THE BEHAVIOR OF FRESH WATER - SALT WATER INTERFACE IN COASTAL AQUIFERS IN THE PHILIPPINES

by

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ABSTRACT

Conducting paper models are utilized to determine the behavior of the fresh water-salt water interface in coastal aquifers. By a series of approximations and successive cutting off of the seaward side of the analog model, the final form of the salt water-fresh water interface is located. The effect of discharge wells, recharge or impermeable barriers can be studied by the method. Quantitative values are determined by the use of scale factors determined by ratios of equivalent elements of an aquifer and the analog model.

CHAPTER I

INTRODUCTION

1.1 Nature of Problem

Most of the towns and cities in the Philippines need a large supply of water for domestic and industrial uses. A considerable part of this supply will be drawn from ground water resources due to limited surface reservoirs. Though abundant rainfall and high recharge imply a vast reserve of ground water, the danger of sea water intrusion is ever present. The problem is evident because developed areas in the country are invariably situated along the coast of islands. When the development of the ground water resources is increased, the problem becomes compounded.

In order to prevent or minimize cases of salt water intrusion into coastal aquifers, a water management program should be worked out. However, at present, the formulation of any program is hampered by the lack of information regarding the hydrologic properties of the aquifers and the pumping rate in different areas. There is also the need for a better understanding of the behavior of the fresh water-salt water interface in conditions obtaining in the country.

However, because of limited facilities for research in the Philippines, the method of approach should be simple at the start.

The electric analog method with the use of conducting paper is best suited to this particular problem. The method requires few materials and is also very simple to operate. There is also a wide variety of conducting paper upon which different values of permeability can be simulated.

1.2 Scope of Problem

After studying the movement of the interface when there was no interference, the next step was to study the behavior of the interface when pumping was imposed on the system. Such preventive measures as the introduction of a line of recharge wells between discharge wells and the shore or the erection of an impermeable barrier were later simulated in the conducting paper model.

This work was done to determine the usefulness of this method with regard to the solution of salt water intrusion problems in the Philippines. More particularly, the objective of the experiment was to evaluate the limitations and capabilities of the method.

1.3 Geology and Hydrology of Coastal Aquifers

The coastal aquifers consist principally of limestone, clastic rocks of volcanic composition, and alluvium. A few are highly fractured volcanic rocks but they are of minor importance. The rock units range in thickness from two meters to about 500 meters; a thickness of about 100 meters is fairly common. Although the sedimentary rocks often dip in the order of one to two degrees toward the coast, dips as steep as 30° are not unusual. The rocks range in age from Miocene to Quaternary.

The limestone units are commonly composed of

> limestone, limy tuff, marl, dolomite and limestone conglomerate. The limestone includes accretionary types classified as biohermal limestone and clastic types classified as calcirudite and calcarenite. Much of it is friable and even the fairly dense, well-cemented limestone is porous. (Barnes, et. al. 1956, p. 20)

Because of the presence of caves and sinkholes, the permeability of this rock unit is erratic but is often very high.

On the other hand, the clastic rocks have a slightly lower porosity and permeability, mainly because of cementation. However, in spite of the cementation, these rocks are permeable enough to make good aquifers. They are generally fine to medium grained sandstone with interbedded siltstone and shale.

A few places in the central Philippines make good use of alluvial aquifers. In these places, the alluvium

attains thicknesses of over 300 meters. The alluvium is often poorly sorted "river flood and coastal plain deposits. The alluvium is of Quaternary age." (Melendres and Barnes 1957, p. 29)

Very little is known about the hydrologic properties of these aquifers. Before 1959, no pumping tests were made to determine the properties of any aquifer in the Philippines. Recently, the Philippine Bureau of Public Works conducted tests on some aquifers around Manila. The reported values of the coefficient of transmissibility can be grouped into three categories: 12,000 gallons per day per foot, 40,000 gallons per day per foot, and 100,000 gallons per day per foot. No storage coefficients were given, but most of the aquifers are under artesian pressure. These values are for aquifers composed of clastic rocks and fractured volcanic rocks. In the central Philippines where most of the limestone aquifers are found, no information is available except for the capacity of existing wells.

CHAPTER II

THEORY OF FRESH WATER - SALT WATER INTERFACE

More than 60 years ago, Badon Ghyben (1889) in Holland, and Herzberg (1901) in Germany found that the depth to salt water was a function of the height of the water table above sea level and the densities of the fresh and salt water. This relationship can be expressed as

$$z_{23} = \frac{d_f}{(d_s - d_f)} \quad z_{12} \qquad (2.1)$$

where z_{23} is the depth to the interface between the fresh water and salt water below sea level, z_{12} is the height of the fresh water above sea level, d_f is the density of fresh water, and d_s is the density of the salt water (Fig. 1). As the density difference between sea water and fresh water is only about one-fortieth of the density of fresh water, a simple algebraic computation shows that the fresh water body has a thickness below sea level of about 40 feet for each foot of fresh water above sea level. These deductions are based mainly on the assumption that a hydrostatic equilibrium exists between the fresh and salt water.

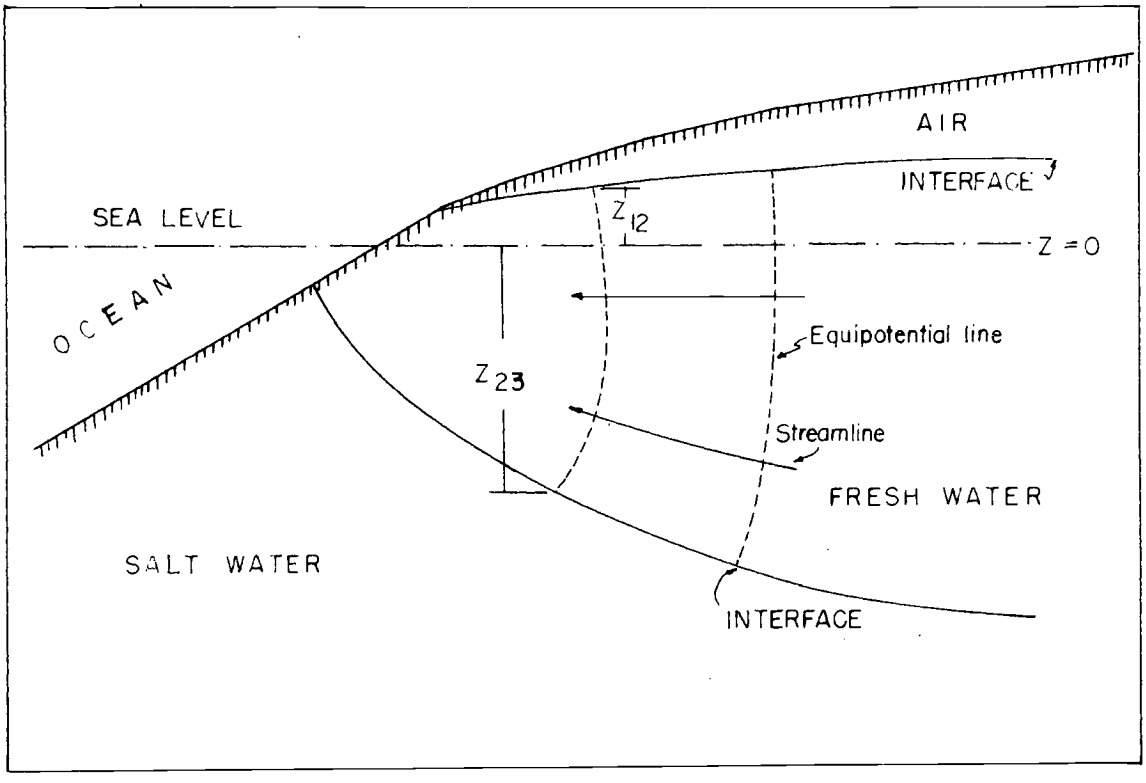


Fig. 1 Schematic diagram showing interfaces between fresh water and air, and between fresh and salt water in an unconfined aquifer. (Todd 1953, p. 750)

On the contrary, M. King Hubbert (1940) clearly demonstrated that the principle is valid only for hydrostatic conditions and does not apply completely to ground water flow conditions. However, Glover (1959) observed that a short distance back from the beach, static conditions may be met. Near the shore, dynamic factors are more significant. Moreover, because the flow of fresh water toward the sea must balance natural recharge from rainfall, a seaward gradient should exist. One other point to be considered is that if static conditions prevail, the fresh water body would taper to a knife edge at the beach and no fresh water could escape. Hubbert showed instead that fresh water must flow through a zone of finite width between the interface and the water table outcrop at the beach. This zone is called the zone of seepage.

Furthermore, a horizontal interface between the fresh water and salt water with the fresh water everywhere above the salt water would result if static conditions existed. Hubbert (1940) again showed that this idea is incorrect. In Figure 1, the differences in elevation from sea level are measured to points of intersection of a constant fluid potential with the two interfaces. These two points lie on a single vertical line only if the fresh water is flowing uniformly and horizontally. As this assumption cannot exist in the field, the points are not

aligned vertically. Therefore, theoretically, at any given point, the height of fresh water above sea level is not a simple function of the fresh water depth below sea level at the same point.

