A HYDRAULIC TECHNIQUE FOR DESIGNING SCAVENGER-PRODUCTION WELL COUPLES TO WITHDRAW FRESHWATER FROM AQUIFERS CONTAINING SALINE WATER

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ABSTRACT

Aquifers in coastal areas of Puerto Rico often contain very limited quantities of freshwater, occurring as a thin lens at the surface of the water table. Many wells have been abandoned because they were inadvertently screened in saltwater parts of the aquifer.

Scavenger-production well couples installed in abandoned wells, screened in both fresh and saltwater parts of the aquifer, provide an effective method for extracting only the freshwater from the well. Withdrawing a sufficient quantity of low-chloride water using the couple depends upon the degree of upward movement of saltwater within the aquifer when the well is pumped. Vertical saltwater movement depends upon the relative concentrations of chloride in the borehole and the distribution of horizontal and vertical hydraulic conductivity of the aquifer.

For any well screened in an aquifer containing both freshwater and saltwater, there exists a family of curves representing all combinations of pumping rates and corresponding chloride loads for the scavenger well and the production well pumping simultaneously from the well. The curves are derived empirically by splitting the total chloride load withdrawn from a well into the individual loads produced by the production and scavenger wells at various pumping rates.

The curves developed permit the optimization of freshwater withdrawals based on pumping desired rates and levels of chloride concentration required for each well. The techniques can be applied to any other wells which exhibit radial flow and maintain the same well efficiency over a wide range of pumping rates.

INTRODUCTION

The occurrence of saltwater in aquifers throughout coastal Puerto Rico has caused many wells to be abandoned and threatens the further development of ground-water resources. Salty ground water can occur either as encroached seawater or as a mix of residual, salty, connate water and advancing freshwater from the recharge areas of the aquifer. Seawater encroachment occurs when large ground-water withdrawals depress the water table or potentiometric surface such that the hydraulic gradient is reversed between the ocean and inland pumping areas. Regardless of its origin, saline water occupies most of the surficial sediments near the coast in Puerto Rico; freshwater occurs in these areas only as a thin layer above the saline water.

When well screens are placed within the thin, freshwater layer and the well is pumped, the underlying saltwater may move upward toward the screens. The upward advance of saltwater can sometimes be controlled by reducing the pumping rate. However, wells that are partially open to saltwater zones in the aquifer have been abandoned because when pumped, the composite mix of water produced by the well is usually of unacceptably high dissolved-solids concentration. Cementing the bottom screens where saltwater occurs has proved unsatisfactory. The proximity of the remaining freshwater screens to underlying saltwater continues to produce upward saltwater movement within the aquifer even though the well is no longer open to saltwater zones.

Salty water contains high concentrations of many ions, which constitute the dissolved solids of the water. Dissolved solids can be estimated empirically by measuring the specific conductance of a particular water sample. The concentration of chloride is generally used as a measure of salinity because chloride is the major ionic constituent of saltwater and is chemically conservative. Specific conductance can also be used to approximate the concentration of chloride in ground-water samples from wells on the north coast of Puerto Rico.

THEORY OF SCAVENGER-PRODUCTION WELL COUPLES

The development of a hydraulic technique to design scavenger-production well couples to withdraw water from aquifers having a thin layer of freshwater overlying salty water was investigated by the U.S. Geological Survey, Water Resources Division, Caribbean District during 1983 and 1984. The investigation was conducted in cooperation with the Water Resources Research Institute, University of Puerto Rico, Mayaguez Campus. Scavenger-production well couples (fig. 1) can be used to selectively extract some quantity of freshwater from a well where ground-water withdrawals would otherwise cause saltwater to be drawn into the well bore.

Scavenger-production well couples can be installed either as two adjacent wells within the aquifer (fig. 1A) or placed within a larger well screened in both freshwater and saltwater(fig. 1B). In each case, the intake of the production well is placed where the largest amount of freshwater is available to the well bore and as distant as possible from the saltwater. The intake of the scavenger well is placed within the saltwater section. In general, the scavenger-production well couple operates more efficiently when placed directly within the aquifer (fig. 1A). However, in Puerto Rico, most wells have been abandoned because they were inadvertently screened in both freshwater and saltwater regions of the aquifer (fig. 1B), and no methodology has been available for reclaiming the freshwater. This investigation, therefore, tests the hydraulic theory of scavenger-production well couples by utilizing an existing abandoned well, screened both in freshwater and saltwater parts of an aquifer (fig. 1B).

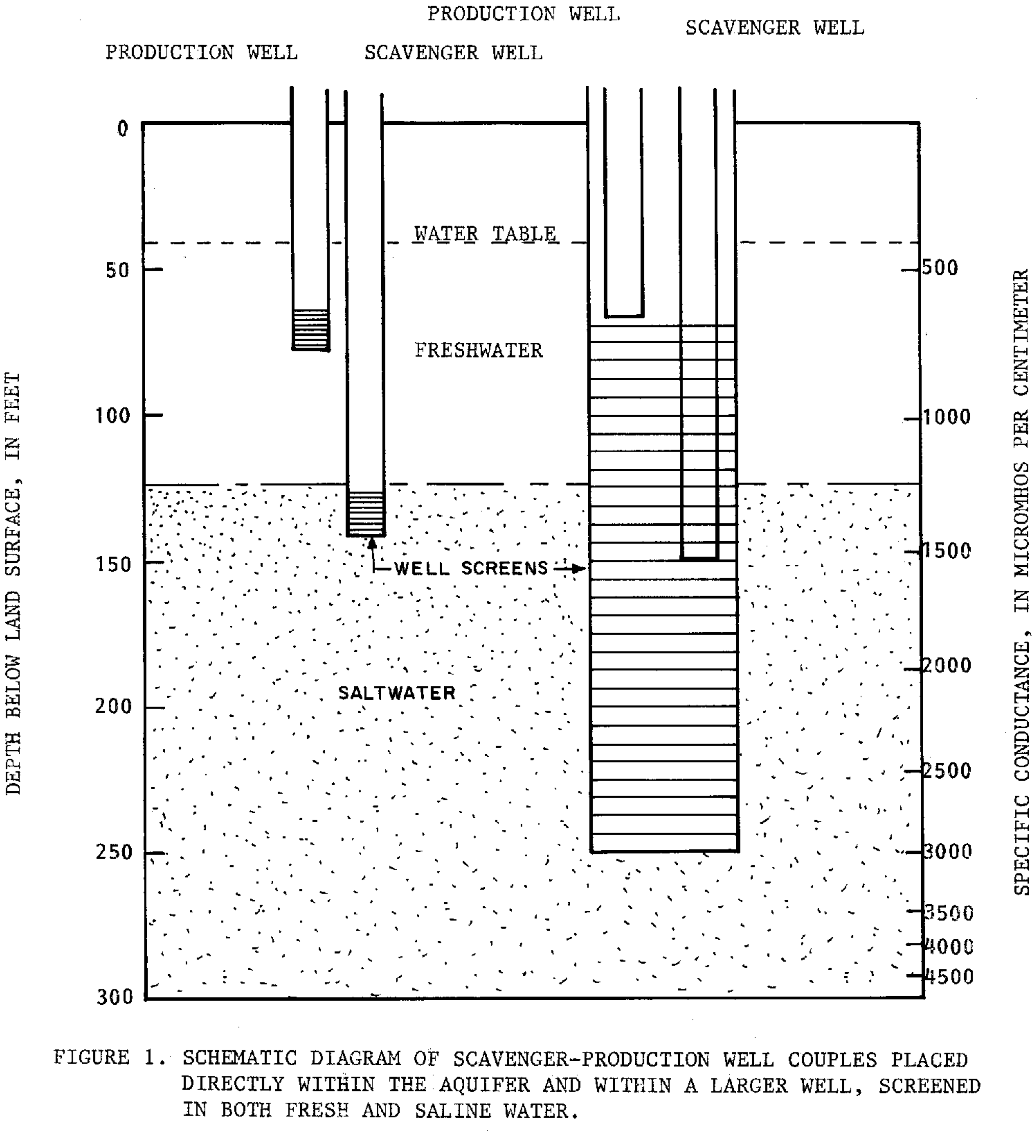

FIGURE 1. SCHEMATIC DIAGRAM OF SCAVENGER-PRODUCTION WELL COUPLES PLACED DIRECTLY WITHIN THE AQUIFER AND WITHIN A LARGER WELL, SCREENED IN BOTH FRESH AND SALINE WATER.

The scavenger well and the production well - each pumping at a particular rate from appropriate depths within a large well, screened both in freshwater and saltwater zones - extract a portion of the water entering the well bore. Each portion is dependent upon the vertical distribution of saltwater and freshwater and the hydraulic conductivity of aquifer material opposite the well screens. Theoretically, the scavenger well withdraws the saline water at a particular rate which permits the production well to simultaneously extract some amount of water within acceptable limits of water quality, dictated by its intended use. The salty water entering the borehole is extracted by the scavenger well before migrating toward the production-well intake. The salty water produced by the system is usually pumped to waste.

In the past, well couples have not been considered as a means of selectively extracting freshwater from coastal aquifers because of uncertainties associated with well-screen placement and the optimum, conjunctive pumping rates required to produce a usable quantity of freshwater. In fact, where scavenger-production well couples have been used (outside of Puerto Rico), the most efficient operation of the couple has usually been achieved by trial and error, in terms of well-screen placement and conjunctive pumping rates. However, by applying a relatively straightforward hydraulic analysis, described herein, the feasibility of using the scavenger-production well couple to produce freshwater from an aquifer containing saltwater can be assessed. The design of the couple to optimize freshwater production based on the analysis can proceed, and engineering decisions concerning utilization can be made.

Scavenger-production well couples are not particularly cost-efficient because of the added expense of an additional well, pump, and electricity or fuel. In addition, where no suitable discharge point exists for the pumped saltwater, the system cannot be operated. Nevertheless, given an acceptable discharge site and sufficient need for a freshwater supply, scavenger-production well couples may be a means of developing freshwater supplies in coastal aquifers where the thin layer of freshwater which overlies salty water cannot be developed by conventional methods.

HYDROLOGIC CONSIDERATIONS AND WELL CONSTRUCTION AT LA TROCHA

The application of hydraulic analysis to determine the usefulness of the scavenger-production well couples was investigated at Barrio La Trocha, near Vega Baja in north-central Puerto Rico (fig. 2). A water-supply well drilled in 1969 by Autoridad de Acueductos y Alcantarillados de Puerto Rico (PRASA) was used during the investigation. The well was drilled to a depth of 192 feet (ft) and cased with 16-inch (in) black iron pipe to 100 ft (fig. 3). Perforated pipe of 16 in. diameter extends from 100 to 192 ft, and is open to the relatively porous Aymamón Limestone. This formation is the principal geologic unit comprising the water-table aquifer in northern Puerto Rico (Giusti, and Bennett, 1976). Although the well has a relatively high specific capacity (95 gallons per minute per foot (gal/min/ft) of drawdown) at withdrawal rates in excess of 200 gal/min, the well was abandoned because a mix of freshwater and saltwater was immediately discharged from the well. A limited amount of freshwater (760 to 1100 micromhos per centimeter (umhos/cm) or approximately 100 to 200 milligrams per liter (mg/L) of chloride) was known to occur at a depth of approximately 100 ft, but the requirement for large quantities of water at the site prompted PRASA engineers to extend the depth of the well. The water quality under static, equilibrium conditions in the well grades from a specific conductance of 760 umhos/cm at 100 ft to 5500 umhos/cm (2020 mg/L chloride) at 190 ft

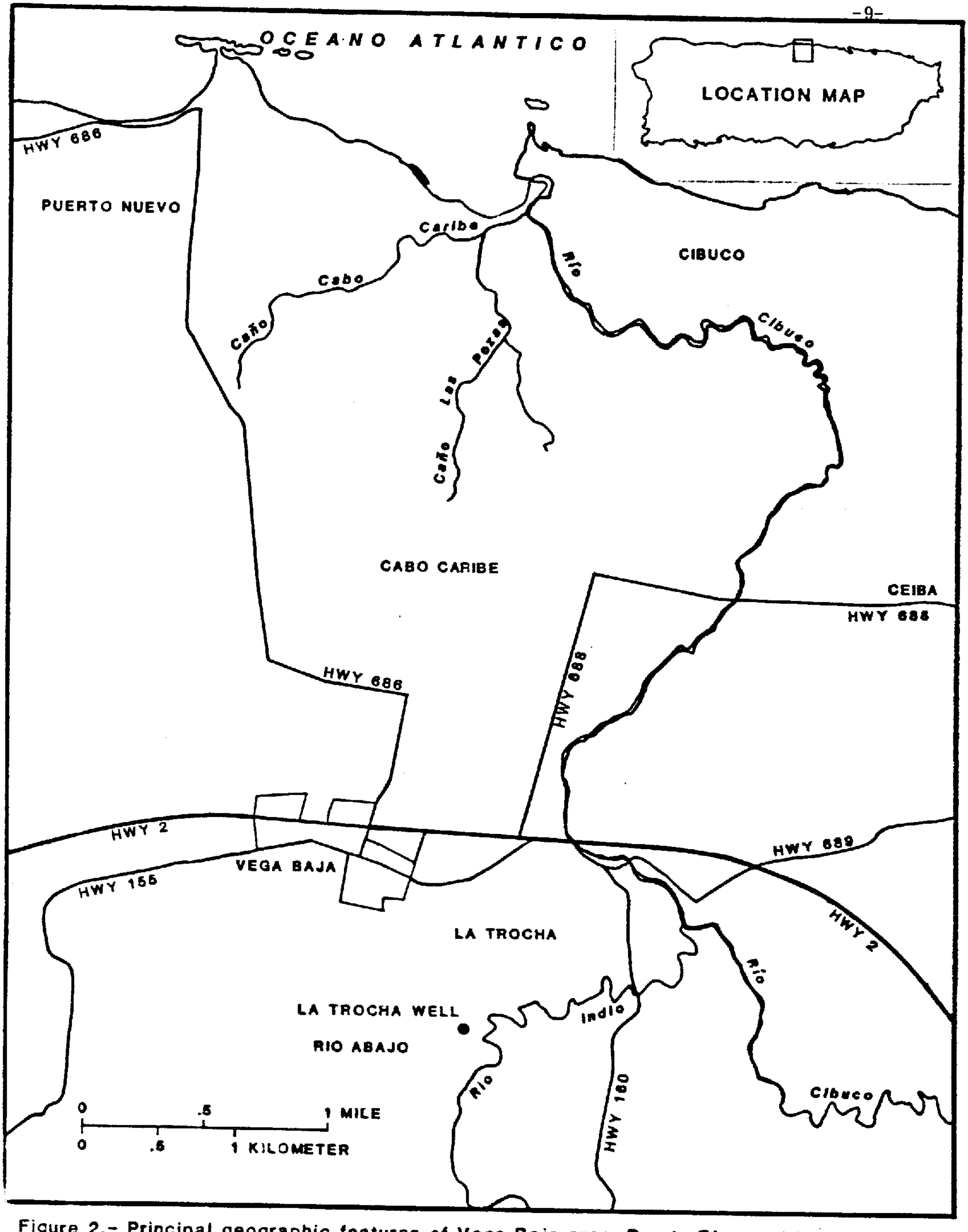

Figure 2.- Principal geographic features of Vega Baja area, Puerto Rico and location of La Trocha well.

