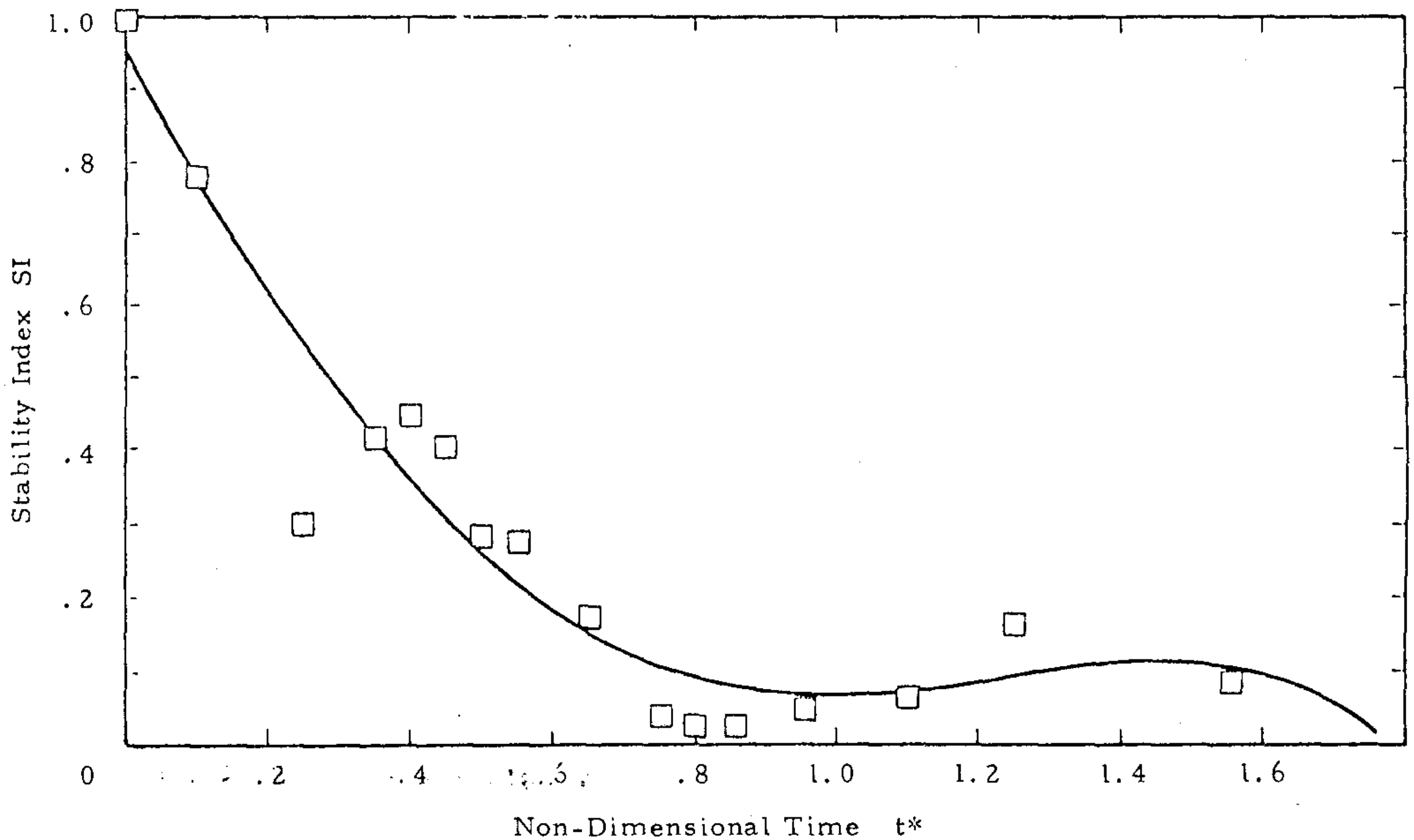


Figure 13 Plot of the stability index versus time for the prototype destratification experiment.