It must also be understood that under actual dynamic conditions, the interface would not be as sharply defined as under assumed static conditions. Tidal action and the fluctuations of the water table maintain a zone of diffusion between the fresh and salt water. A better but nevertheless inadequate assumption is that sea water is static and only the fresh water is in motion. Kohout (1960) in an investigation of the coastal part of the Biscayne aquifer of the Miami area in Florida found evidence that the salt water body is also in motion. From cross sections showing lines of equal fresh water potential, he concluded that during periods of significant recharge, the fresh water head is high enough to push the fresh water, the sea water and the zone of diffusion between them seaward. Conversely, when the fresh water head is low, salt water flows inland at the lower part of the aquifer. At the same time, some of the diluted sea water in the zone of diffusion continues to flow seaward. Thus, "salt water circulates inland from the floor of the sea through the lower part of the aquifer becoming progressively diluted with fresh water to a line along which it moves upward and returns to the sea." (Kohout 1960, p. 2133)

What processes then operate in the zone of diffusion to induce this cyclic flow of sea water? Cooper (1959) suggests that the circulation is caused by the transfer of salts out of the sea. Firstly, because of the reciprocative motion of the interface, a fairly wide zone of diffusion is produced wherein native sea water is mixed and diluted with fresh water. Secondly, the diluted sea water within this zone, being less dense than the native sea water, rises and moves along the interface back to the zone of seepage. Although dilution and dispersion would occur across any interface between fresh and salt water, the width of the interface along coastlines is greatly enlarged and the rate of dispersion is increased by the aforementioned reciprocative motion caused by tides and the fluctuations of the water table.

The slope of the interface is an important consideration in the study of the balance between sea water and fresh water. Hubbert (1940) derived expressions to determine the slopes of interfaces in terms of fluid potential gradients. By applying Darcy's law on Hubbert's equations, Todd (1953, p. 750) expressed them as

$$\sin \alpha_{12} = -(1/g)\, q_f / \sigma_f \qquad (2.2)$$

$$\sin \alpha_{23} = (1/g)\, d_f / (d_s - d_f)\, q_f / \sigma_f \qquad (2.3)$$

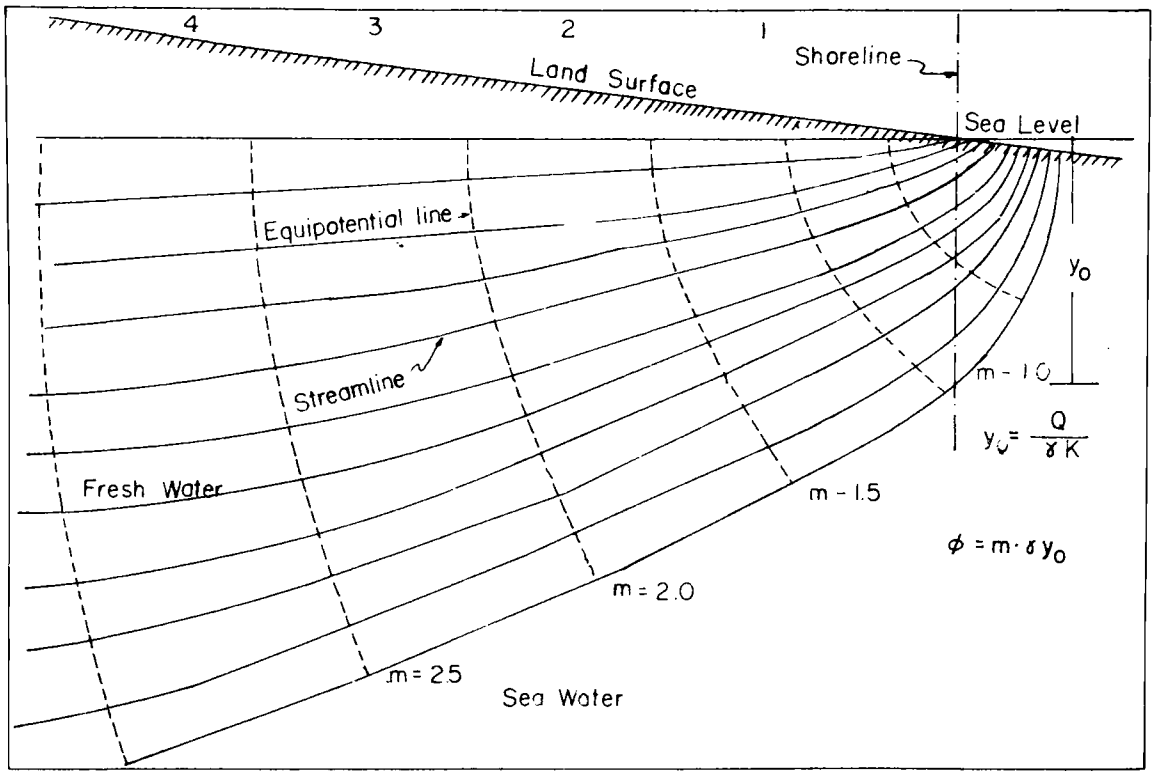
where q is the discharge per unit area, σ_f is the combined permeability parameter, d_s and d_f are the densities of salt

water and fresh water, respectively, and α is the angle of the interface measured from the horizontal in the direction of the fresh water flow. Equation 2.2 shows that the slope is directly proportional to the magnitude of the fresh water flow and that the fresh water interface tilts downward in the direction of fresh water flow, whereas the lower interface tilts upward in the same direction as shown by equation 2.3. As a result of this convergence, the interfaces will be concave toward the fresh water body.

Although the existence of dynamic equilibrium in ground water flow is already accepted, most of the formulas regarding the interface are derived under the assumptions of complete or partially static conditions. A flow net to represent the flow conditions near a beach has been derived by Glover (1959) based on Kozeny's previous work. The interface between the fresh and sea water can be plotted from the expression

$$y^2 = \frac{2Qx}{\gamma K} - \frac{Q^2}{\gamma^2 K^2} \qquad (2.4)$$

where x is the distance measured horizontally landward from the shoreline, y is the distance measured vertically downward from sea level, Q is the fresh water flow per unit length of shoreline, K is the permeability of the stratum carrying fresh water flow and γ is the excess of the specific gravity of sea water over that of fresh water. Fig. 2 shows the flow



Total flow is Q.

Flow above any streamline is nQ.

For a measured potential ϕ_1 at $y = 0$ and $x = x_1$

$$Q = \frac{K\phi_1^2}{2\gamma x_1}$$

For ordinary water, $\gamma = 0.025$ approx.

Fig. 2 Flow pattern near a beach (Glover 1959)

pattern near a beach. The width of the gap through which the fresh water escapes to the sea is expressed by

$$x_o = \frac{Q}{2\gamma K} \qquad (2.5)$$

Work on similar problems by Muskat, Botset, Wyckoff, Reed and others is discussed in the following chapter.

CHAPTER III

THE USE OF CONDUCTING PAPER

3.1 Theoretical Basis for Analogy

The usefulness of the electrical analogy in ground water flow studies stems from the similarity between Darcy's law and Ohm's law. Darcy's law states that

$$Q = PIA \qquad (3.1)$$

where Q is the rate of flow of water, P is the permeability of the medium, I is the hydraulic gradient and A is the area of cross section through which the fluid flows. On the other hand, Ohm's law states that the voltage is equal to the product of the current passing through the conductor and the resistance of the conductor. In symbols

$$E = IR \qquad (3.2)$$

where E is the voltage, I is the current and R is the resistance of the conductor.

The analogy is more evident after slight modifications of the two equations. By substituting h/l for the hydraulic gradient, Darcy's law becomes

$$Q = P(h/l)A \qquad (3.3)$$

where h is the fresh water head and l is the length through which the fluid flows. Similarly, by rearranging and expanding Ohm's law to show the relation of the resistivity ρ, length L and cross sectional area A of the conductor, equation 3.2 becomes

$$I = \frac{1}{\rho}(E/L)A \qquad (3.4)$$

or

$$I = \gamma\frac{E}{L}\ A \qquad (3.5)$$

where γ is the conductivity of the material.

Equations 3.3 and 3.5 now show distinct similarities. In the electric analog, the conductivity is equivalent to the permeability as the voltage is to the head. The amount of current passing through an electrical conductor is similar to the volume rate of flow of ground water. Similarly, a capacitor in an electrical circuit stores electrical energy in a way comparable to water storage in permeable earth material.

3.2 Assumptions and Limitations

To be valid, several assumptions regarding the behavior of the numerous factors that influence the salt water-fresh water interface were made.

First, the balance between the fresh water and salt water is assumed to be a steady state condition. This simplification is necessary because dynamic conditions

cannot be simulated in the model. Kohout has shown that although in nature some 'diluted' sea water may circulate, in the conducting paper model, the salt water is considered motionless.

As fresh water and salt water are miscible, mixing is bound to happen along the interface. Instead, the salt water-fresh water interface is assumed to be sharp and well defined. In other words, dispersion is ruled out.

From previous discussions, the interface was shown to extend out into the sea floor, because the higher gradient of the fresh water tends to push back the sea water front. However, to simplify the analog model, the line sink which should slope parallel to an imaginary sea floor was reduced to a short vertical discharge line or a round discharge "point." Although this change would affect the shape of the interface near the shore line, it should have negligible effect on the problems dealt with below. Furthermore, a semi-infinite aquifer is presumed, for flow lines to be parallel at the source electrode.

It must be realized that pumping is seldom continuous. However, the cessation of pumping cannot be simulated in the analog model to determine the reversal of movement of the interface. The experiment determined only the final shape of the interface. Actually, after cutting away at the discharge end of the paper, the retreat of the salt water front is impossible to retrace. Similarly, the effect of recharge on the movement of the interface cannot be assessed as

desired. Rather, its effect is inferred from the final configuration of the interfaces in models with and without recharge imposed on the model.

A pumping well will invariably draw up an inverted cone of depression with time. Owing to the method of cutting the paper, the coning is only shown on the inland side of the paper. The seaward portion is often shown as a flat or gently sloping surface even though an injection well may be present near the shore.

3.3 Previous Works

As late as ten years ago, very little work was done on ground water flow through porous media by the electrical analog method and practically none by the use of conductive sheets. At present, most hydrologists use resistance network analogs and dimensional models.