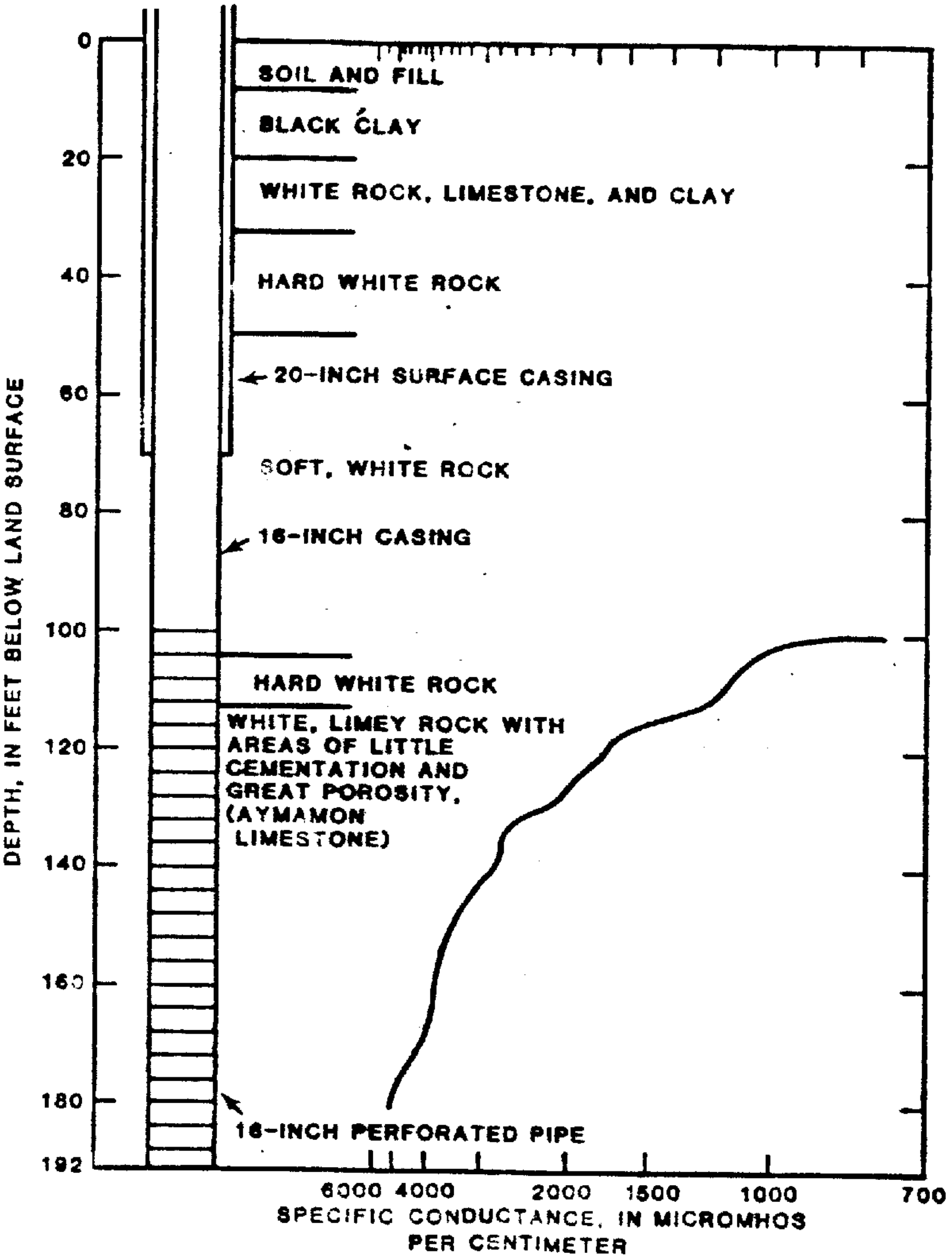

Figure 3.- Lithologic log and completion data for the La Trocha well with specific conductance profile measured in the well under static conditions.

(fig. 3). The relationship between specific conductance and chloride concentration for the entire range of salinity encountered within the La Trocha well is shown in figure 4. Even very low pumping rates of the deepened well withdrew water of unacceptable quality for drinking immediately after the initiation of pumping.

For convenience, water within the aquifer at La Trocha will be designated "freshwater" or "saltwater" depending on whether it originates in the upper part of the aquifer or lower (above or below 130 ft or so). The terms will be used in a relative way, fully recognizing the gradational nature of salinity in the aquifer.

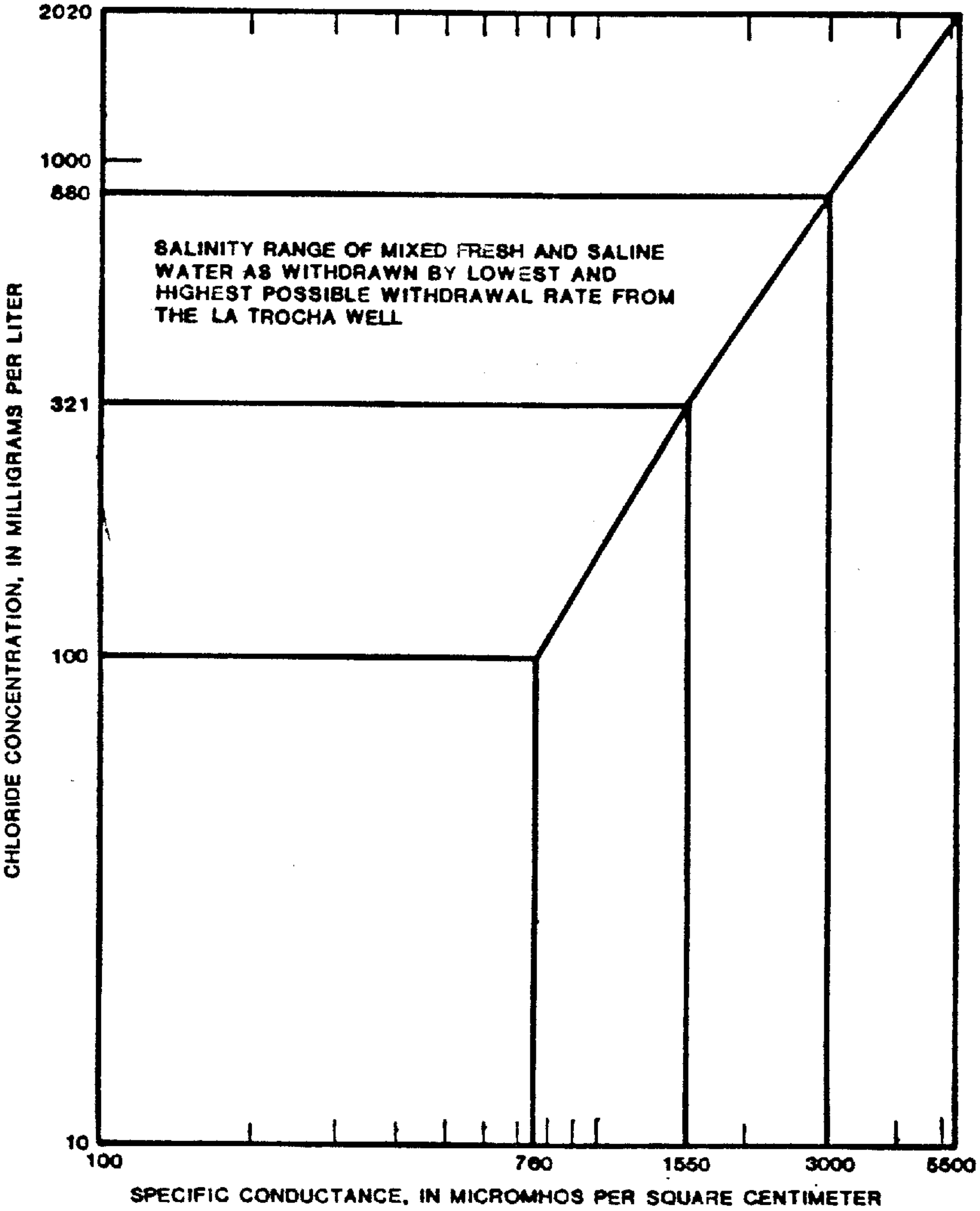

Figure 4.- Relation between specific conductance and chloride for all water occurring at depths 100 to 192 feet below land surface at the La Trocha well

The freshwater-saltwater system at La Trocha has evolved over centuries of dilution of old seawater by downward-percolating meteoric recharge water (fig. 5). This fresh ground water reaches the water table and mixes with the underlying saltier water. Eventually, given a static sea level, salty water would be flushed from the aquifer to a downgradient freshwater sea water interface. The flushing action in the aquifer where salty water occurs is however foreshortened by the tendency of the accumulated percolated freshwater to travel downgradient, toward the ocean, above the more dense freshwater saltwater dilution product. A vast amount of the freshwater is thereby lost to development and is relatively ineffective in freshening the deeper, saltier water.

The vertical distribution of specific conductance in the well at La Trocha (figure 3), idle for 14 years, reflects the mixing/dispersion mechanism described above: chloride increases with depth with an increasing salinity gradient.

In order to develop freshwater from the La Trocha well using the scavenger-production well method, the hydraulics of vertical saltwater movement within the well and within the aquifer as pumping stresses are applied must be clearly understood and documented. The efficient correspondence of pumping rate and intake location of the scavenger and production wells to produce freshwater can therefore be determined hydraulically, rather than depending on trial and error.

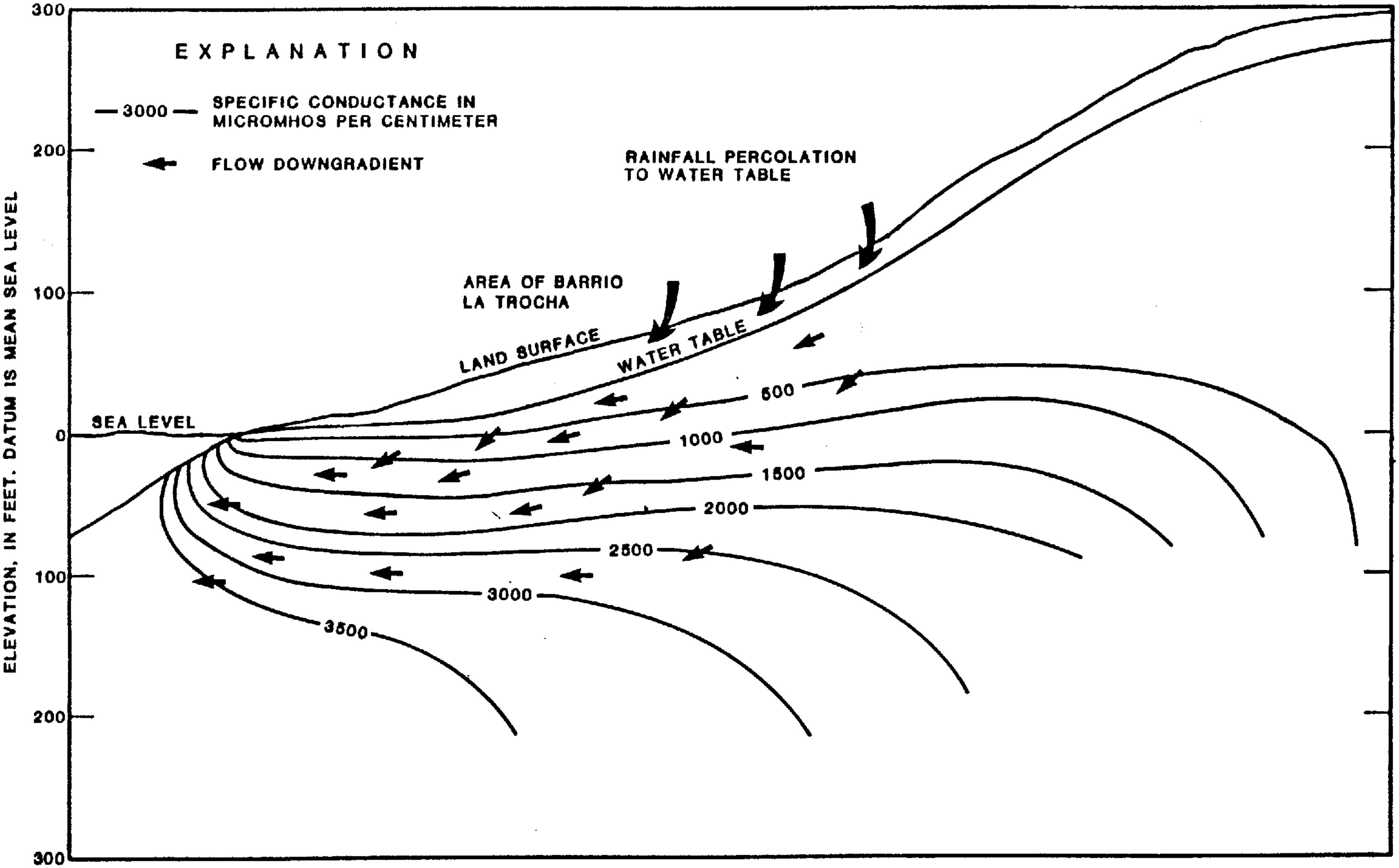

Figure 5.- Schematic diagram of the freshwater-saltwater system at Barrio La Trocha.

