s_1 = drawdown difference per log cycle, in ft
S = aquifer storativity, dimensionless
t_0 = zero-drawdown intercept, in min
r = distance from production well, in ft

Distance-drawdown slope and zero-drawdown intercept equations are (see Cooper and Jacob, 1946, pp. 526–534):

$$T = 528Q/s_1 \tag{3.41}$$

$$S = Tt/(4790r_0^2) \tag{3.42}$$

where t = time after pumping started, in min
r_0 = zero-drawdown intercept, in ft

Induced Streambed Infiltration

When a production well is pumped near a stream hydraulically connected to an aquifer, water is first withdrawn from storage within the aquifer in the immediate vicinity of the production well. The cone of depression then spreads, drawing water from storage within an increasing area of influence. Water levels in the vicinity of the stream are lowered, and more and more of the water which under natural conditions would have discharged into the stream as groundwater runoff is diverted toward the production well. Water levels are lowered below the surface of the stream in the immediate vicinity of the production well, and the aquifer is recharged by the influent seepage of surface water (see Walton, 1963).

The cone of depression continues to grow until it intercepts sufficient area of the streambed and is deep enough so that induced streambed infiltration balances discharge. If the hydraulic conductivity of the streambed is high, the cone of depression may extend only partway across the stream; if the hydraulic conductivity of the streambed is low, the cone of depression may expand across and beyond the stream.

Recharge by induced streambed infiltration takes place over an area of the streambed. However, to make flow problems amenable to mathematical treatment, the area is replaced by a recharging image well. The assumption is made that water levels in the aquifer will behave the same way whether recharge occurs over an area or through a recharging image well (see previous discussion on image well theory) located at an effective distance from the production well. It is further assumed that streambed partial penetration and aquifer stratification impacts are integrated into that effective distance. Representative values of induced streambed infiltration are presented in Table C.6 of Appendix C.

Aquifer transmissivity is determined with steady-state distance-drawdown data at the end of the pumping test for observation wells on a line through and close to the production well and parallel to the stream. These observation wells should be approximately equidistant from the recharging image well, and the impacts of the induced streambed infiltration on water levels in these wells should be equal. Thus, the hydraulic gradient toward the production well along the line is not distorted to any appreciable degree and closely describes the hydraulic gradient that would exist if the aquifer were infinite in areal extent. A plot of drawdown in the observation wells parallel to the stream versus the logarithm of the distances from the production well will yield a straight line graph. The slope of the straight line and the discharge rate are inserted into Equation 3.41 and aquifer transmissivity is calculated.

Although the hydraulic gradient is not distorted, the total values of drawdown in the observation wells are much less than they would be without recharge from the stream. Aquifer storativity (specific yield) cannot be determined directly from the distance-drawdown graph. Instead, specific yield is determined by the method of successive approximations based on drawdown data at the end of the test and the location of the recharging image well.

The distance from the production well to the recharging image well is calculated with the following equation (see Rorabaugh, 1956, pp. 101–169):

$$D_i = 2\{[r^2(10^{Ts/(528Q)})^2 - r^2]/4\}^{1/2} \tag{3.43}$$

where D_i = distance from production well to recharging image well, in ft
r = distance from the production well to observation well, in ft
T = aquifer transmissivity, in gpd/ft
s = drawdown in observation well, in ft
Q = production well discharge, in ft

Equation 3.43 is valid for observation wells on a line parallel to the stream and the distance D_i is measured at a right angle to the stream (see previous discussion concerning the image well theory).

Microcomputer Programs

With the recharging image well located and aquifer transmissivity calculated, aquifer specific yield may be determined using observation well data at the end of the test and Equations 3.1, 3.2, and 3.13–3.16. The production, observation, and image wells are drawn to scale on a map and the distances between the image well and the observation wells are determined. Several values of aquifer specific yield are assumed and microcomputer program PT7 is utilized to determine observation well drawdowns for each assumed value. Calculated drawdown values are compared with actual drawdown values, and that specific yield used to calculate drawdowns equal to actual drawdowns is assigned to the aquifer. The interactive input section of microcomputer program PT7 prompts the user to enter values of production well discharge which are equal to the image well recharge rate, aquifer transmissivity, aquifer storativity, distance between the observation well and the production well, distance between the image well and the observation well, and the time after pumping started. Total drawdowns in observation wells due to both production and image well impacts are generated and displayed as output by the program.