The use of conductive sheets in electrical analogs began with Kirchoff in 1845, who used copper sheets to model heat flow problems. In the early 1930's, graphite sheets were used in the analysis of ground water flow by Muskat and later by Wyckoff and Reed (1935).

Although not specifically on the subject of salt water intrusion, comparable work can be obtained from studies made by petroleum engineers in their attempt to get more information regarding gas and water coning in oil wells. Foremost among the men who applied electrical analog techniques in solving coning problems was Muskat. Before

Muskat (1937) published his book on the flow of homogenous fluids through porous media, he, together with Wyckoff and Botset, made studies on the theory of water coning in oil production by electrolytic and conductive sheet models. For the latter, they used a "radial sector of pressed carbon at the broad end of which was soldered a metal plate to give the effect of a uniform reservoir pressure and at the vertex of which was soldered a thin copper rod representing the partially penetrating well." (Muskat 1937, p. 485)

Muskat also used graphite paper in the analysis of the suppression of water coning in partially penetrating oil wells by shale lenses. Much of their work involved mapping the potential distribution over the conducting sheet models. However, in the above experiment, Muskat arrived at the water cone by the trial and error method of cutting away part of the conducting sheet.

Karplus (1953) in a study of water coning in oil wells by a resistance-network analog emphasized that "the new steady state shape of the interface depends upon the depth of penetration, the thickness of the oil zone, the production rate, the hydraulic permeability of the sand, the viscosity and density of oil and water." Except for viscosity, these parameters are similar to the factors affecting the behavior of the salt water-fresh water interface.

In 1954, Meyer and Garder (1954) discussed the mechanics of two immiscible fluids in relation to water

coning in oil wells. They also offered an equation to determine the maximum production rate under given conditions that would still avoid intersection of the salt water cone with the production well.

Very recently, Richard Tinlin, of the United States Geological Survey, Phoenix, Arizona office, attempted to study the fresh water-salt water interface phenomenon on Teledeltos conducting paper. The author extended this work when Tinlin left it to work on a more pressing project.

3.4 Procedure

Muskat (1937, p. 244) cautioned that

> although the absolute dimensions are determined primarily by convenience and the accuracy desired, it is absolutely necessary for the model and original flow system to be geometrically similar if the results obtained with the model are to be similar to the physical flow problem.

The experiments utilized the following materials: conducting paper of appropriate resistivity, clip board with electrical sockets, Keithley voltmeter, ammeter, dry cells, helipot or potentiometer, and razor blades.

A wooden board at least eight inches wide and two feet long was used in the construction of the clip board. A clamp is attached to one end and the sockets were soldered into the clamp. On the other end of the board, a screw with a wing tip bolt is the discharge electrode. To convert into a line discharge electrode, a copper plate with a straight electric wire soldered parallel to the length of the plate is used as in Figure 3.

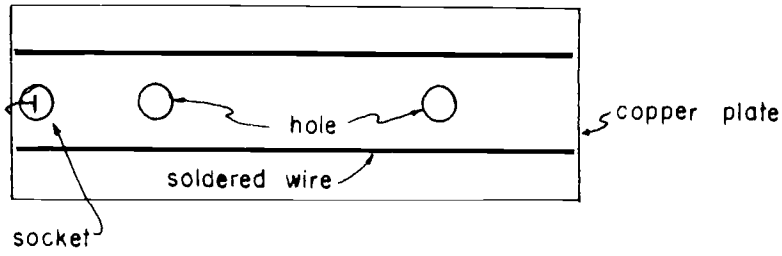


Fig. 3 Bottom view of copper plate used as discharge electrode.

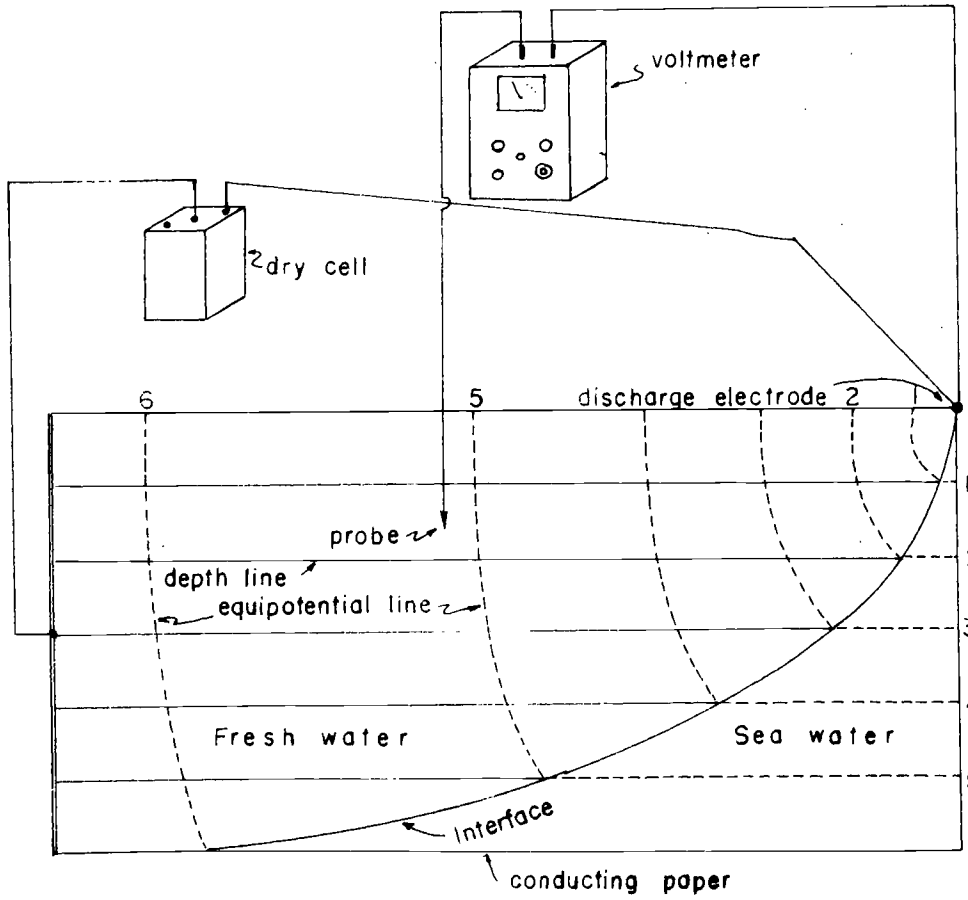


Fig. 4 Schematic diagram of set-up of a model.

Cut a rectangular piece of the conducting paper four or five inches wide and long enough to fit the clip board. Divide the vertical into quarter-inch strips to represent the depth lines. Then clamp the paper to the electrodes. Adjust the paper so that the discharge electrode is at the desired depth to approximate the zone of seepage in the sea floor.

As in Figure 4, it is assumed that at the fresh water-salt water interface, a certain potential corresponds to a certain depth. Choose a convenient value such as a potential interval of one volt per depth line. In this case, at the first line below the tip of the discharge electrode, the potential should be one volt; at the next line, it should be two volts, and so forth. Connect the ammeter to the system to determine the amount of current passing through.

Slide the probe along the first line below the tip of the discharge electrode and locate the point at which the voltage reading is one volt. Probe along the succeeding horizontal depth line to the point where a reading of two volts is registered in the voltmeter. Repeat the probing for each of the lines until the voltage corresponding to the last line has been located. In the course of the probing process, refrain from leaning on the conducting paper and insure that the probe is held in a uniform position. Cut the paper back approximately halfway between the line determined by the points and the edge of the conducting paper on the seaward

Repeat the probing along each line and cut again midway between the lines determined by the located points and the edge of the paper. Repeat the process until the voltage readings along each line at the edge of the paper are the required potentials. This cut edge is the theoretical fresh water-salt water interface. Then outline the potential distribution over the field. Run the probe and determine equipotential lines at an interval of one or two volts.

Proceed with the experiment using a new sheet of the conducting paper which has been subdivided into depth lines. The factors influencing the behavior of the interface are permeability, water table gradient thickness of the aquifer, depth of penetration of discharging wells, the rate of pumping, presence of recharging wells, and the presence of impermeable barriers.

To introduce effects of non-uniformity, cut lenticular or rectangular slots at desired locations to simulate impermeable beds. To increase the permeability of certain strips, paste strips of the same conducting paper at proper locations. The effect of the thickness of the aquifer is modelled by the width of the conducting paper. Attempt to approximate the sloping of the water table as it approaches the shore by cutting off a portion of the top edge of the paper.

Use a slim steel cotter pin to simulate a discharging well. Pull up or push down the cotter pin to desired depths

to simulate differences in the depth of penetration of the wells.* It is suggested that increments of half an inch be used to simplify the analysis. The cotter pin can also be moved laterally to study the effect of the distance of wells from the shore. Place the pin at the 2-inch, 4-inch, or 6-inch marks, as measured from the discharge electrode.

A capacitor of the appropriate value is inserted into the models to determine the effect of storage. Clamp a narrow steel plate to the top edge of the conducting paper to simulate natural recharge. Insure good connections with the paper, since loose connections result in erratic voltage readings.

To study the effect of recharging wells, a cotter pin is inserted between the discharge wells and the discharge end electrode. A source is connected to this pin. Variations in position can be made as in the discharge well pin. Cut off holes of appropriate shape and size at desired locations to simulate the effect of an impermeable barrier. The depth, size and shape of the subsurface dike can be varied as is necessary.

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*Strictly speaking, the cotter pin models a trench rather than a well. However, the trench may be replaced by a line of wells to give approximately the same effect.

CHAPTER IV

EXPERIMENTAL RESULTS

4.1 Qualitative Results

It must be emphasized that in this study, the equilibrium form of the fresh water-salt water interface is the objective. In the interpretation of the results then, deductions are made from the comparison of several cases.