HYDRAULIC THEORY OF VERTICAL SALTWATER MOVEMENT

The amount of saltwater a well will ultimately withdraw depends upon the pumping rate, the distribution of horizontal and vertical hydraulic conductivity within the aquifer (which determines the distribution of head which develops in the aquifer during pumping), and the density and dynamic viscosity of aquifer fluids.

Screens which fully penetrate an aquifer containing both fresh and saltwater draw both fresh and saltwater into the well bore upon the initiation of pumping. Screens which partially penetrate the aquifer and are placed in the freshwater zone may cause saltwater to move upward (upconing) toward the screens as the well is pumped. Saltwater is less accessible to the borehole because more energy is required to "lift" the saltwater to the well screens than in the case where the screens actually penetrate the saltwater. However, the degree and behavior of vertical saltwater movement is more dependent on the distribution of horizontal and vertical hydraulic conductivity than whether the well fully or partially penetrates the aquifer.

A well fully penetrating a freshwater-saltwater-bearing aquifer which is isotropic with respect to horizontal hydraulic conductivity will produce no vertical flow component, regardless of variations in vertical hydraulic conductivity. The well admits saltwater into the well bore, but upward saltwater movement does not occur within the aquifer. However, if such an aquifer is partially penetrated by screens placed only in the freshwater zone, an upward advancement of saltwater will be initiated (fig. 6). Flow lines develop to the well screens from all directions including a vertical flow component from beneath the screens. Upward saltwater advancement will proceed more rapidly if the aquifer is of large vertical hydraulic conductivity as compared to horizontal. If the aquifer is of considerably larger horizontal hydraulic conductivity as compared to vertical, there will be proportionately more horizontal flow to vertical, and upward movement will be less.

The development of equipotential and flow lines within aquifers becomes more complicated when there are variations in the horizontal hydraulic conductivity occurring within the vertical section of aquifer. When either a partially or fully penetrating well is pumped, flow lines converge in the more hydraulically conductive layers and heads are maintained in layers of smaller hydraulic conductivity. Within the aquifer, a vertical flow component develops from layers of low to high hydraulic conductivity (fig. 7). In general, saltwater movement will follow the flow lines which develop according to the ratios of horizontal to vertical hydraulic conductivity whithin the aquifer. In the plausible but unlikely case where vertical hydraulic conductivity is zero throughout the vertical section of aquifer, no vertical flow lines will develop. Saltwater will not advance upward, regardless of head differences occurring in the vertical sections of aquifer resulting from differences in horizontal hydraulic conductivity.

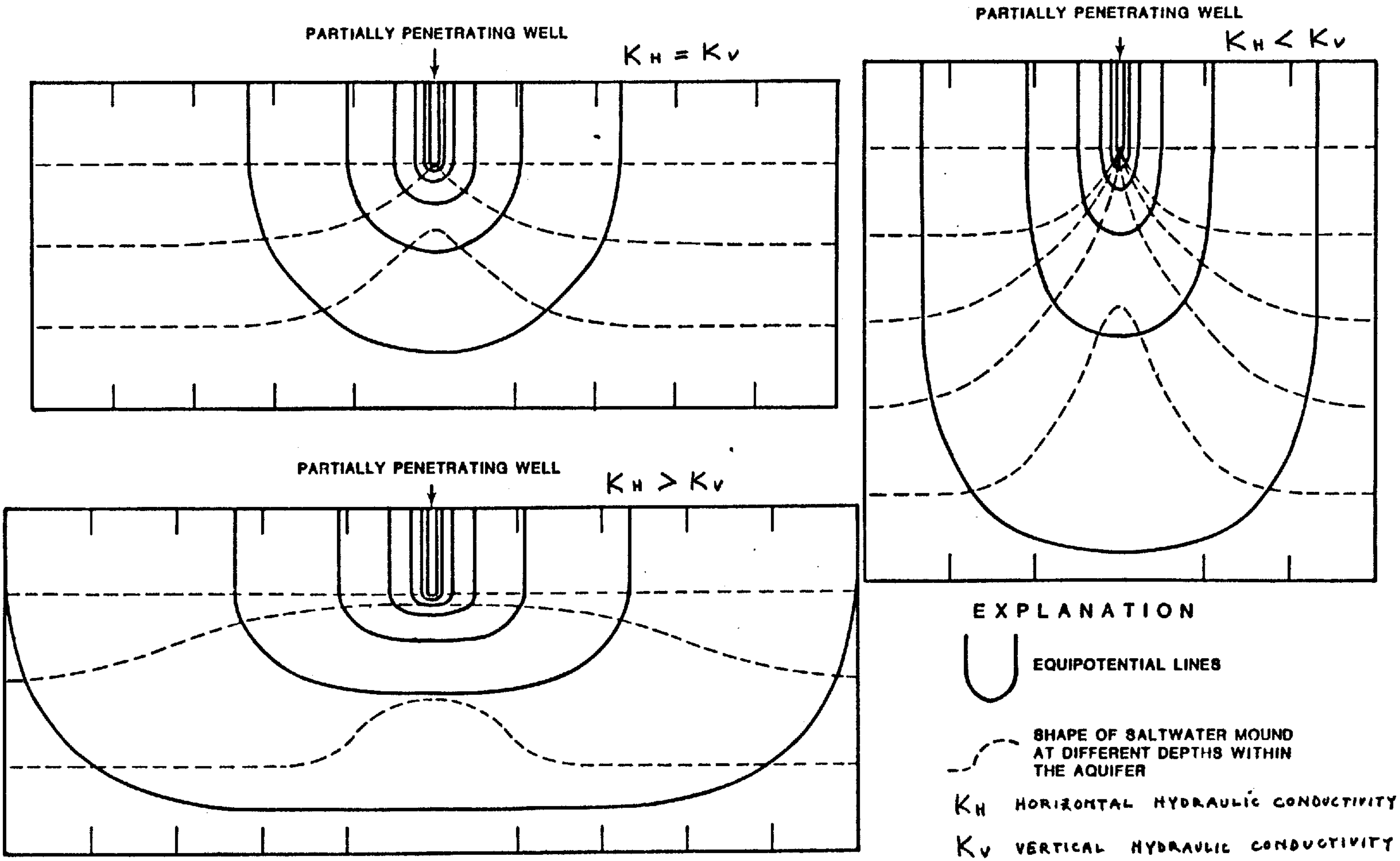

Figure 6.- Schematic diagram of equipotential lines and the upward advancement of saltwater in partially-penetrated isotropic aquifers having different horizontal with respect to vertical hydraulic conductivity.

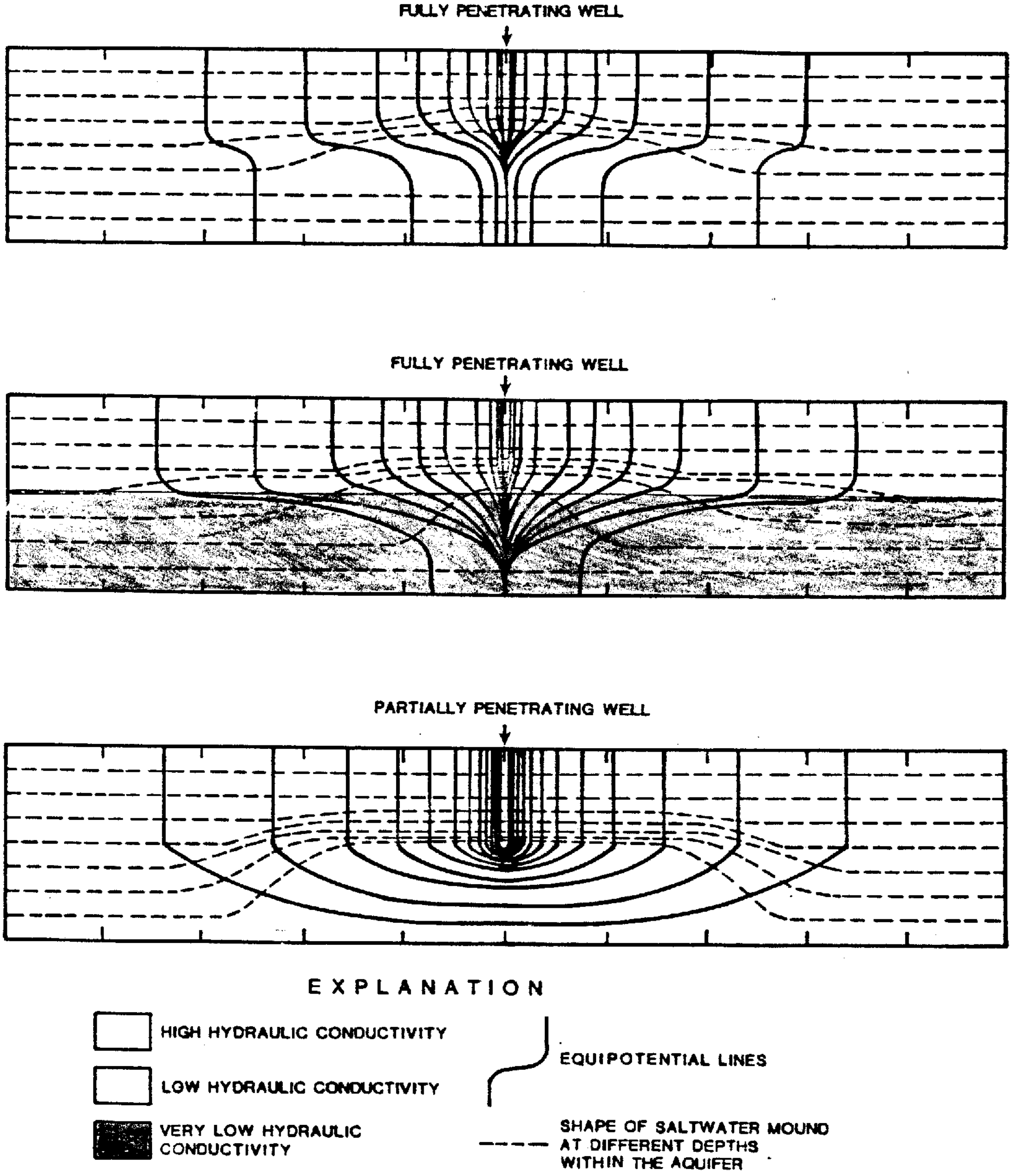

Figure 7.- Schematic diagram of equipotential lines and saltwater response to ground-water withdrawals from fully penetrated and partially penetrated anisotropic aquifers having vertical differences in horizontal hydraulic conductivity.

A fully-penetrating well will behave as a partially-penetrating well as differences in horizontal hydraulic conductivity become greater in the vertical section of aquifer. In the extreme case when part of the screened, fully penetrated, aquifer approaches a horizontal hydraulic conductivity of zero, saltwater reacts to pumping stresses as if the aquifer is partially penetrated. The system reacts to pumping stresses differently in terms of head distribution, but the effects, in terms of upward-advancing saltwater within the aquifer and the mix of water achieved, are similar (fig. 7).

To observe the actual advance of saltwater as it progresses upward within the aquifer, a well (USGS-1) was drilled 8.5 ft away from the La Trocha well and screened only within the freshwater part of the aquifer, from 99 to 109 ft. As the well was pumped at a rate of 53 gal/min, specific conductance of the water withdrawn increased (fig. 8) and velocity surveys (using brine injection and flowmeters) and conductivity profiles in the La Trocha well were obtained at different times (fig. 9). Zero upward flow was measured within the La Trocha well indicating that water was probably not transferred through the well bore, from salty parts of the aquifer to fresh. The profiles of specific conductance indicated, however, that water of relatively high conductivity (below 130 ft) was advancing upward (downgradient) toward the most hydraulically conductive parts of the aquifer, from 100 to 105 ft or so. The La Trocha well served as a "window" into the aquifer while well USGS-1 was pumped. The saltwater could be monitored as it advanced upward, gradually replacing the freshwater which originally occupied the aquifer from 100 to 130 feet. Apparently, after pumping well USGS-1 for 390 minutes, conductivity (fig. 8) and the upward advance of saltwater (fig. 9) had stabilized.