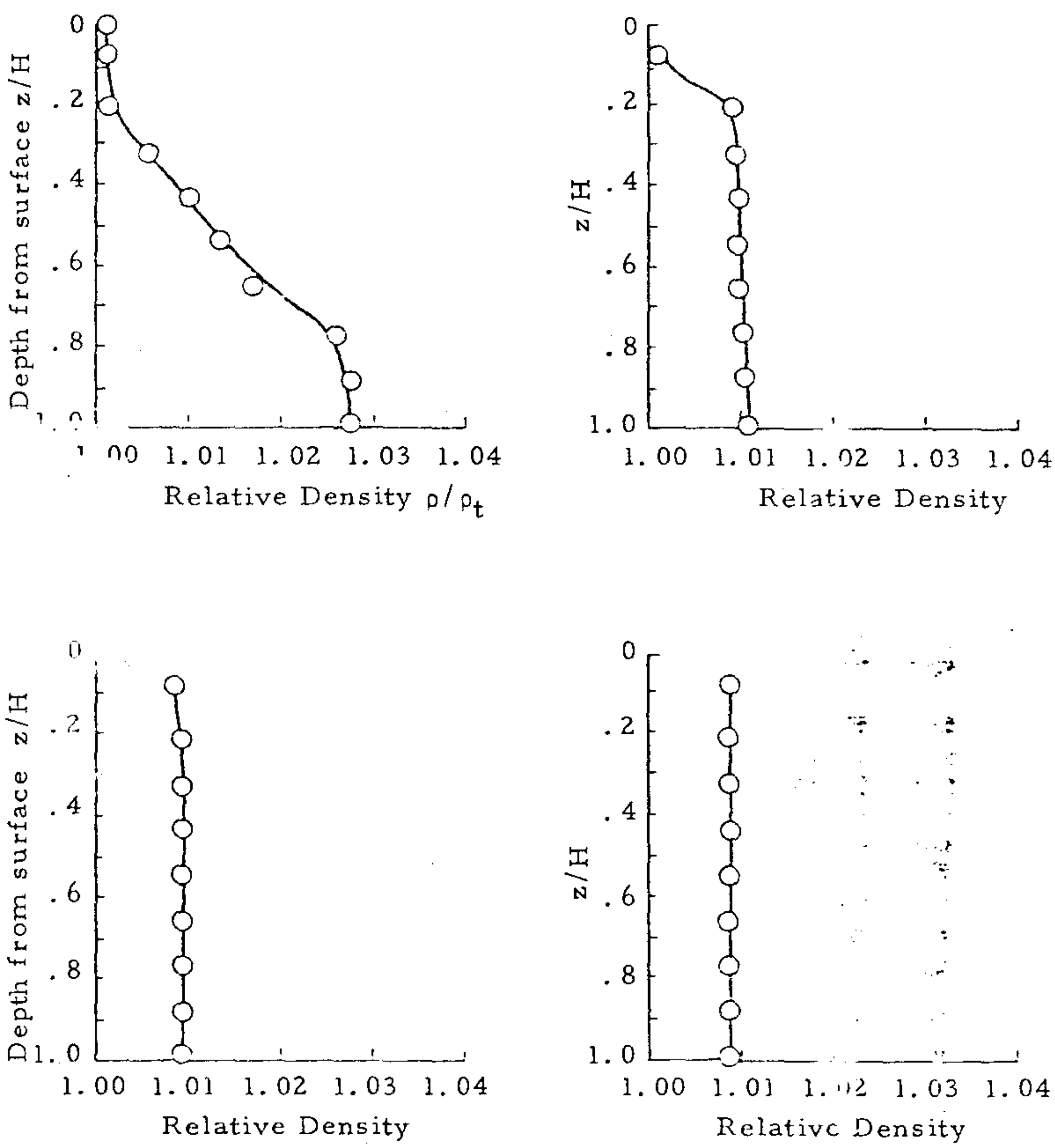
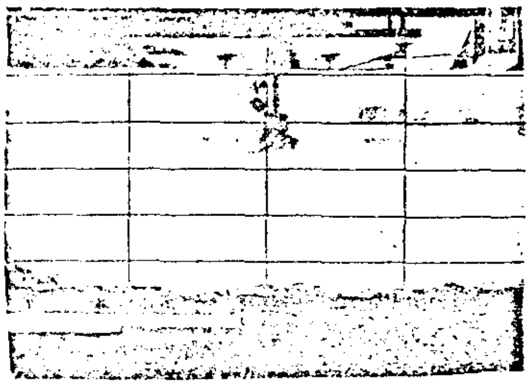
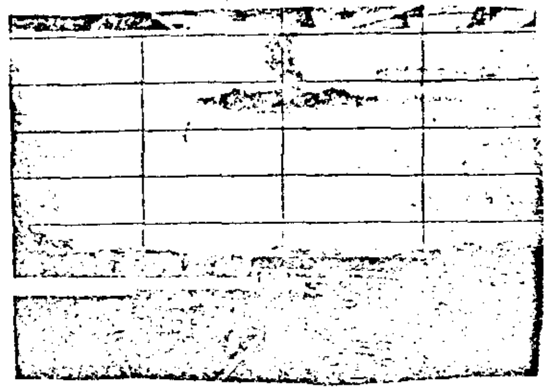


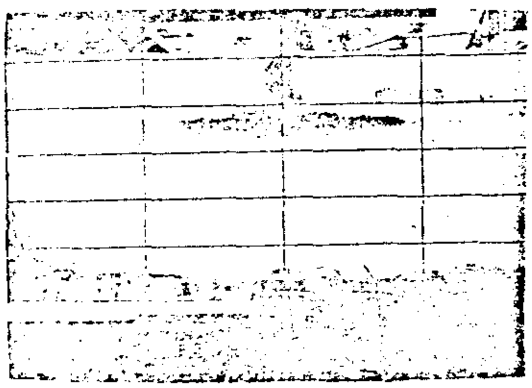
Figure 14 Density profiles recorded throughout the model destratification experiment A.