In this connection, diagrams show the final form of the interface and also how far the paper is cut back each time. It takes six cuttings at the most to obtain the required voltage at the interface. After the fourth or fifth cutting, it is normal to find that a slight overcutting results in a higher potential at the interface than desired.

The non-uniformity of the aquifer either accelerates or retards the movement of the interface depending on whether the impermeable beds are on the seaward or the landward side of the discharge well. The creep of the interface is reduced at points above impermeable beds. However, the interface moves father inland beneath the impermeable beds than when there are no variations in permeability.

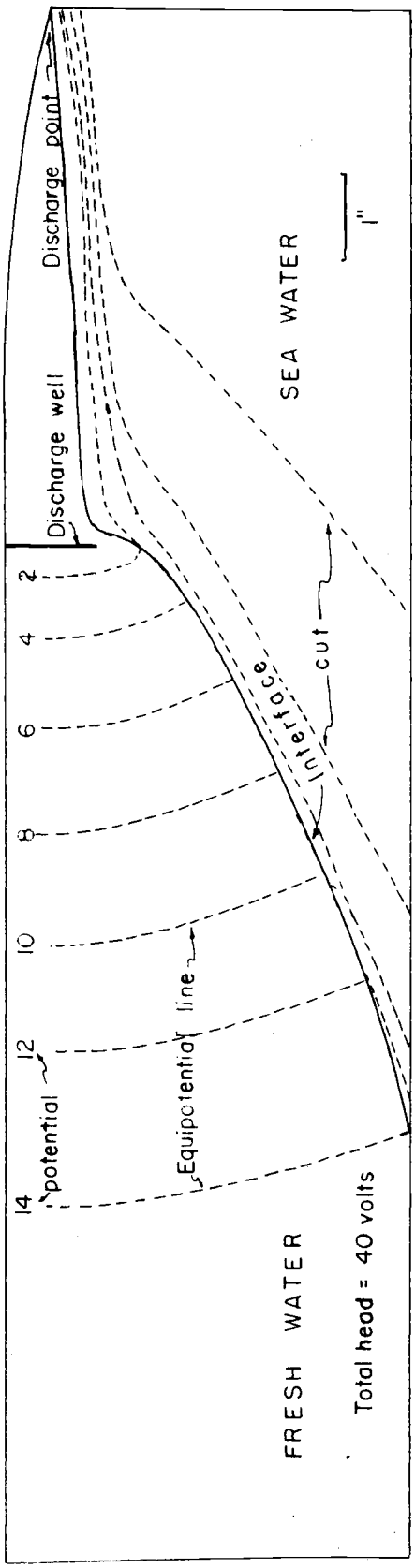
Aquifer thickness alone does not have any variable effect on the position of the interface. Early experiments

showed that the final shapes of the interface were similar in all cases. In models where discharge wells were not added, the form of the interface at the bottom of the thicker aquifers is only a landward extension of the interface in the thinner aquifers.

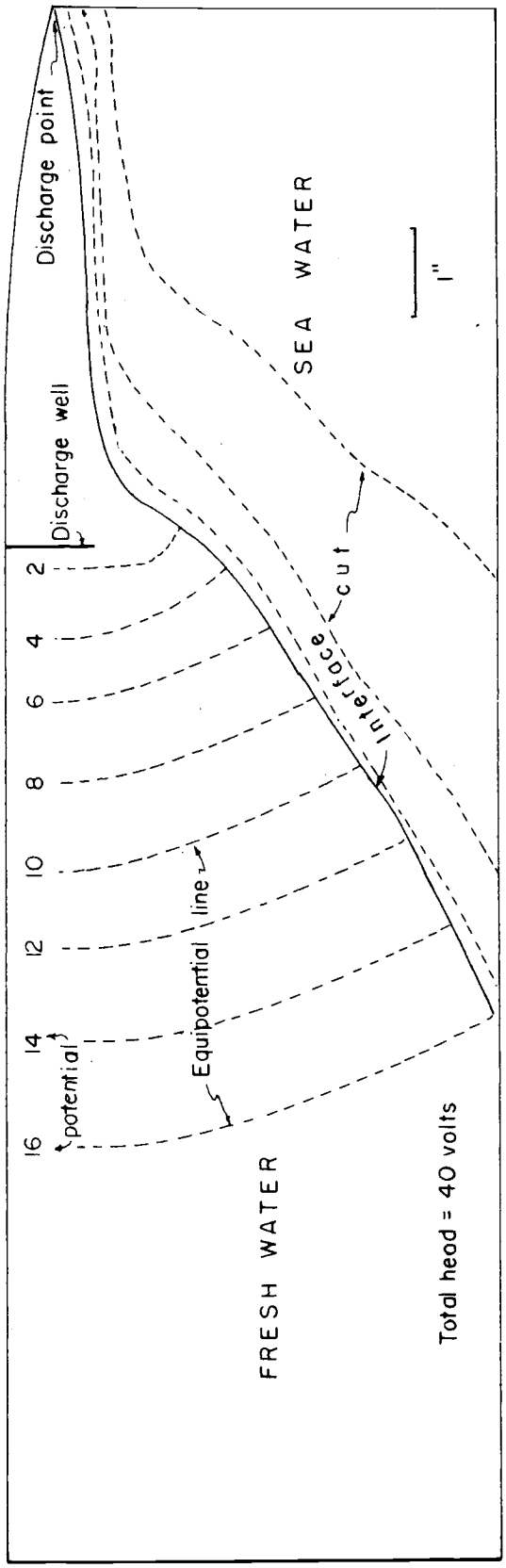
The depth of penetration of pumping wells has a profound effect on the movement of the interface. The interface readily moved up to the deeper discharge wells and in most cases, did not reach the tip of the shallower wells. Exceptions are when the shallow wells are very near the shore. In this instance, the interface also approaches the discharge well.

The pumping rate has the most pronounced effect on the movement of the fresh water-salt water interface. The heavier the pumping rate of a well, the greater the extent of the encroachment of the salt water and the faster the rate. Heavy pumping is decidedly very critical when the discharge well is very close to the shore. At a greater distance from the shore, the movement of the interface is much more limited.

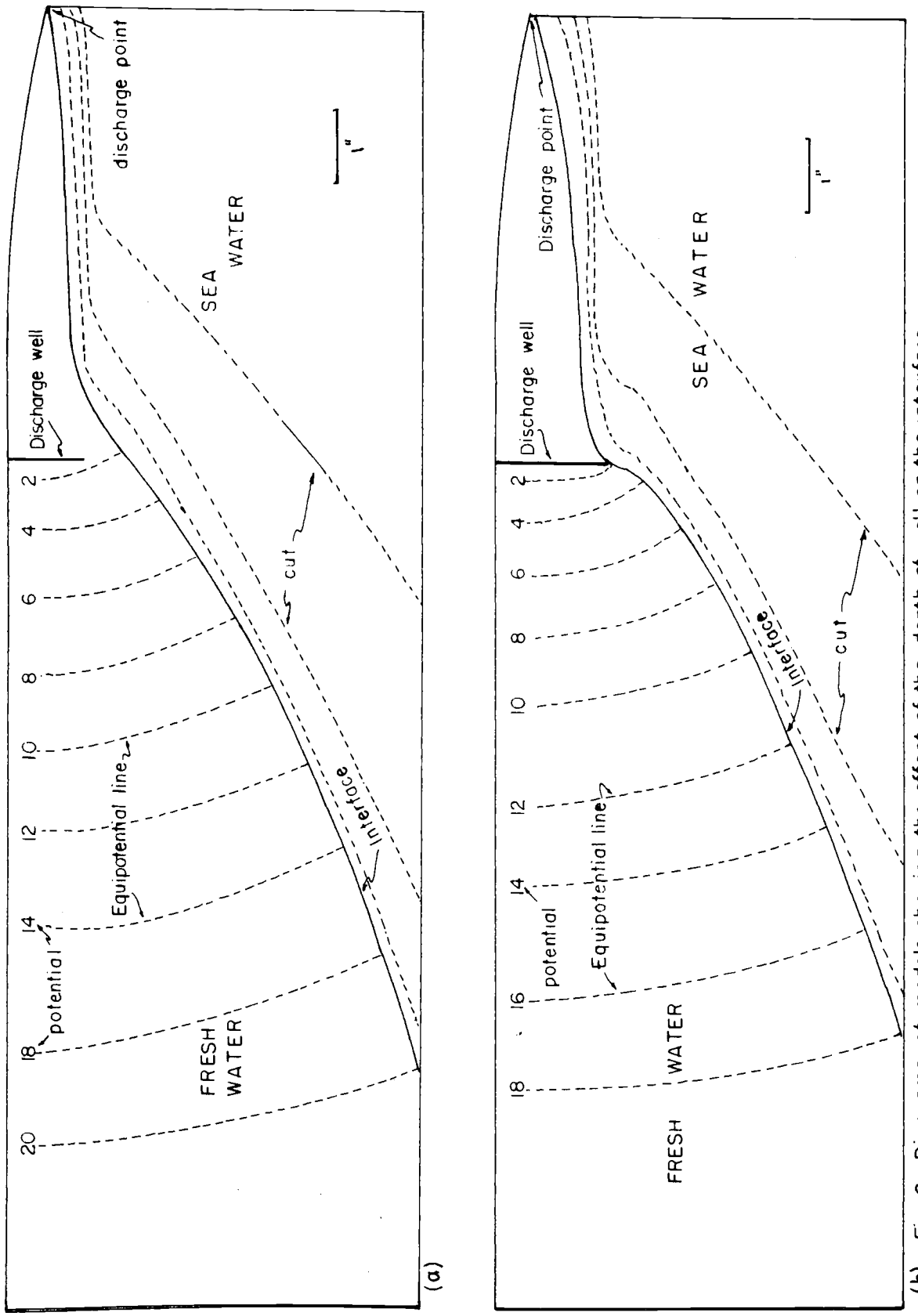
The results obtained in the determination of the effect of storage are doubtful. The problem originated from the poor contact between the capacitor and the conducting paper. Taping the capacitor to the paper resulted in unstable readings from the voltmeter. Metallic paint was used instead of cellulose tape.