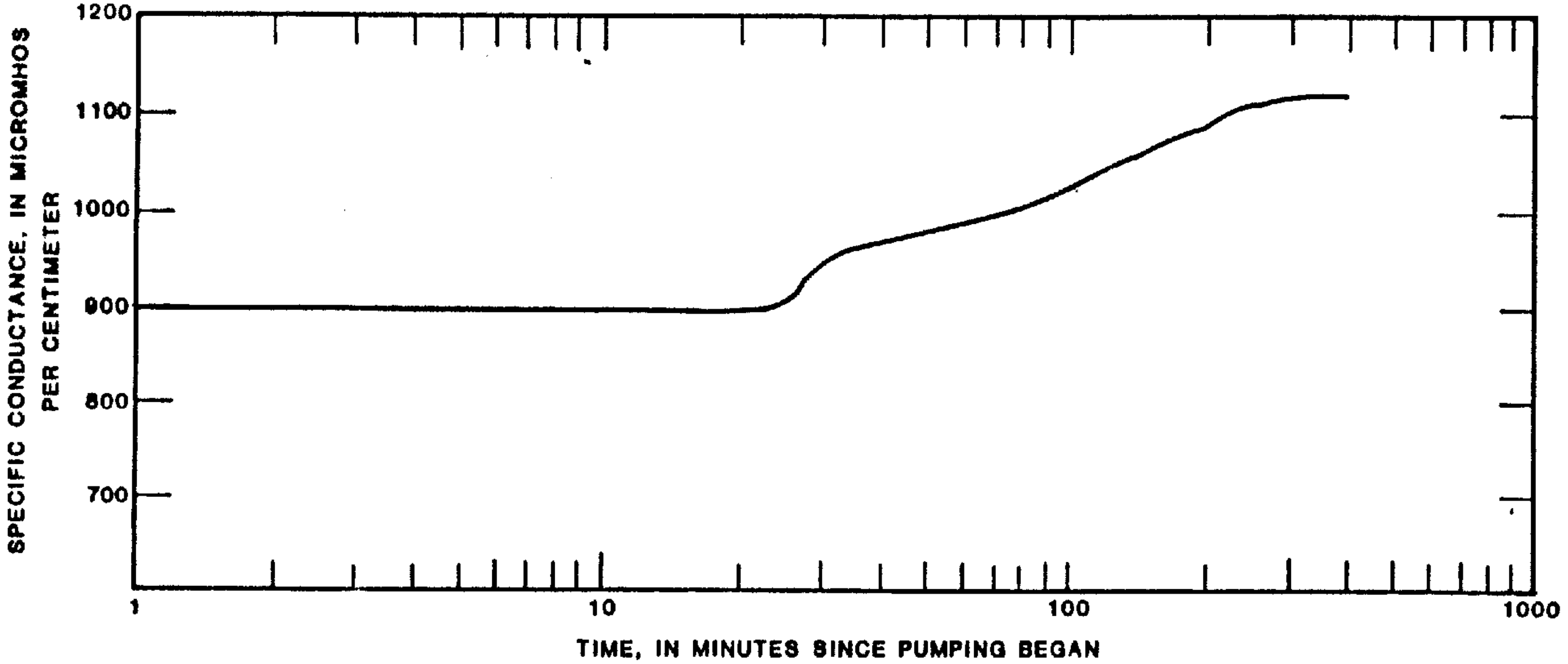

Figure 8.- Time-conductivity profile of water withdrawn at 53 gallons per minute from well USGS-1 drilled 8.5 feet from the La Trocha well, and screened 99 to 109 feet.

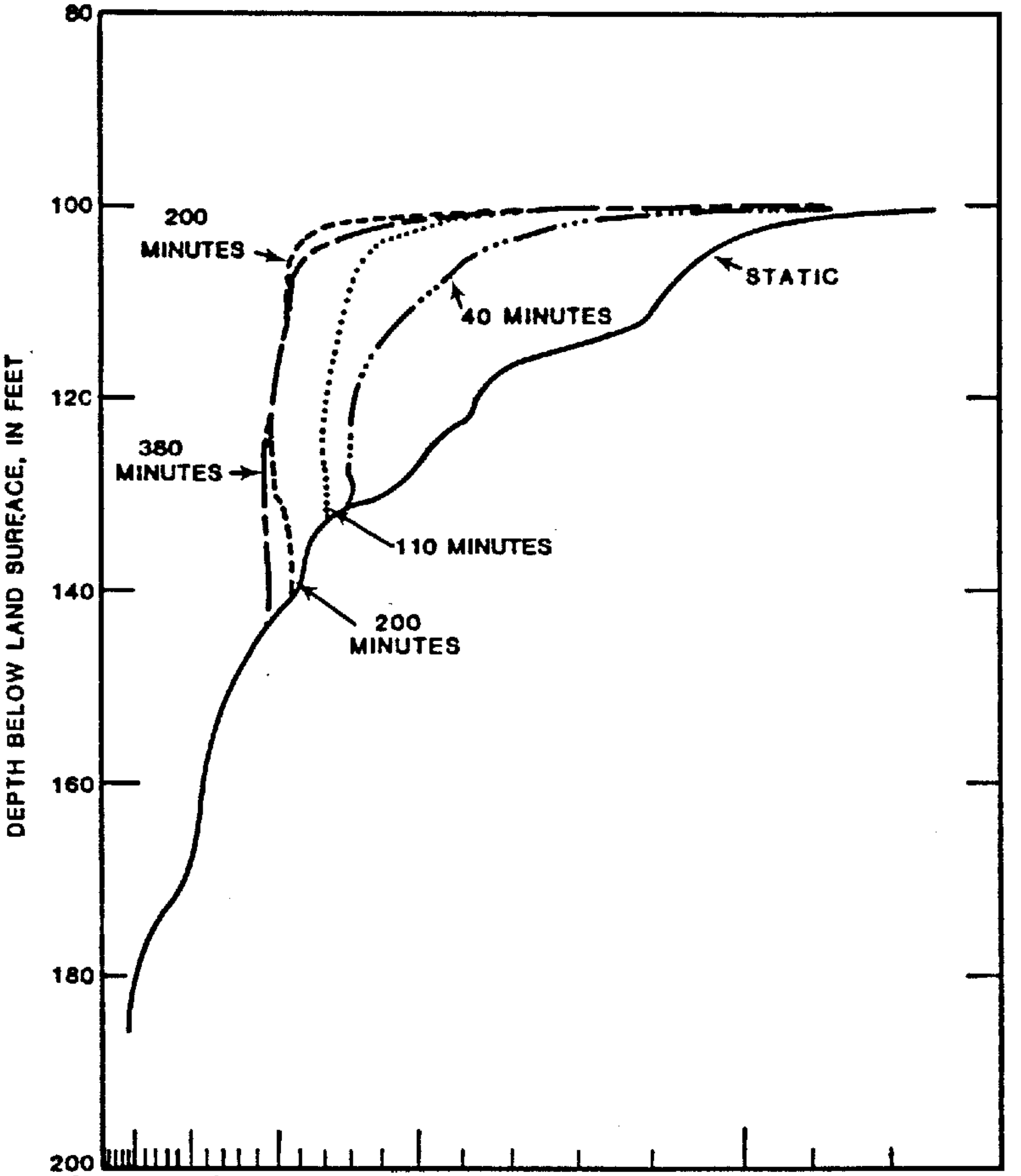

Figure 9.- Depth-conductivity profiles at various times in La Trocha well as well USGS-1 withdraws water at 53 gallons per minute.

The upward advance of the chloride "cone" stabilizes as a well is pumped at a constant rate because of differences in the density and dynamic viscosity of the "freshwater" and "saltwater" within the aquifer. According to Darcy's Equation (Hubbert, 1940) the amount of water that enters a borehole along its length depends upon the hydraulic gradient, permeability of aquifer sediments, and the density and dynamic viscosity of aquifer fluids at every point. As pumping commences, permeability and gradient effect the greatest control on flow; but as differences in head become smaller with time, the fluid properties of density and dynamic viscosity gain in importance. Ultimately, a balance between gradient and fluid properties are achieved; the height and shape of the upward-advancing saltwater have reached equilibrium and the chloride concentration of the composite water withdrawn from the well pumped at a particular rate, has stabilized. The smaller the difference in chloride concentration along the borehole, the smaller influence there will be in achieving equilibrium and stabilization will occur in a greater length of time.

The vertical movement of saltwater in a fully penetrating well cannot be considered to be saltwater upconing in the classical sense. The redistribution of water in a freshwater/saltwater-bearing aquifer in response to pumping from a fully penetrating well depends principally upon the vertical distribution of both vertical and horizontal hydraulic conductivity within the aquifer. It is intuitive that if freshwater parts of the aquifer have higher horizontal hydraulic conductivity than underlying saltwater parts (fig. 6A and B), saltwater will migrate upward within the aquifer (if vertical hydraulic conductivity is sufficiently large), in response to vertical differences in head when the well is pumped. Flow lines converge in the freshwater part of the aquifer - where the greatest hydraulic conductivities occur - providing an upward hydraulic gradient and influencing the shape of the chloride "cone", which is mound-shaped (fig. 10). The saltwater mound broadens as equilibrium conditions are achieved. If the saltwater parts of the aquifer are of greater hydraulic conductivity than the freshwater parts, a downward gradient will develop upon pumping. Freshwater will migrate downward within the aquifer creating a freshwater "basin" within the saltwater.

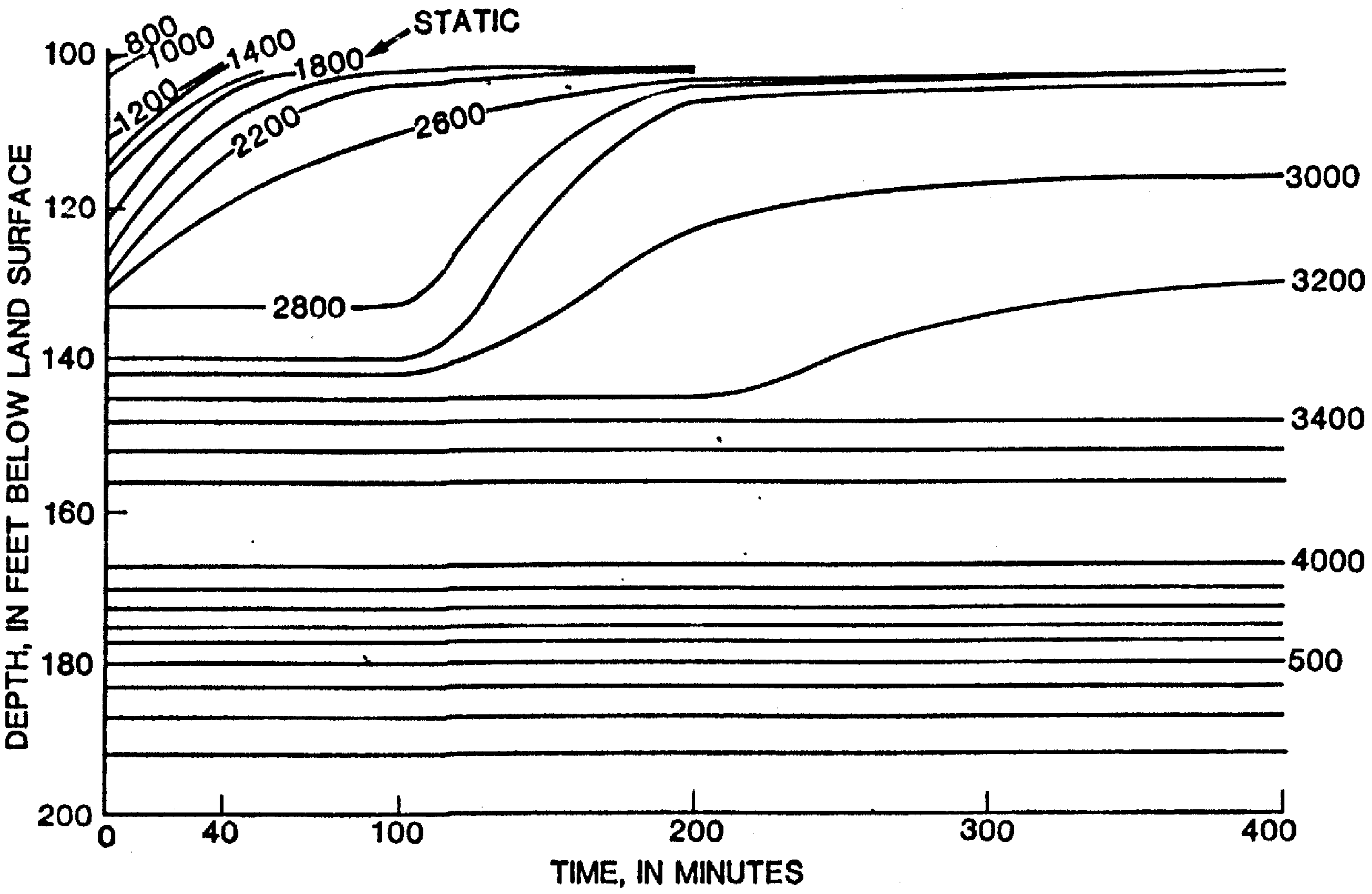

Fig. 10 – Shape of upward–advancing saltwater at different times within the La Trocha well as well U. S. G. S. 1 pumps 53 gallons per minute.