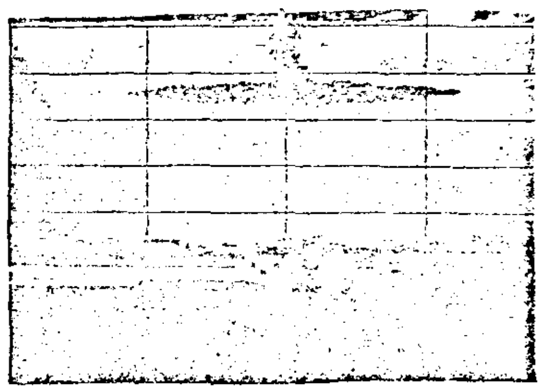
Elapsed time 3 seconds



Elapsed time 8 seconds



Elapsed time 12 seconds



Elapsed time 18 seconds

Figure 15 Flow visualization of the flow out of the mechanical destratification pump.

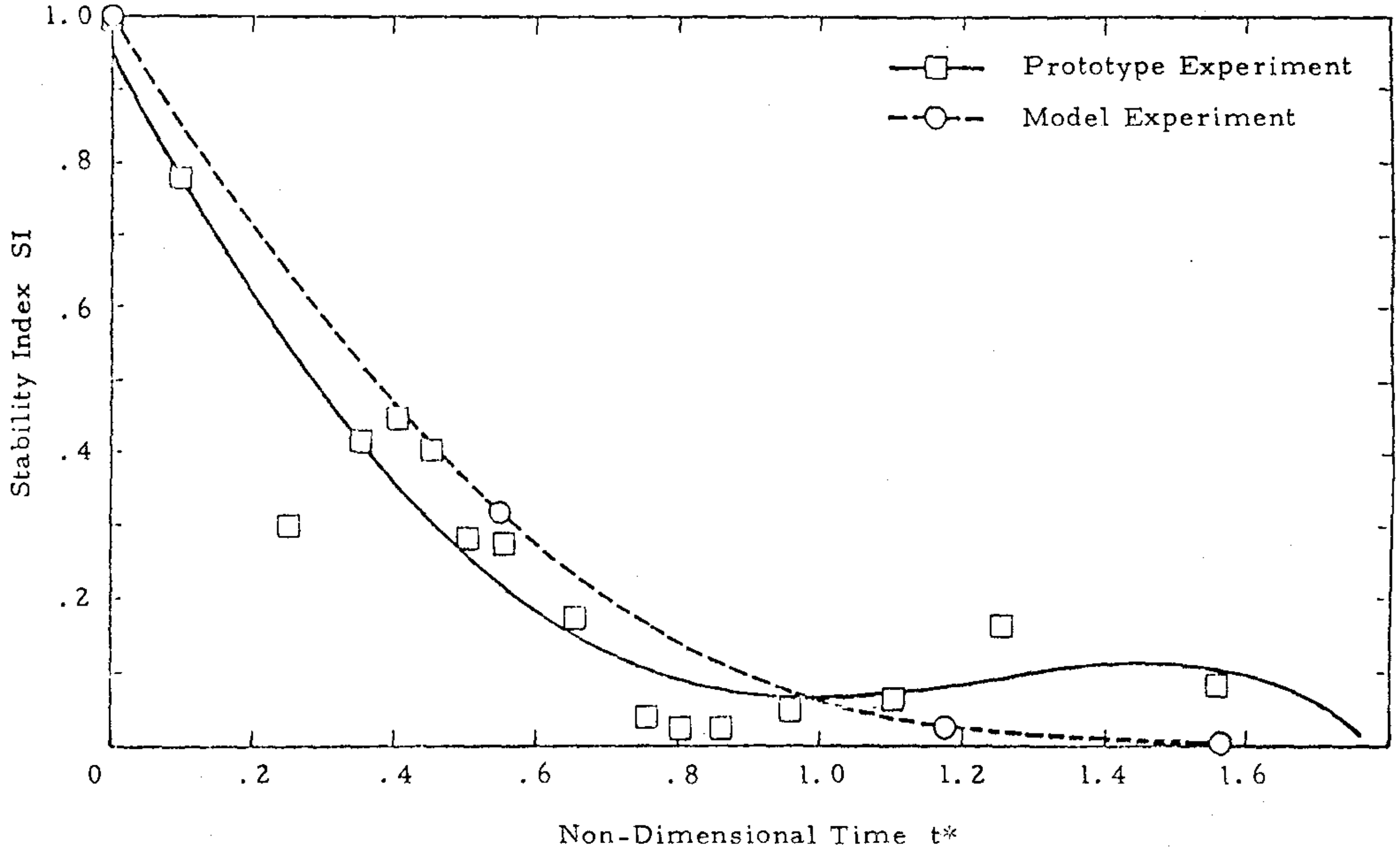


Figure 16 Comparison of stability index measurements made in the model with those made in the prototype lake during destratification.