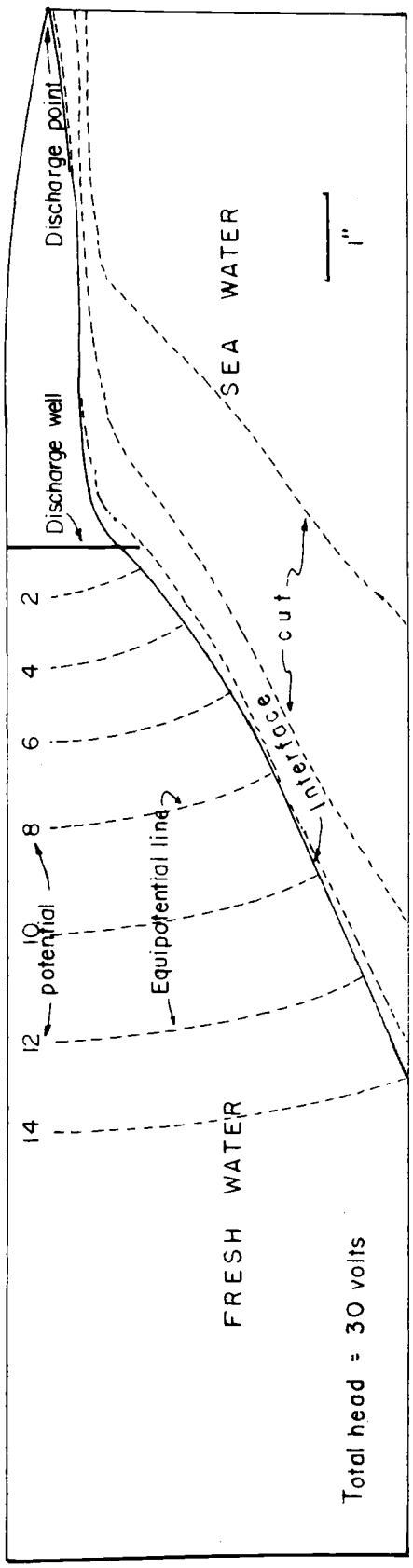
(a)



(b) Fig. 5 Diagrams of models showing the effect of aquifer thickness on the interface.



(b) Fig. 6 Diagrams of models showing the effect of the depth of well on the interface.



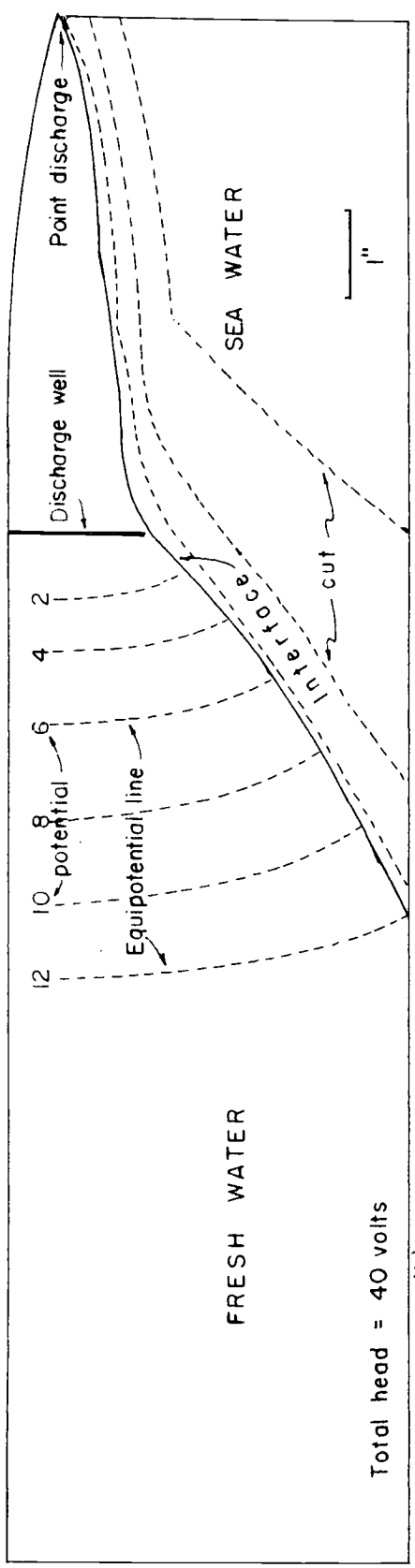


Fig. 7 Diagrams of models showing the effect of varying the head on the interface.

Considering the cumulative effects of these various factors, some factors seemingly cancel out each other's effect, but minute differences are still discernible in the shape and extent of the interface.

In two cases studied (Figs. 7a and 7b: Figs. 5b and 6a), the aquifer thickness and the depth of penetration of wells are similar in each case but the pumping rates are unequal. Comparisons showed that the two wells with the higher pumping rate tend to draw the interface into the wells. On the other hand, the wells with a lower rate did not pull the interface into the wells. In the second case (see Figs. 5b and 6a), where there was no sea water drawn into the well, it was noted that the interface had a steeper slope near the discharge well in the model of the thinner aquifer but the interface extended farther inland in the thicker model.

In Figure 7, and Figures 6a and 5b, the aquifer thickness and the pumping rates are the same while the depths of the penetration are different. It is obvious that at greater depths, the wells acquire greater chances of drawing salt water into the well. In one case (Fig. 7b), the interface has already crossed the foot of the deeper well while the salt water front barely reached the shallower well (Fig. 5a). There is a notable difference in the steepness of the slope of the interface near the discharge well. Furthermore, the landward movement of the salt water front

is retarded by the deeper well.

Natural recharge tends to push back the salt water front. However, since ground water withdrawal may cause a landward gradient locally, the danger of sea water intrusion cannot be disregarded. Studies made on the conducting paper models confirm these views. Models where recharge was added show that the landward movement of the interface is more subdued than in previous models where recharge was not considered. There is always some natural recharge to most aquifers to justify the superimposition of these quantities over all the succeeding models.

As far as natural conditions are concerned, the above experiments provide a qualitative description of conditions. However, in some places salt water intrusion problems have reached such an extent that artificial methods of controlling the salt water become necessary. Of the several methods possible (Todd 1953), only the two methods previously mentioned were simulated in conducting paper models.

The models of an impermeable barrier confirmed some features that were anticipated from a general knowledge of potential flow. They showed that widening the barrier does not have any further effect on the shape and form of the interface. However, the depth of the barrier is a significant factor. The comparison of three models which indicated subsurface dikes of different widths and depths suggests

that the optimum depth of the barrier is approximately the same depth as the nearest pumping well.

Although a shallow barrier can retard the movement of the salt water front into the discharge well, prolonged heavy pumping may still induce salt water intrusion.

Another interesting revelation is that a barrier deeper than the discharge wells may also induce salt water intrusion. This can be explained by the fact that the barrier will in effect produce a greater drawdown on the seaward side of the discharging well and will eventually cause a rise of the sea water from beneath instead of laterally from the sea.

Since recharge by injection wells will produce a more or less controllable fresh water mound, the recharge method is technically practical, economics permitting. However, the depth to which fresh water is injected into the aquifer seems to be a critical factor. Shallow wells or water flooding (Fig. 8a) may not produce a noticeable mound of fresh water, but it can control the possible entrance of salt water into discharging wells if they are far enough from the shore. When the wells are very close to the coast, a deeper injection well is necessary to inhibit salt water intrusion.

Figures 9, 10 and 11 show diagrams of models to determine the effect of the distance of the wells from the