The degree and behavior of vertical saltwater movement within the aquifer was monitored as the La Trocha well was pumped in order to measure the amount of freshwater section replaced by upward-advancing saltwater at different pumping rates. A variable-discharge submersible pump was placed within the well casing at a depth of 60 feet and water was withdrawn at pumping rates of 18, 24, 30, 36, and 54 gal/min. For each individual pumping rate, conductivity profiles and flowmeter surveys were conducted and water samples were collected and analyzed for specific conductance. The results of the water samples were plotted against the time they were collected (see examples in fig.11). If equilibrium values for specific conductance of the composite water withdrawn had been equal in each of the five pumping scenarios, there would have been no vertical saltwater movement within the aquifer; that is, salinity at various depths within the aquifer would have remained constant regardless of pumping rate. However, different values of specific conductance were measured at the different withdrawal rates, indicating that more saltwater was drawn into the well at increased pumpage rates. Saltwater had migrated upward, within the aquifer, in response to vertical-flow components produced by pumpage in the freshwater section of aquifer which has a greater horizontal hydraulic conductivity than the saltwater section.

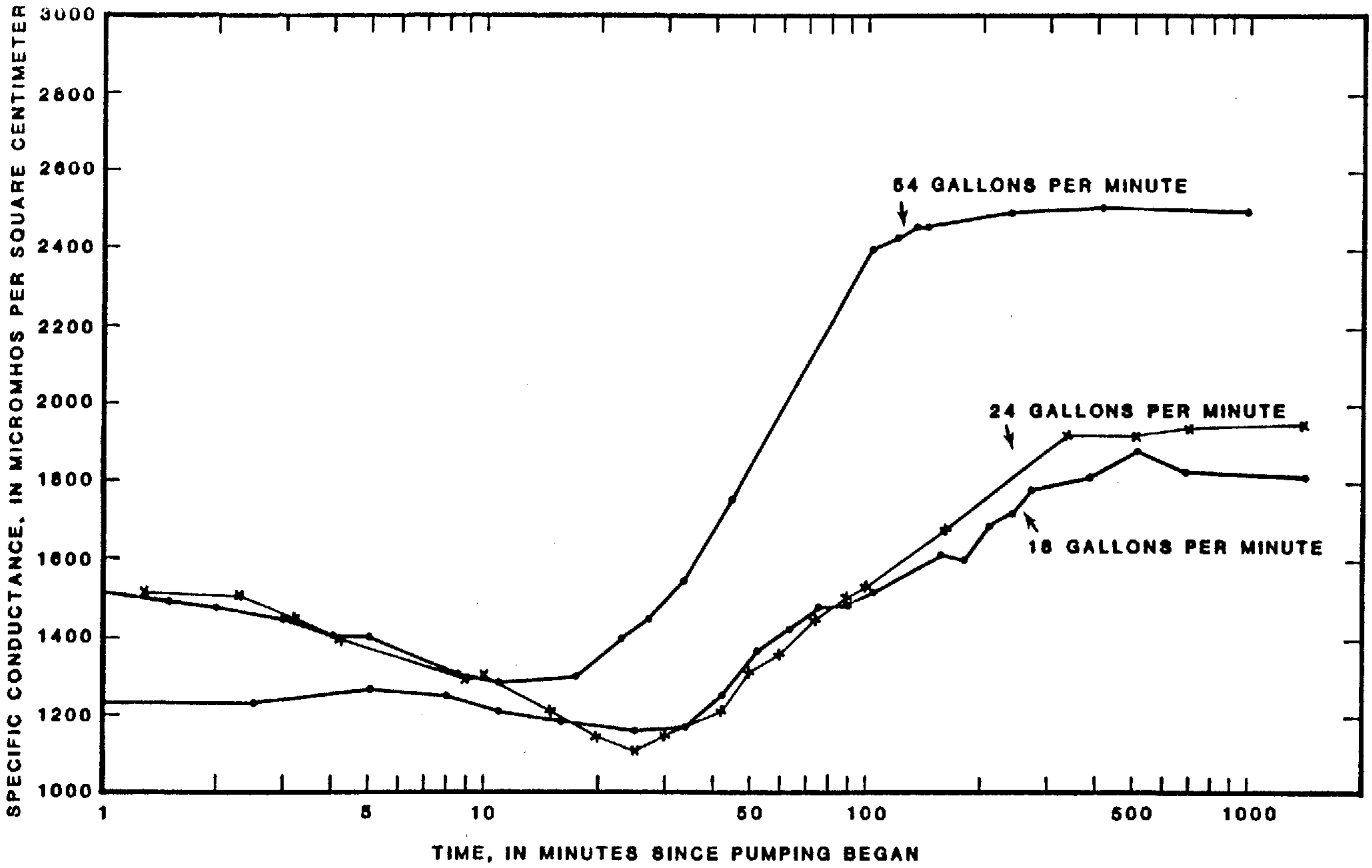

Figure 11.- Time-conductivity profile of water withdrawn from La Trocha well at various pumping rates.

The proportion of water entering the well at every point along its screen remains the same at all withdrawal rates even though the aquifer is vertically inhomogeneous in terms of horizontal hydraulic conductivity (anisotropic). This phenomenon persists as the saltwater advances upward within the aquifer in response to vertical flow components if the efficiency of the well does not vary with pumping rate (excepting very small influences from fluid density and dynamic viscosity). In effect, the saltwater section becomes thicker and the freshwater section thinner in the vicinity of the well as the pumping rate is increased, but the proportion of water entering the borehole along its length remains the same.

The conductivity profiles and flowmeter surveys (examples in fig. 12) indicate that although the well is screened from 100 to 192 ft, it only admits measurable quantities of water from depths of 100 to 145 ft. The amount of water entering the well bore reflects the strong inhomogeneity of the aquifer. In fact, 40% of all the water withdrawn from the La Trocha well enters the well bore through the upper two ft of screen. Water at a depth of 130 to 145 ft has an average specific conductance of 3000 umhos/cm or 880 mg/L chloride (fig. 4). As this relatively salty water advances upward within the well, it mixes with entering water of less salinity, producing a conductivity gradient from 130 ft to 100 ft both at 18 gal/min and 54 gal/min but at a considerably different mix in each case (fig. 12). When pumping ceased, the vertical distribution of specific conductance returned to its original prepumping profile within hours.

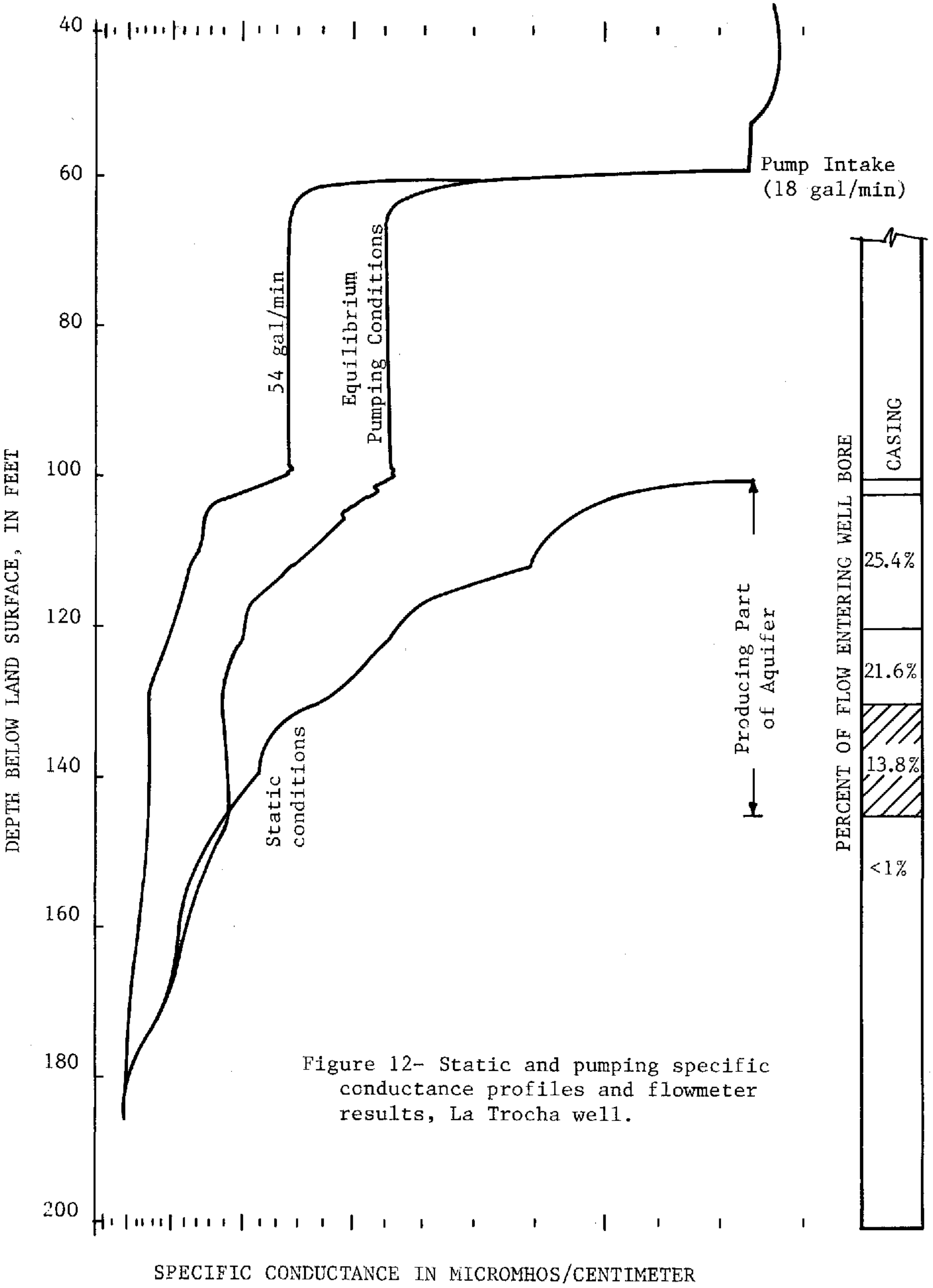

Figure 12- Static and pumping specific conductance profiles and flowmeter results, La Trocha well.

After equilibrium-chloride concentrations were achieved at various pumping rates of the La Trocha well, the relationship between the pumping rate in (gal/min) and the specific conductance (or chloride concentration was plotted) producing a curve (fig. 13), which is unique for this well. The various chloride concentrations result from the proportions of mixed fresh and saltwater, determined from the height the saltwater has encroached into the freshwater parts of the aquifer. Chloride increases with increasing pumping rate because a progressively greater section of the screen admits saltwater. The upward-advancing saltwater is slowed by freshwater entering the well bore at a progressively greater velocity (as pumping rate increases), but through a progressively decreasing freshwater section. The values of specific conductance and chloride approach lower and upper limits asymptotically (fig. 13) which represent maximum fresh and saline mixes of water, respectively, available to the screened section of aquifer (fig. 4).

The chloride-concentration curve at various pumping rates (fig. 13) can be represented as a chloride-load curve (fig. 14) to facilitate computations when a scavenger-production well couple is placed within the La Trocha well and optimum freshwater discharges are sought. Chloride load is chloride concentration multiplied by flow rate. The chloride-load curve reveals some important hydraulic considerations not obvious with the chloride-concentration curve.

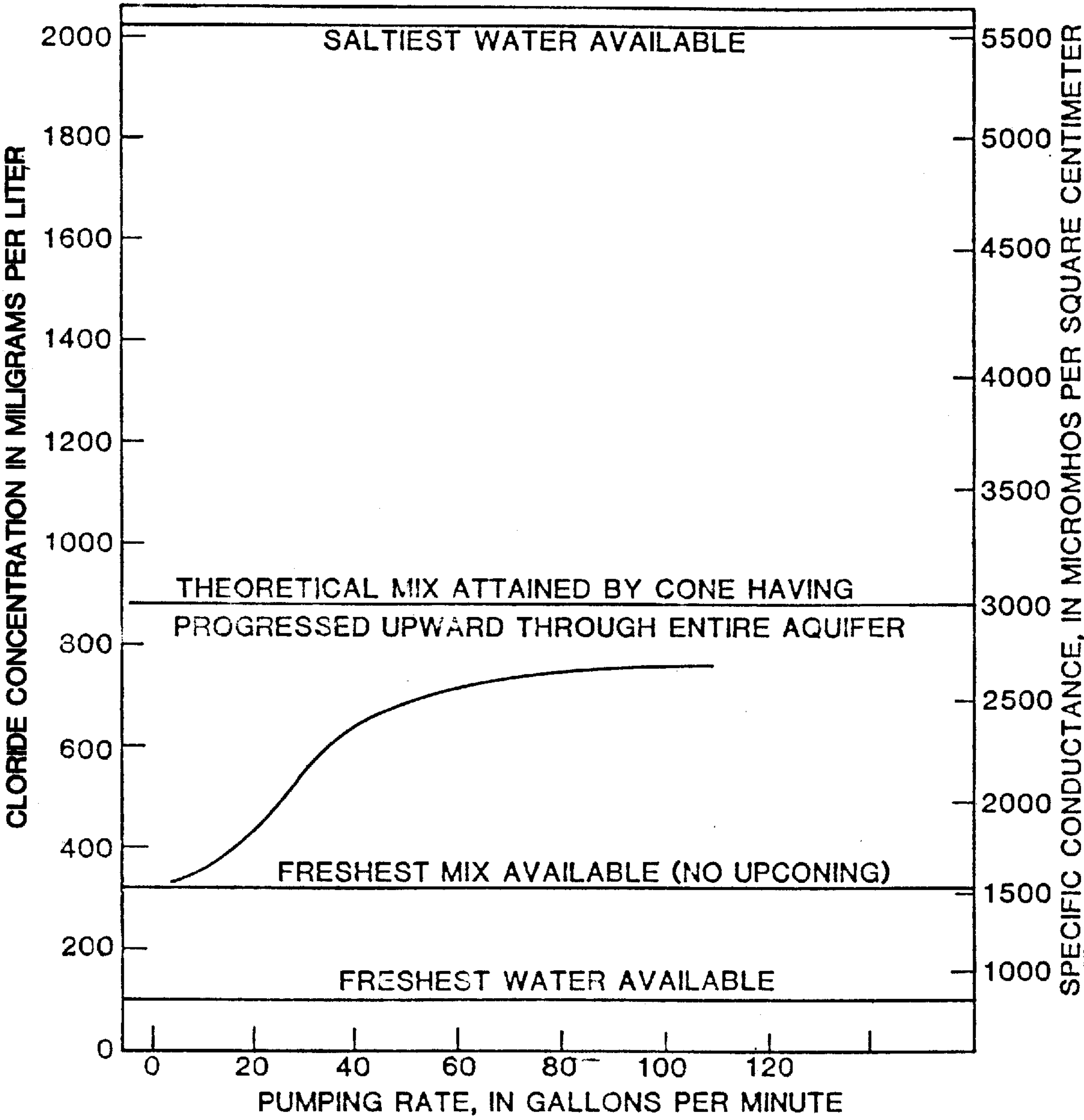

Fig. 13

Cloride concentration and specific conductance of the water withdrawn from the La Trocha well at various pumping rates.

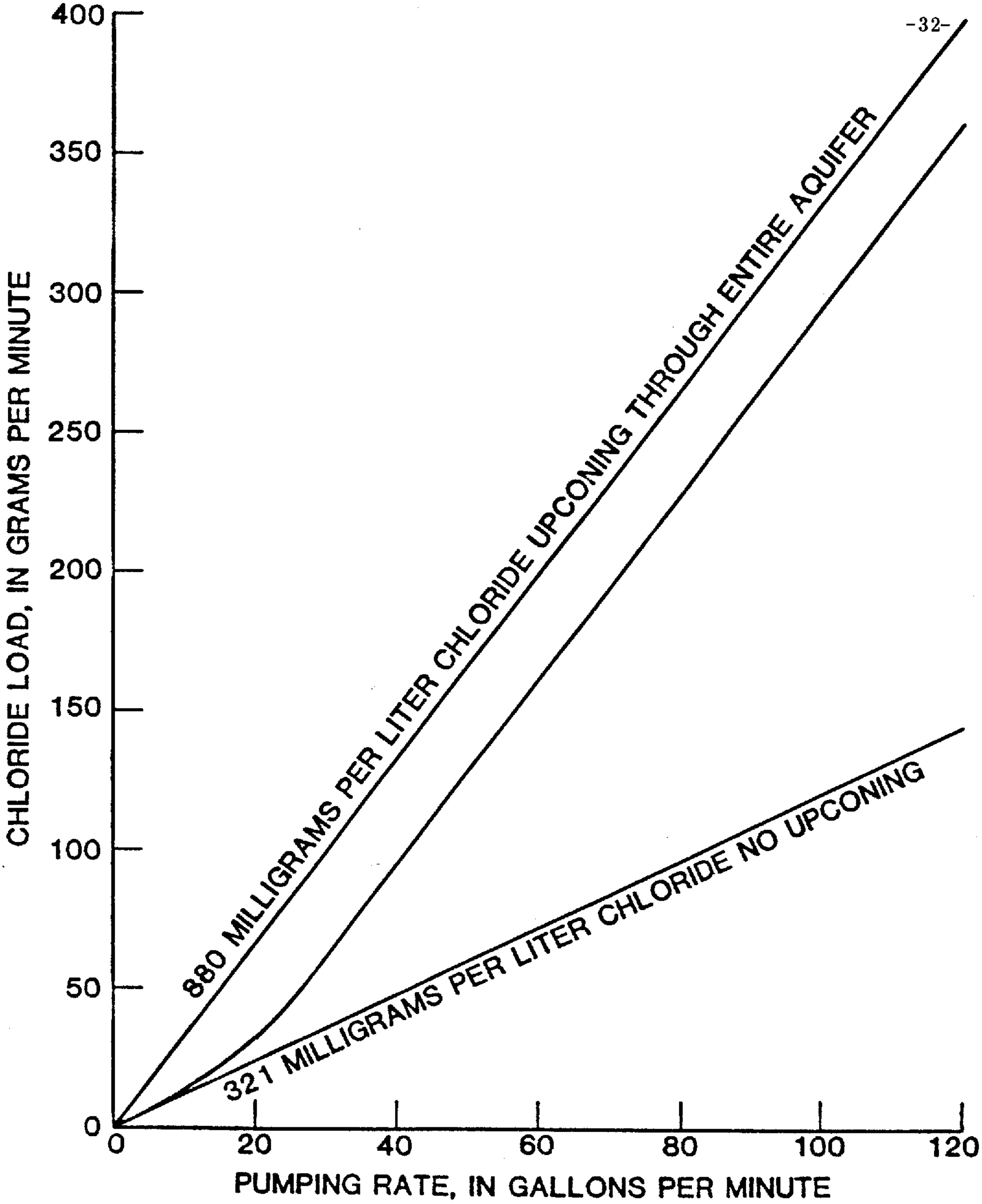

Fig. 14– Chloride Load at various pumping rates withdrawn from The La Trocha well and asymptotes representing the freshest and saltiest mix of water attainable.

When plotted as chloride load versus withdrawal rate, the relationship is linear, except at very low withdrawal rates. The chloride-load line represents the combined load of fresh and saltwater contribution to the well bore. Had the La Trocha well described a perfect alignment of points through the origin of abscissa and ordinate, chloride concentration would have been the same at all withdrawal rates. Upward saltwater migration would not be occurring. However, the load increases faster than can be attributed to increasing pumping rate at a constant chloride concentration, indicating that the increased load includes contribution from an increased saltwater thickness.

The chloride-load line is necessarily straight (curved only as it approaches zero) because water flows radially to the well bore during pumping and vertical differences in horizontal hydraulic conductivity remain constant. These differences, however, permit upward (or downward) saltwater movement in an aquifer which causes the differences in chloride concentration observed in fig. 13. If aquifer materials had been horizontally anisotropic or if the well had not been properly developed, the relation of chloride load versus pumping rate would not have been linear, owing to non-radial flow to the well or a changing proportion of water entering the well at points along the screen at different pumping rates.

A line with zero intercept and parallel to the chloride-load line (fig. 14) represents a theoretical chloride concentration of 880 mg/L if the upward-advancing cone was capable of replacing entirely the freshwater section of aquifer at La Trocha (figs. 4 and 13). Of course, the saltwater is unable to progress completely through the freshwater section, because freshwater is continuously contributed to the borehole, albeit through an ever-decreasing length of section. The offset of the lines indirectly represents a measure of anisotropy in terms of horizontal hydraulic conductivity occurring in the screened part of the aquifer. The greater the separation, the greater difference in horizontal hydraulic conductivity. If the chloride-load line had occurred above the parallel, zero-intercept line, the saltwater section of the aquifer would have had a higher horizontal hydraulic conductivity than the overlying freshwater section. A line passing through zero and tangential to the curve (fig. 14) represents the freshest mix of water available to the well (figs. 4 and 13).

The height of the upward-advancing saltwater having 880 mg/L chloride concentration experienced in the aquifer (fig. 15) at increasing pumping rates can be calculated from the percentages of the freshest water mix available (321 mg/L chloride) and the salinity of the "upconing" saltwater (880 mg/L chloride) required to produce the chloride-load curve of fig. 14. The vertical anisotropy with respect to horizontal hydraulic conductivity described earlier controls the amount of water that enters the well bore at different depths according to a constant percent of the total water pumped. The differences in

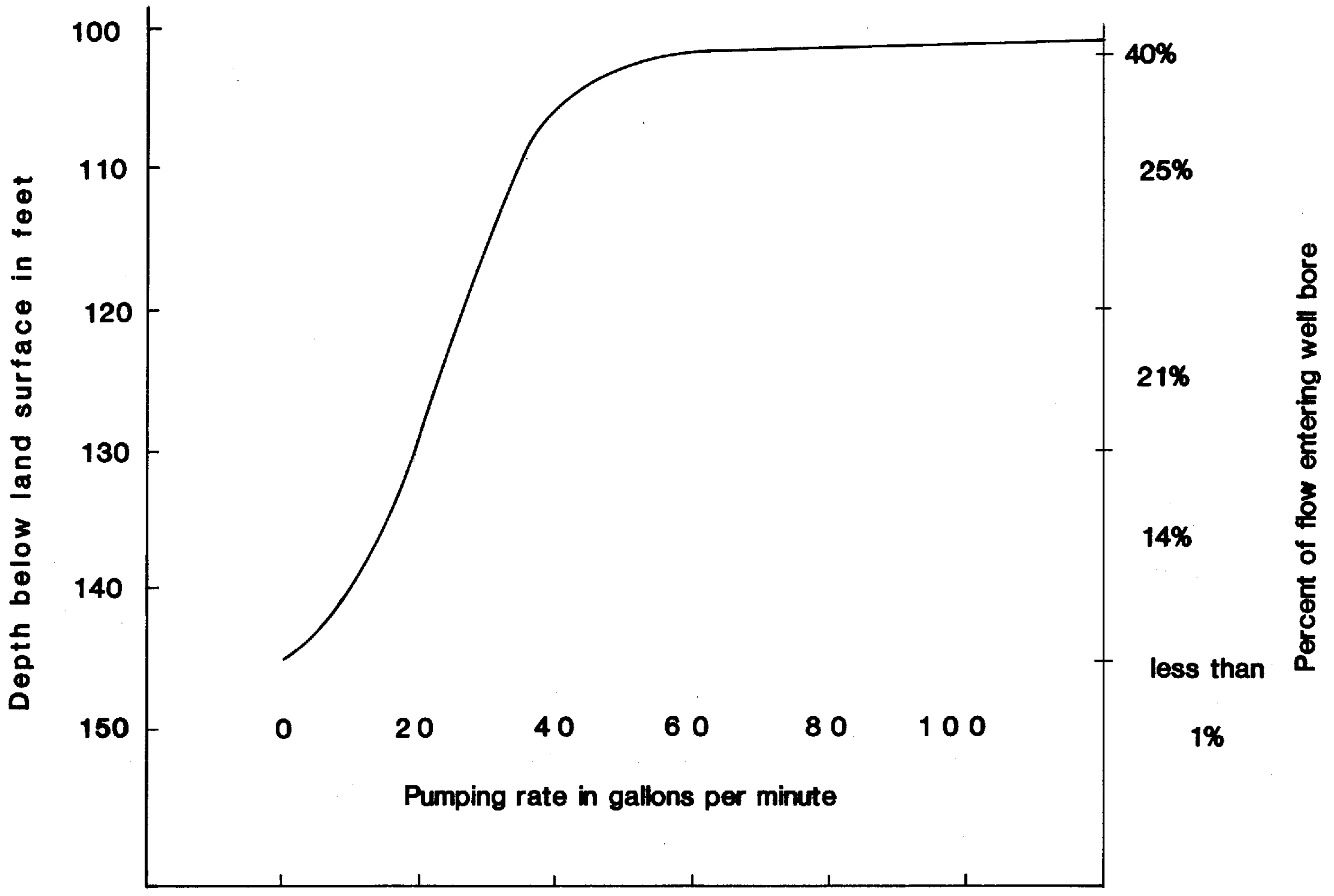

Fig. 15– Upward saltwater advancement in the adjacent aquifer as the La Trocha well is pumped at various rates.

hydraulic head that develop within the aquifer produce flow gradients from areas of lower horizontal hydraulic conductivity (where saltwater occurs) to higher (where freshwater occurs). It is, therefore, the distribution of horizontal hydraulic conductivity which determines the shape of the upward-advancing chloride mound.

The above relations, show that by measuring a sufficient number of chloride loads at different pumping rates it is possible to establish a straight line correlation. The maximum salinity of the upward-advancing saltwater can then be determined as well as the freshest mix available to the system. The concentration vs withdrawal rate curve, and the height of upward advancement of saltwater than can be estimated at elevated pumping rates.

A depth profile of specific conductance of the water within a well, both at rest and as it is pumped, yields additional information as regards the freshest and saltiest water available to the well.

Wells partially penetrating the aquifer and screened only in the freshwater zones follow the hydraulic theory also, even if saltwater responses to stresses are attenuated by the increased energy required to "lift" the saltwater to the screens. In this case, the chloride-load curve will follow the line representing the freshest mix attainable by the well until a pumping rate is reached which is capable of "lifting" the saltwater to the screens. As pumping rates are further increased, the curve deflects upward, eventually becoming parallel to the line representing the saltiest mix of water attainable by the well.

FIELD TESTING THE SCAVENGER-PRODUCTION WELL COUPLE

Having determined the behavior of the upward-advancing saltwater at the La Trocha test site, it is clear that freshwater cannot be developed from the well without installing a scavenger-production well couple. A small submersible pump capable of withdrawing 18 gal/min was to serve as the scavenger well. It was placed at a depth of 130 ft, designed to intercept or, at least, retard saltwater as it advanced upward. The same variable-discharge submersible pump used earlier and placed at 60 ft was to serve as the production well. The two pumps were operated simultaneously; the scavenger well always at 18 gal/min and the variable-discharge production well at rates of 18, 24, 30, 36, and 54 gal/min. After equilibrium-chloride concentrations were reached for each couple (see examples of time-concentration profiles in figure 16), the combined flow rate and corresponding combined-chloride load for the scavenger well and production well pumping together were calculated for various pumping combinations. These values were plotted on figure 14 and fall on the straight line described earlier by pumping the La Trocha well from a depth of 60 feet at various rates of pumping. Apparently, the amount of chloride pumped from the La Trocha well increases linearly, according to the total water withdrawn from the system, irrespective of individual withdrawal rates or the location of the pump intakes.