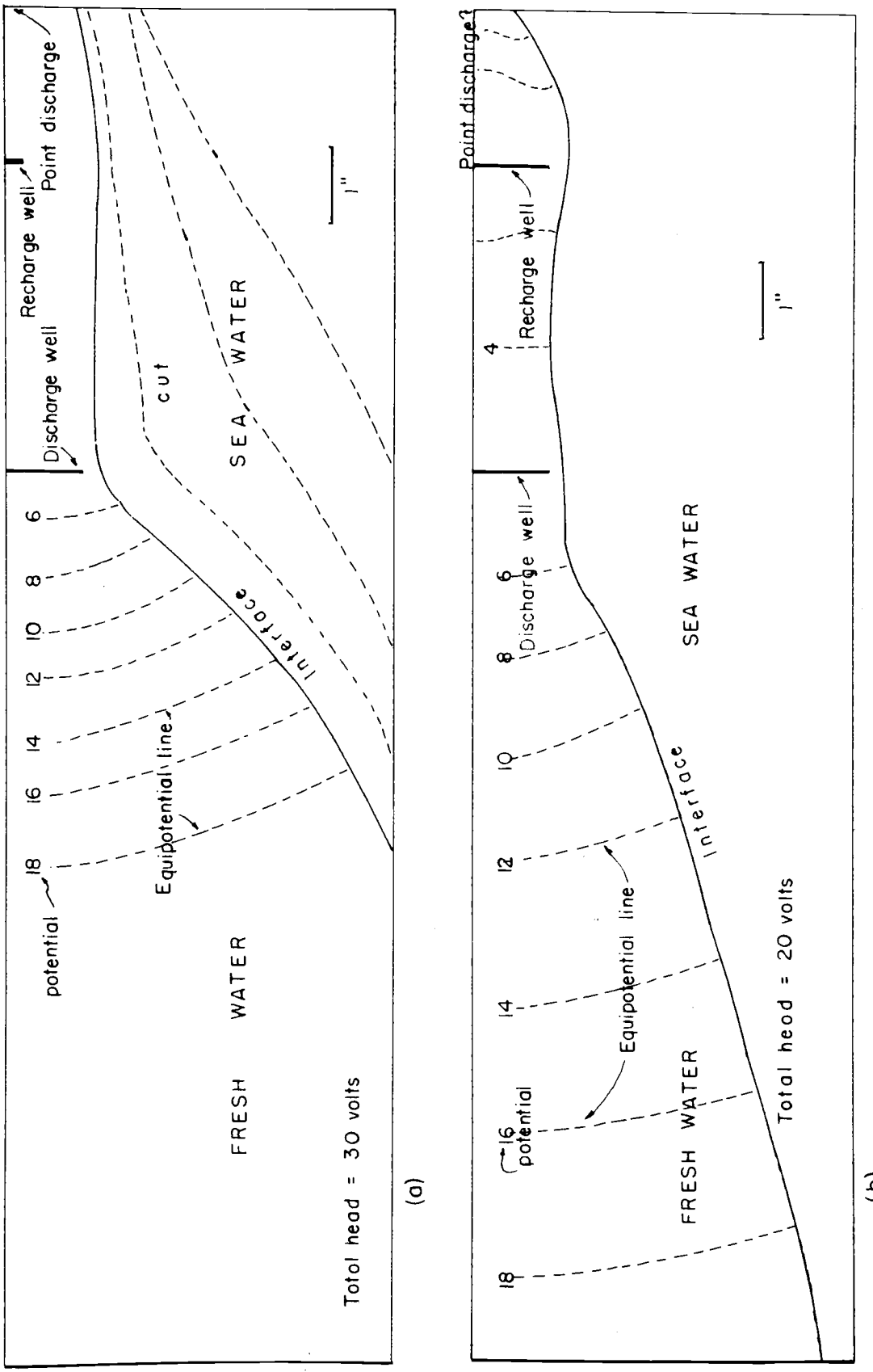


Fig. 8 Diagrams showing the effect of depth of recharge well on the interface.

shore when artificial recharge is superimposed on the system. The effect of recharge was most pronounced in Figure 10 where the discharge well is 4 inches from the injection well. As the discharge well is moved toward the source electrode, the effect of the recharge well is apparently reduced.

These results are merely qualitative. For the method to be more useful, quantitative results should be obtained. Values are given in the following chapter.

4.2 Scale Factor

Consider a vertical cross section of an aquifer as in Figure 12. The equivalent of the aquifer will be a strip of conducting paper model with proportional dimensions such that the width, length and thickness of the paper corresponds to the same dimensions of the aquifer; the electrical properties of the model should likewise be equivalent to the hydrologic properties of the aquifer. The scale factor for a model is determined from the ratios of corresponding values.

The ratios referring to the length and thickness of the aquifer is first considered, thus:

$$K_1 = \frac{M_e}{M_a} \qquad (4.1)$$

$$K_2 = \frac{L_e}{L_a} \qquad (4.2)$$

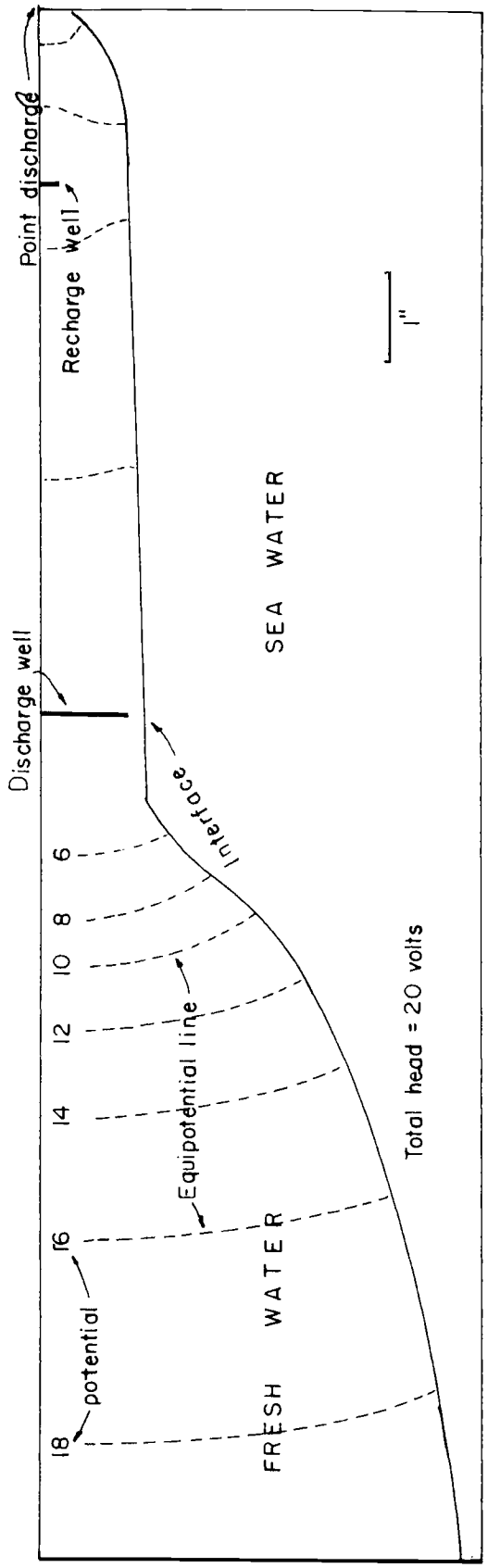


Fig. 9 Diagram of conducting paper model showing effect of recharge on the interface.

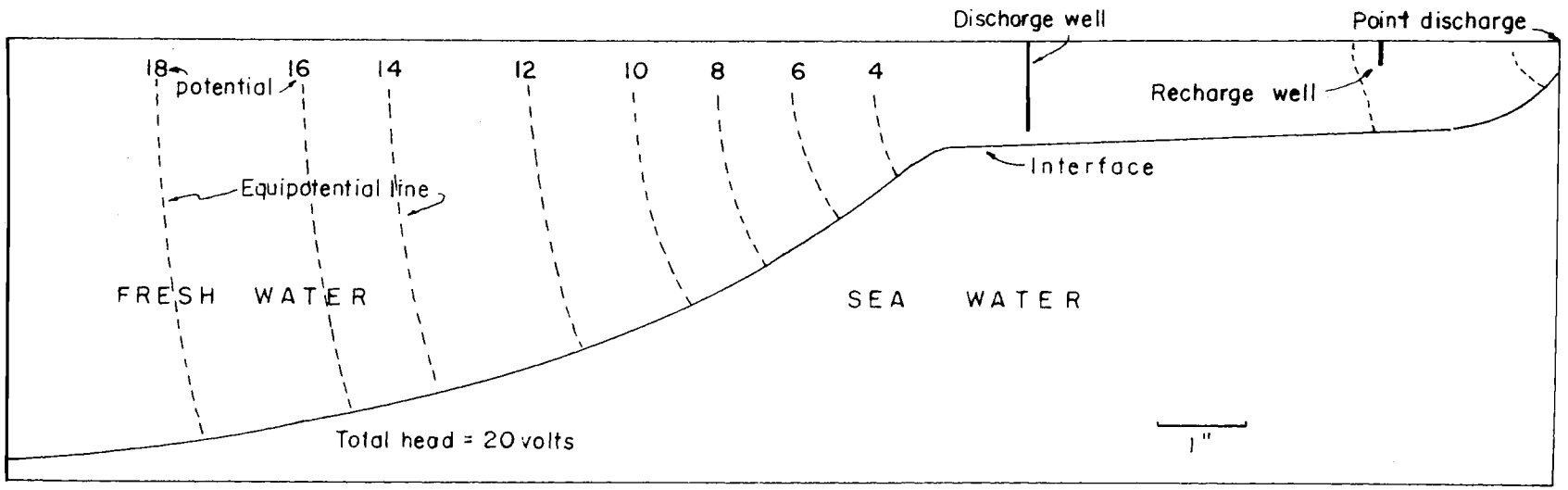


Fig. 10 Diagram of a conducting paper model showing effect of recharge on the interface.

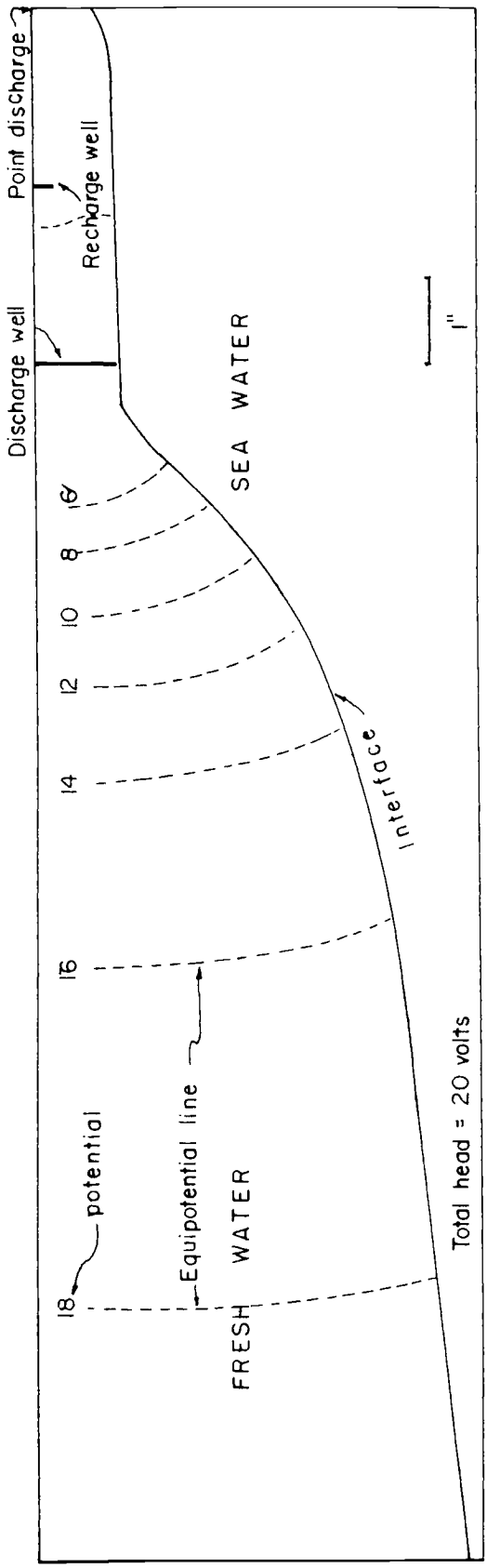


Fig. 11 Diogrom of conducting paper model showing effect of rechorge on the interfoce.