The intake location can affect the distribution of water entering the well bore as pumping rates increase, and as aquifer transmissivities and well diameters decrease. However, the low withdrawal rates and large screen diameter of the La Trocha well causes a uniform head reduction throughout the well during pumping; water enters at a rate

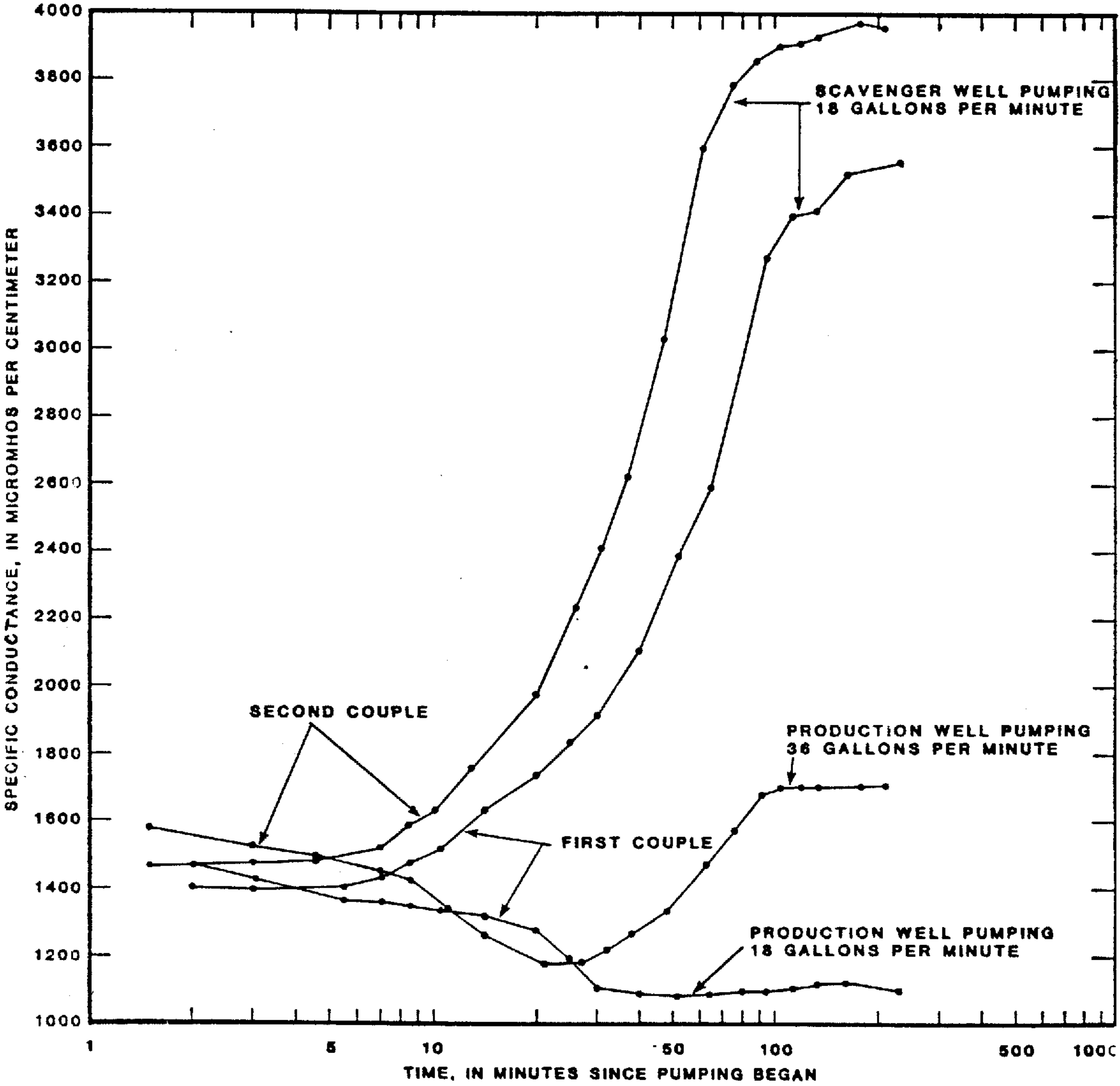

Figure 16- Examples of time-conductivity profiles for two scavenger-production well couples at different pumping rates.

dependent on hydraulic conductivity alone. Many pumping combinations at many different pump-intake depths were performed at La Trocha, and after equilibrium values of specific conductance were achieved, every pumping rate and chloride load or combination of pumping rates and chloride loads maintained the linear relationship of figure 14. A chloride load produced from the La Trocha well at a particular pumping rate represents therefore, the sum of chloride loads and pumping rates achieved by the scavenger and production well pumping simultaneously from within the La Trocha well. This phenomenom persists for all combinations of pumping rates. It is expected that at very high pumping rates, head losses of water entering the well and traveling to the intakes might cause deviations from the linear relationship.

The chloride-concentration and chloride-load data for the production well (variable discharge) and scavenger well (18 gal/min) are plotted (figs 17 and 18 respectively) and clearly demonstrate the utility of the couple in producing freshwater from the aquifer. Whereas water could not have been obtained from the La Trocha well having less than 321 mg/L chloride, the production well is capable of producing approximately 25 gal/min of water having a chloride concentration of 250 mg/L while the scavenger well pumps 18 gal/min of water having 1230 mg/L chloride (fig. 17). The combined chloride loads and pumping rates of the scavenger and production wells equal the total chloride load and pumping rate from the La Trocha well, whether one or two pumps are used (fig. 18).

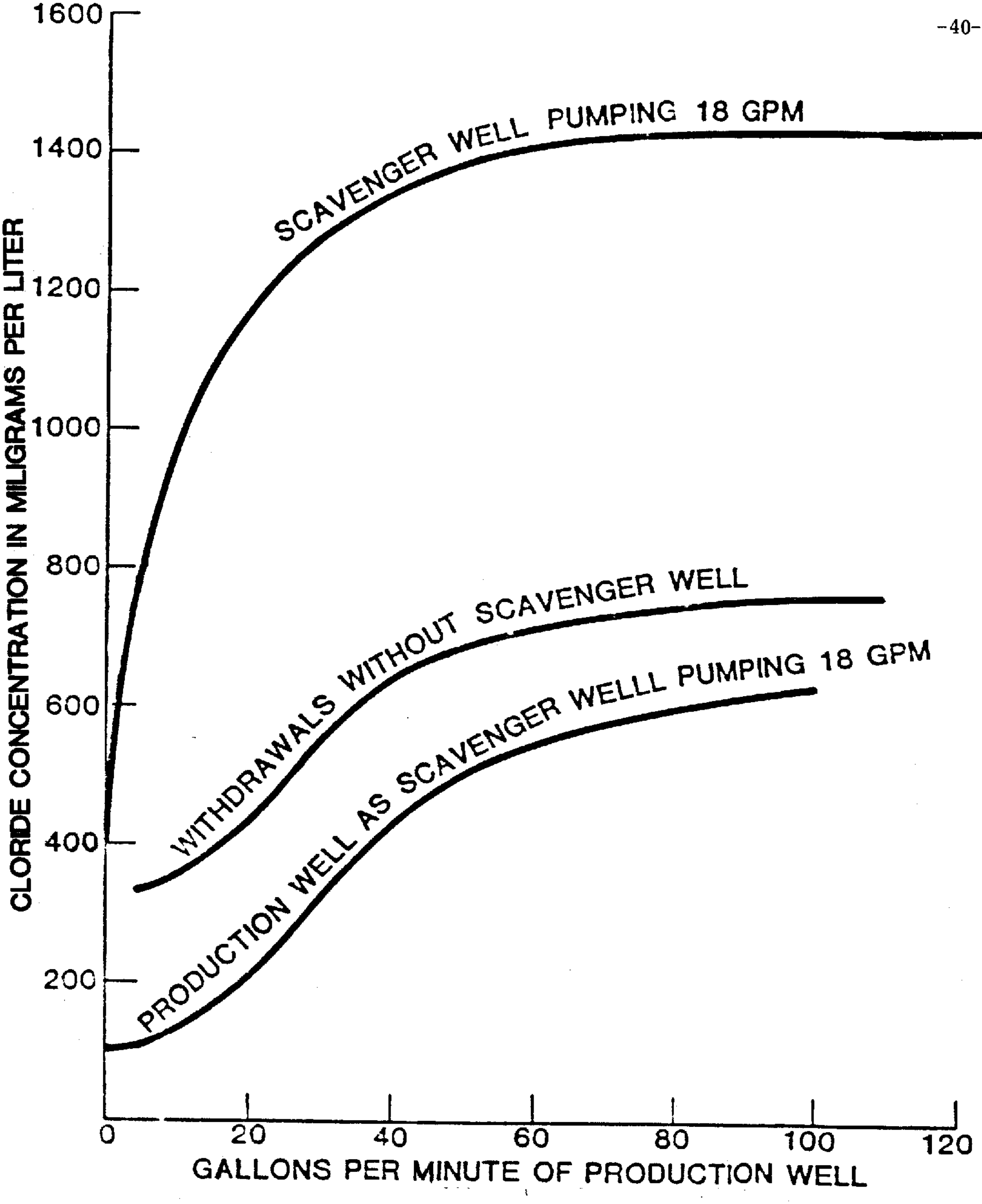

Fig. 17– Cloride concentration of water withdrawn by the production well and scavenger well pumping at a constant rate of 18 gallons per minute and the production well at various rates, La Trocha.

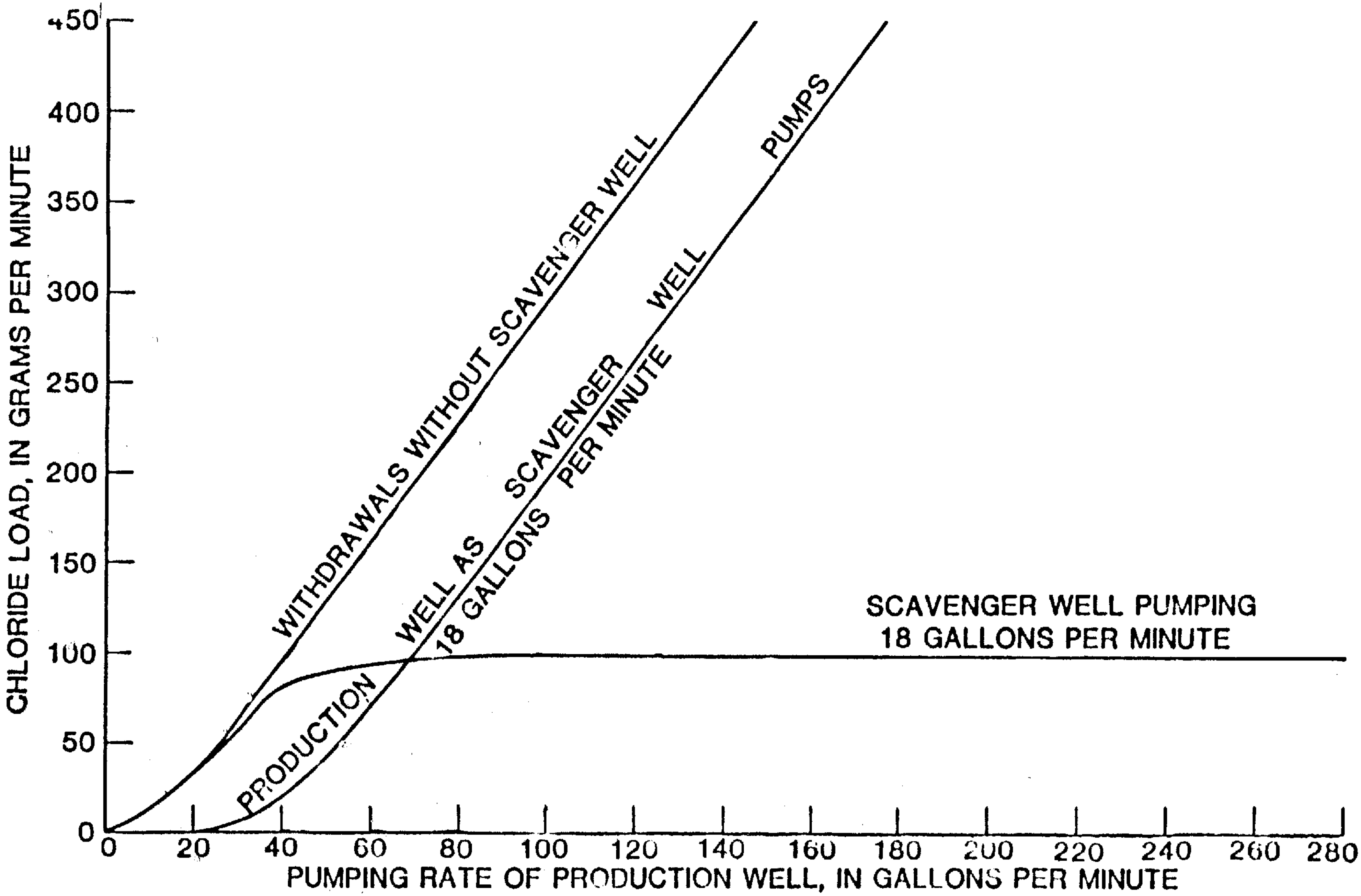

Fig. 18– Cloride load of water withdrawn by the production welland scavenger well pumping simultaneously the scavenger well pumping at a constant rate of 18 gallons per minute and the production well at various rates, La Trocha well.

The linear relation and additive nature of the combined chloride loads and pumping rates for a scavenger-production well couple described above allow for the development of other pumping-rate combinations, assuming the linear relation continues to apply. After having established the total pumping rate and chloride load, the allotment of loads and pumping rates to various scavenger-production well combinations can proceed.

Assuming that the chloride concentration achieved by the scavenger well (1430 mg/L) when withdrawing 18 gal/min (fig. 17) will be the same at higher scavenger well withdrawal rates (maximum upward-advancing chloride available to the scavenger well), the same concentration will be approached asymptotically by larger scavenger well withdrawal rates (arbitrarily selected at 36, 54, and 72 gal/min) (fig. 19). Asymptotes for the production well are automatically generated if it can be assumed that the addition phenomenon observed in fig. 18 persists at elevated withdrawal rates: the chloride load of the production well plus that of its scavenger well is equal to the chloride load of the total well production. The precise placement of the remaining curves is more or less conjecture, but the asymptotes and the curve shapes from figure 18 serve as guidelines to help with the curve fitting (fig. 19).

The values of chloride load are translatable to chloride concentration (fig. 20). Using the couple, it is apparent that as much as 60 gal/min of water with 250 mg/L chloride or less can be withdrawn by the production well if the scavenger well withdraws 72 gal/min.

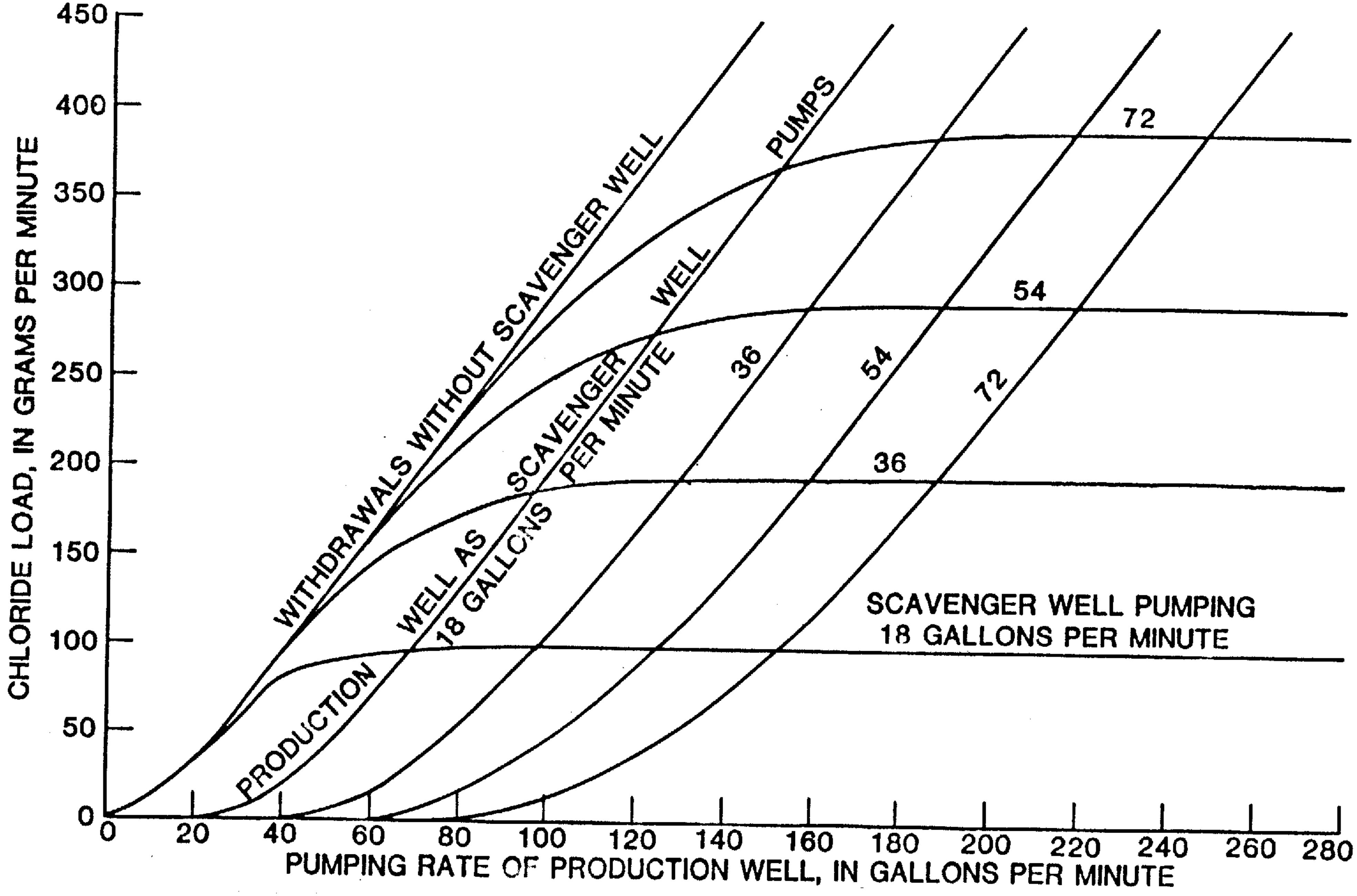

Fig. 19– Cloride load of water withdrawn by the production well and scavenger well pumping simultaneously, the scavenger well pumping at various constant rates and the production well at variable discharge rates, La Trocha well.

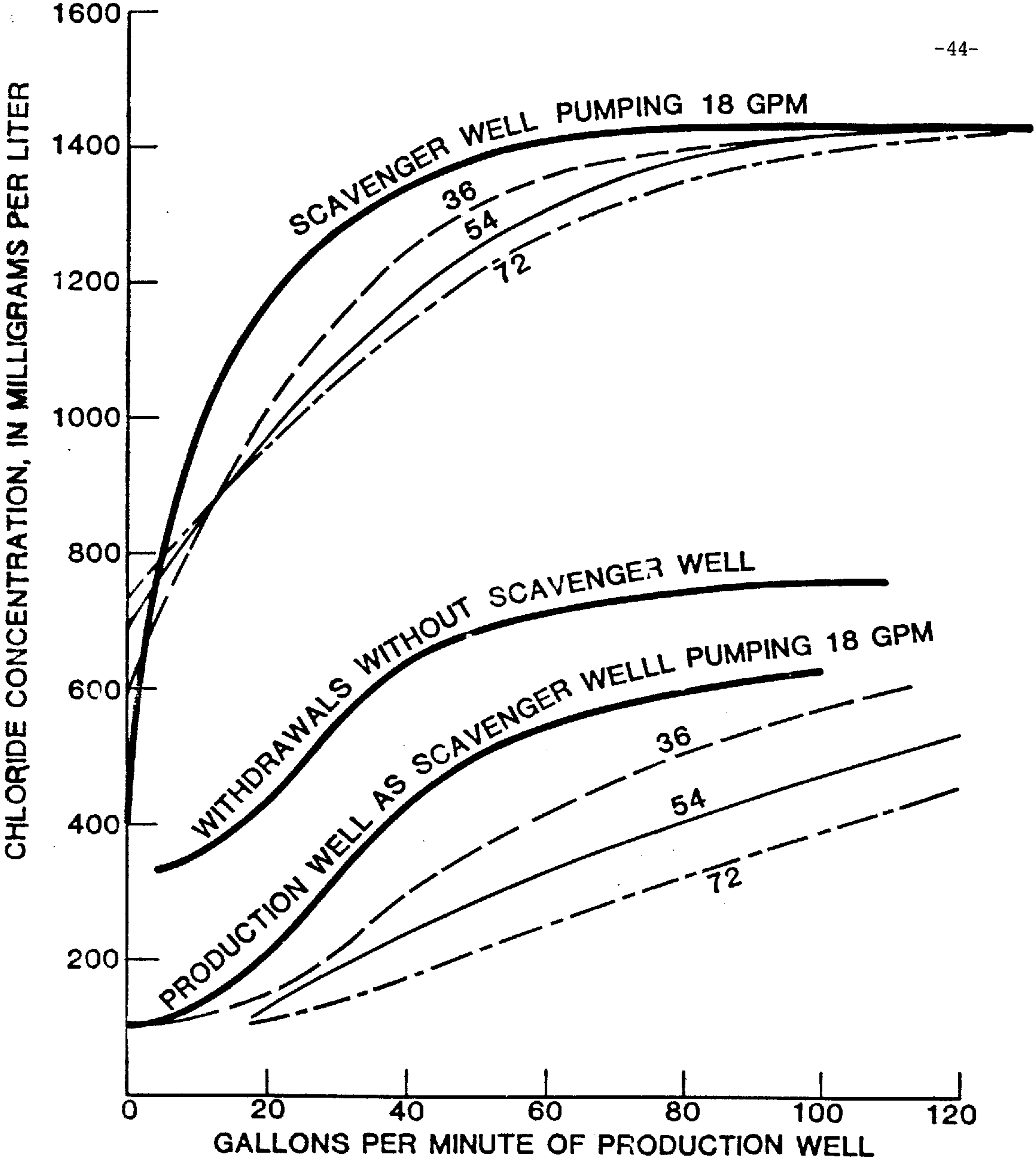

Fig. 20– Cloride concentration of water withdrawn by the production well and scavenger well pumping simultaneously, the scavenger well pumping at various constant rates and the production well at variable rates, La Trocha well.

It is likely that the family of curves basically remain the same, regardless of the location of the intakes of the production and scavenger wells. The asymptotes would be the same, although the approach to the asymptotes might differ. For example, if the scavenger-well intake were to be placed somewhat higher than 130 feet, it follows that the curves generated would be more gradual and the asymptote would be reached somewhat later.

APPLICATION FOR OTHER WELLS

Five important assumptions must be made in order to utilize the methods herein described to design scavenger-production well couples for other wells. They pertain to aquifers which exhibit radial flow when stressed by pumping from a well and they pertain to wells which are 100% efficient or, at least, maintain the same efficiency over a wide range of withdrawal rates.

First, equilibrium conditions will develop in an aquifer under constant pumpage in terms of the upward advance of saltwater and corresponding stabilization of chloride concentration. Depending on the vertical distribution of horizontal hydraulic conductivity, hydraulic gradient, and the difference in fluid properties between the "saltwater" and "freshwater" (density and dynamic viscosity), equilibrium conditions could develop immediately or require hours or days to be achieved.

Second, the placement of the intakes of the scavenger and production wells is not particularly critical, if the production well is placed high in the freshwater section and the scavenger well high in the saltwater part of the well profile. The placement becomes more critical as the well diameter decreases, transmissivities decrease, and pumpage rates increase.

Third, the chloride load of the pumping well develops a linear relationship to pumping rate and reflects the advancement of saltwater upward, toward more highly conductive parts of the aquifer. The saltwater actually replaces part of the freshwater section in the vicinity of the pumping well.

Fourth, a chloride load produced from a well at a particular pumping rates represents the sum of the chloride loads and pumping rates of the scavenger well and the production well pumping simultaneously from the same well regardless of the placement of the two intakes.

Fifth, an equilibrium chloride concentration is reached by the scavenger well as pumpage from the production well is increased. It is the same at all scavenger well pumping rates and represents the chloride concentration of part of the saltwater intercepted while migrating toward the production well.

The hydraulic theory described herein can be applied to any well having radial flow that exhibits increasing chloride at increasing rates of pumping. The hydraulic response within an aquifer to a pumping well will vary considerably because of variations in hydraulic conductivity and salinity distribution within the aquifer, screen location, and pumping rate. However, if freshwater is known to exist in an aquifer containing saltwater, it can be developed using a scavenger-production well couple according to the following procedure:

1. A profile of specific conductance with depth will identify where freshwater and saltwater exist in the borehole. Ideally, two profiles should be made - one before any withdrawals are made from the well, and another while the well is pumped.

2. The production well and scavenger well should be placed within the well bore near the uppermost screens and near the top of the salt-water section respectively and pumped simultaneously at various rates to provide a range of chloride-load data sufficient to establish asymptotes. It is advisable to keep the scavenger well at a constant pumping rate and vary the production well so that the asymptotes of the relationships become clearly apparent. The pumping rates selected should approximate the rate ultimately required from the well. In general, non-pumping periods between steps will allow equilibrium to return to the borehole in terms of the vertical distribution of specific conductance. If freshwater parts of the aquifer are highly transmissive and respond quickly to changes in pumping in terms of reaching constant values of chloride concentration, it is possible to vary withdrawals without intervals. Results obtained would be very nearly the same as if non-pumping intervals had been provided.

3. Chloride loads and pumping rates for the scavenger and production wells are plotted as in figure 19, and the curves are added to produce the chloride-load curve if withdrawals would have been made from the well using only one pump. Asymptotes are drawn and other pumping combinations are selected and derived from asymptotic differences from the single-pump chloride-load curve. Finally, the chloride-load lines are translated to chloride-concentration curves as in fig. 20 to easily select required pumping rates and acceptable limits of chloride concentration.

CONCLUSIONS

Scavenger-production well couples placed at appropriate depths within abandoned wells, screened in both fresh and saltwater parts of an aquifer, provide an effective method of extracting only the freshwater from the well. The efficient correspondence of flow rate between the two wells depends upon the relative concentrations of chloride and the distribution of horizontal and vertical hydraulic conductivity in the aquifer. For each freshwater/saltwater bearing well, a hydraulic analysis can be applied to derive a family of curves representing all combinations of pumping rates and corresponding chloride loads produced by the scavenger and production wells pumping simultaneously.

The curves can be employed to optimize the production of freshwater withdrawals based on pumping rates desired and levels of chloride concentration required for the well.

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