where M_e is the width of the conducting paper, M_a is the thickness of the aquifer, L_e and L_a refer to the length of the conducting paper and the aquifer, respectively. These two ratios indicate the relationship between the horizontal and vertical scale of the model. The ratio K_1/K_2 is further related to the ratios of the other equivalent values. The other ratios are designated as

$$K_3 = \frac{I}{Q} \tag{4.3}$$

$$K_4 = \frac{\gamma W_e}{P W_a} \tag{4.4}$$

$$K_5 = \frac{E}{h} \tag{4.5}$$

where I is the current passing through the discharge pin, Q is the pumping rate, γ is the conductivity of the conducting paper, P is the permeability of the aquifer, W_e is the thickness of the conducting paper, W_a is the unit width of the section of the aquifer, E is the voltage head at the source end of the model, and h is the fresh water head.

To achieve geometrical similarity between the aquifer and the model, the ratio K_1/K_2 should be equal to the ratio K_3/K_4K_5 which is likewise equal to one, so

$$\frac{K_1}{K_2} = \frac{K_3}{K_4K_5} = 1 \quad \text{or} \quad K_5 = \frac{K_2K_3}{K_1K_4} \tag{4.6}$$

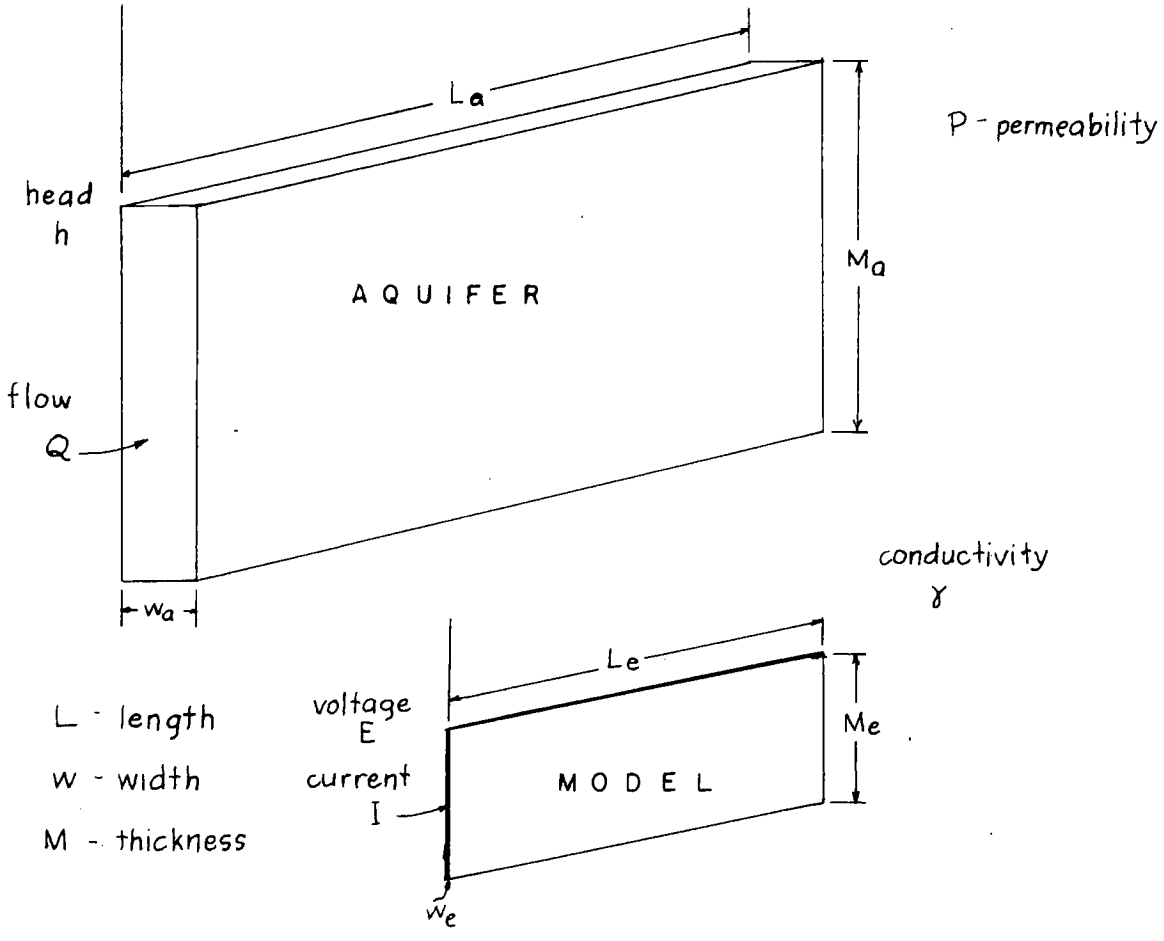


Fig. 12 Diagrams showing equivalent properties of an aquifer and the analag model.

From equation 4.6, an appropriate electrical value can be computed to fit a given set of conditions. Given the proper scale for the model, a solution of salt water intrusion problems can be worked out by the analog method.

4.3 Quantitative results

To illustrate the use of the scale factor, an hypothetical problem was drawn up and the scale factor was applied in the solution of the problem. A vertical cross section of an aquifer and for which the following information was known: the coefficient of permeability, fresh water head, thickness of the aquifer and the pumping rate at which the water is to be withdrawn. It will be noted that the permeability coefficient is used instead of the coefficient of transmissibility because by cutting away a portion of the conducting paper model, the thickness of the aquifer is varied and the coefficient of transmissibility will also be varied. Being independent of thickness of the aquifer, the average coefficient of permeability is a better value to work with.

The problem is to locate a well which is capable of supplying the desired amount of water without drawing in the salt water into the system. From the point of view of economics, the best well should be close to a town or city and consequently to the shore. The problem then converts

to finding a location for a well nearest the shore and at such a depth that will not induce contamination of the fresh water with salt water.

The following information is given: coefficient of permeability of 400 gallons per day per square foot, aquifer thickness of 800 feet, length of aquifer from source to the shore of 7×10^3 feet, and a well which pumps at a rate of 1,000 gallons per minute. First, choose a conducting paper with a suitable resistivity that is nearly a simple multiple of the permeability coefficient. Then choose appropriate dimensions for the model to match the dimensions of the aquifer. Thirdly, compute the amount of current that should equal the pumping rate of the well. A length of 35 inches for the model is deemed sufficient and a width of 4 inches to correspond to an aquifer thickness of 800 feet was chosen. Computations using Eq. 4.6 showed 0.10 milliamperes is required to simulate a pumping rate of 1,000 gallons per minute.

The problem calls for locating the optimum depth for a well at a specified location from the shore. Optimum depth refers to the deepest penetration of a well at which point it may pump water at the given rate without pulling the salt water interface to a distance of 100 feet from the tip of the discharge well. Figure 13 illustrates the meaning of optimum depth.

Results of a series of experiments to determine optimum depth for the conditions set in the problem are summarized in Figure 14. It shows the optimum depth at which a well pumping at the rate of 1,000 gallons per minute for the given set of conditions, and for a certain distance from the shore. The graph shows further that optimum depth increases with increasing distance from the shore. It should be noted, however, that at about 1,800 feet from the shore, the rate of increase of the curve rises slightly. From an extrapolation of the curve beyond the indicated scale, it was found that the optimum depth was well behind the theoretical intersection of the salt water front with the 800-foot depth when there is no withdrawal of ground water from the aquifer.

For greater usefulness, a family of depth-distance curves can be drawn for different pumping rates and/or for different hydrologic properties.

4.5 Accuracy of the Method

The accuracy of the analog method is dependent largely on the uniformity of the resistivity of the conducting paper. The other dimensional and electrical variables can be properly controlled.

The variability of the resistivity of the conducting paper is reflected on the departure of the plotted equipotentials from the theoretical position of the

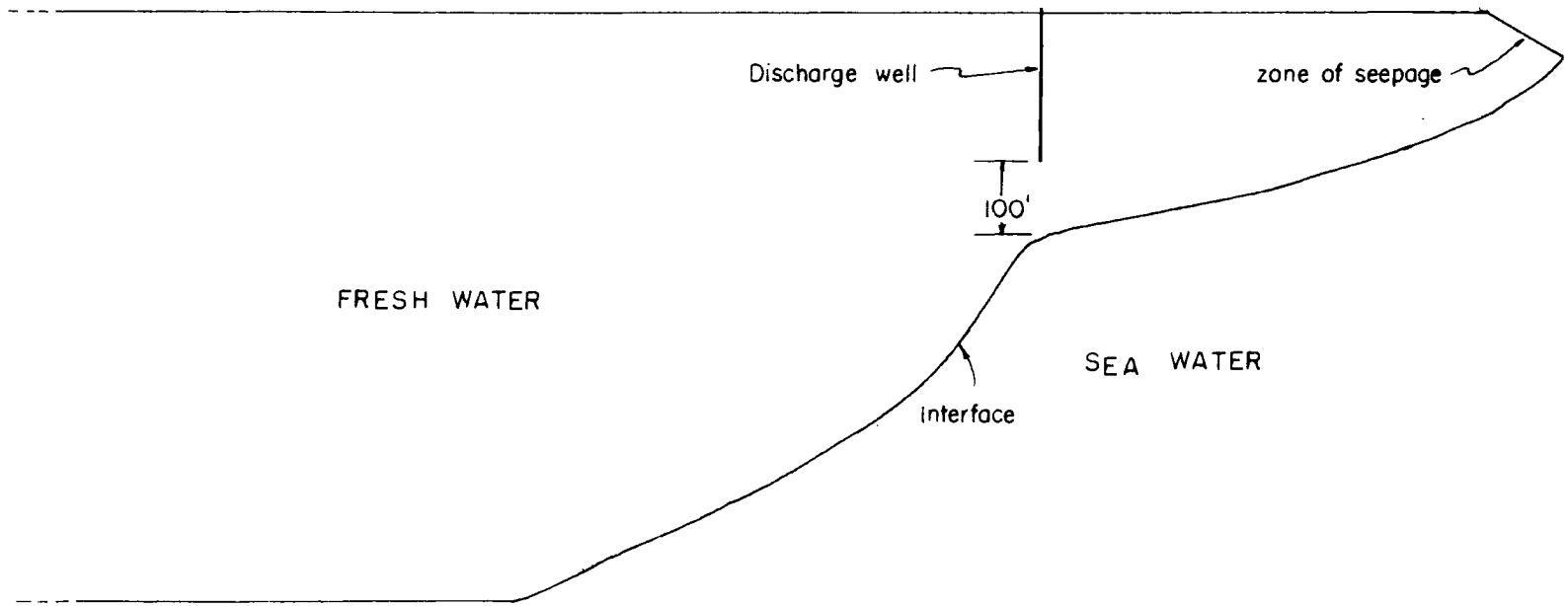


Fig. 13 Diogrom of model showing lower limit of verticol distonce from the interfoce to the well for optimum depth.

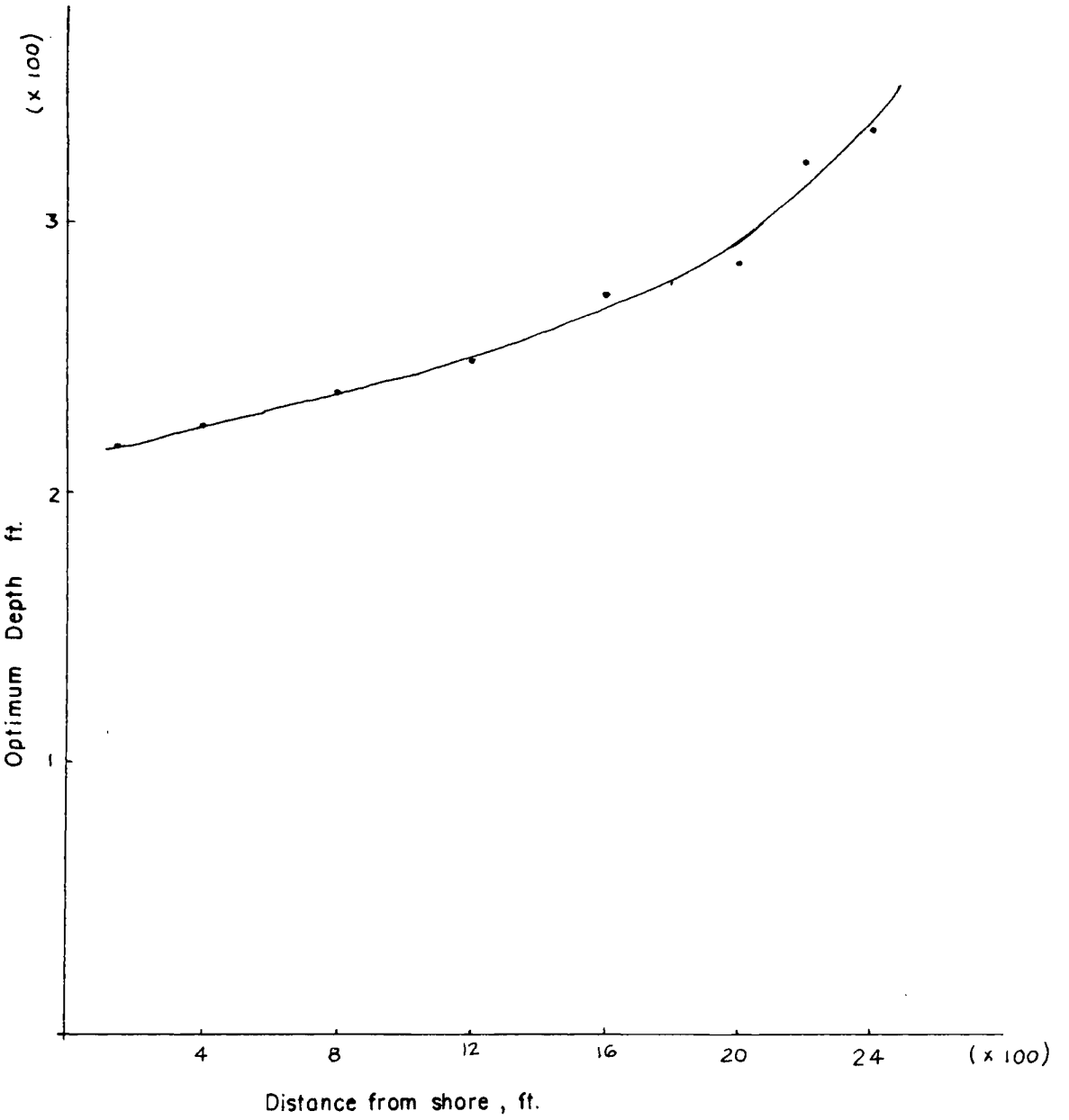


Fig. 14 Optimum depth-distance curve for a well pumping at a rate of 1000 gpm. Coefficient of permeability = 400 gpd/ft^2

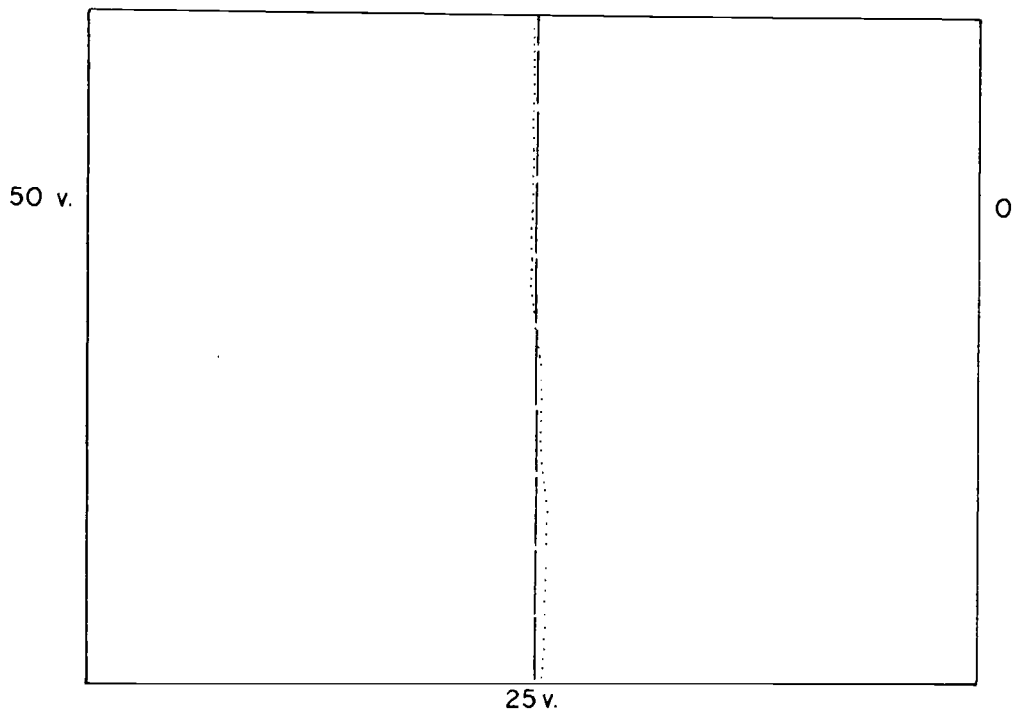


Fig. 15 Sketch of model used to test accuracy of analog method.

equipotential line as in Figure 15. The conducting paper is cut squarely and the voltage between ends set at an even number so that the potential halfway is exactly 25 volts. From the deviation of the plotted equipotential line from the bisecting line, the coefficient of variance and the standard deviation are computed. Based on the preceding test, the conducting paper showed a standard deviation of 0.024 inch from the theoretical equipotential line for every 3 inches from the source electrode.

It must be pointed out that a standard deviation of this magnitude is much less than the errors that are implicit in aquifer tests to determine the coefficients of permeability and transmissibility.

CHAPTER V

CONCLUSIONS

By the proper scaling of the conducting paper model and the pumping rate, optimum location for new wells and the depths that they should penetrate can be studied with the use of conducting paper models. However, the problem of relating time to the various factors involved is still to be solved.

Should there be a need for the implementation of artificial means to combat salt water intrusion, this method of study can be utilized to determine where recharge wells may be set up, the depth, the pumping rate, and the location of wells that may be operated without the possibility of drawing salt water.

There is still the need for better equipment to control the flow of current through different parts of the model. Better techniques should be developed to insure good contact between the conducting paper and electrodes.

Despite these limitations, the simplicity in design and operation of the analog model makes it very enticing to organizations working on salt water intrusion problems but are handicapped by a lack of facilities and money for more sophisticated research.

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