The rate of stream depletion or the rate of recharge by induced streambed infiltration is calculated with microcomputer program PT8, which is based on equations presented by Jenkins (1968, p. 16). The interactive input section of the program prompts the user to enter values of aquifer transmissivity, aquifer storativity, time after pumping started, production well discharge rate, and distance between the production and recharging image wells. The rate of stream depletion is generated and displayed as output by the program.

The production well, recharging image well, and streambed are drawn to scale on a map. A grid is superposed over the map. Several points within the streambed up and down stream are selected for calculation of drawdown beneath the streambed. Values of drawdown at the points are then determined with microcomputer program PT9. The interactive input section of that program prompts the user to enter values of aquifer transmissivity, specific yield, production well discharge rate, time after pumping started, x,y coordinates of the production and image wells, and grid spacing. Total drawdowns due to the production and image wells are generated at grid line intersections by the program and displayed as output. Values of drawdown at the selected points within the streambed may be interpolated from grid intersection values.

The reach of the streambed (L_s) within the influence of the production well is ascertained by noting the points up and down stream where drawdown beneath the streambed is negligible (<0.01 ft). The area of induced streambed infiltration is then equal to the product of L_s and the average distance between the shoreline and the recharge boundary or the average width of the streambed depending upon the position of the recharge boundary.

The induced streambed infiltration rate is calculated with the following equation (Walton, 1963):

$$I_a = 6.3 \times 10^{[illegible]} Q_s / A_s \qquad (3.48)$$

where I_a = average induced streambed infiltration rate, in gpd/acre
Q_s = rate of stream depletion, in gpm
A_s = area of induced streambed infiltration, in sq ft

The average head loss due to the vertical percolation of water through the streambed may be determined from data for observation wells installed within the streambed area of induced infiltration at depths just below the streambed. In many cases, the installation of observation wells in the stream channel is impractical and the average head loss must be estimated with Equations 3.1–3.2 and 3.13–3.16 and microcomputer program PT9. Many points within the reach of the streambed influenced by the production well are located on a map and drawdowns at the points are then interpolated from grid intersection values of drawdown and averaged.

The average induced streambed infiltration rate per unit area per foot of head loss may be estimated with the following equation (Walton, 1963):

$$I_h = I_a / h_r \qquad (3.49)$$

where I_h = average induced streambed infiltration rate, in gpd/acre/ft
h_r = average head loss within the streambed area of induced infiltration, in ft

The induced streambed infiltration rate per foot of head loss varies with the temperature of the surface water. A decline in the temperature of surface water of 1°F will decrease the rate about 1.5% (Rorabaugh, 1956, pp. [illegible]) through the range generally encountered in practical prob lems. The induced streambed infiltration rate for any particular surface water temperature may be calculated with values of dynamic viscosity presented in Table E.7 of Appendix E and the following equation (Walton, 1963):

$$I_t = I_a V_a / V_t \tag{3.46}$$

where I_t = average induced streambed infiltration rate for a particular surface water temperature, in gpd/acre/ft

V_a = dynamic viscosity at temperature of surface water during pumping test, in poise-second units

V_t = dynamic viscosity at a particular temperature of surface water, in poise-second units

Example Problems

An 8-hour pumping test was conducted with a production well and one observation well in a nonleaky artesian aquifer system in Example Problem 3.7. There are no nearby aquifer boundaries or interfering production wells and the wells fully penetrate the aquifer. Observation well OBS-1 is located 234 ft from the production well and the production well has a radius of 0.33 foot. The constant production well discharge rate is 50 gpm. Time-drawdown data for the production and observation wells are presented in Table 3.7. Calculate aquifer transmissivity and storativ-

Table 3.7. Database for Example Problem 3.7

Time After Pumping Started (min)	Production Well Drawdown (ft)	OBS-1 Drawdown (ft)
10	2.88	0.46
20	3.01	0.59
40	3.14	0.71
70	3.24	0.82
150	3.38	0.98
300	3.51	1.09
480	3.60	1.17

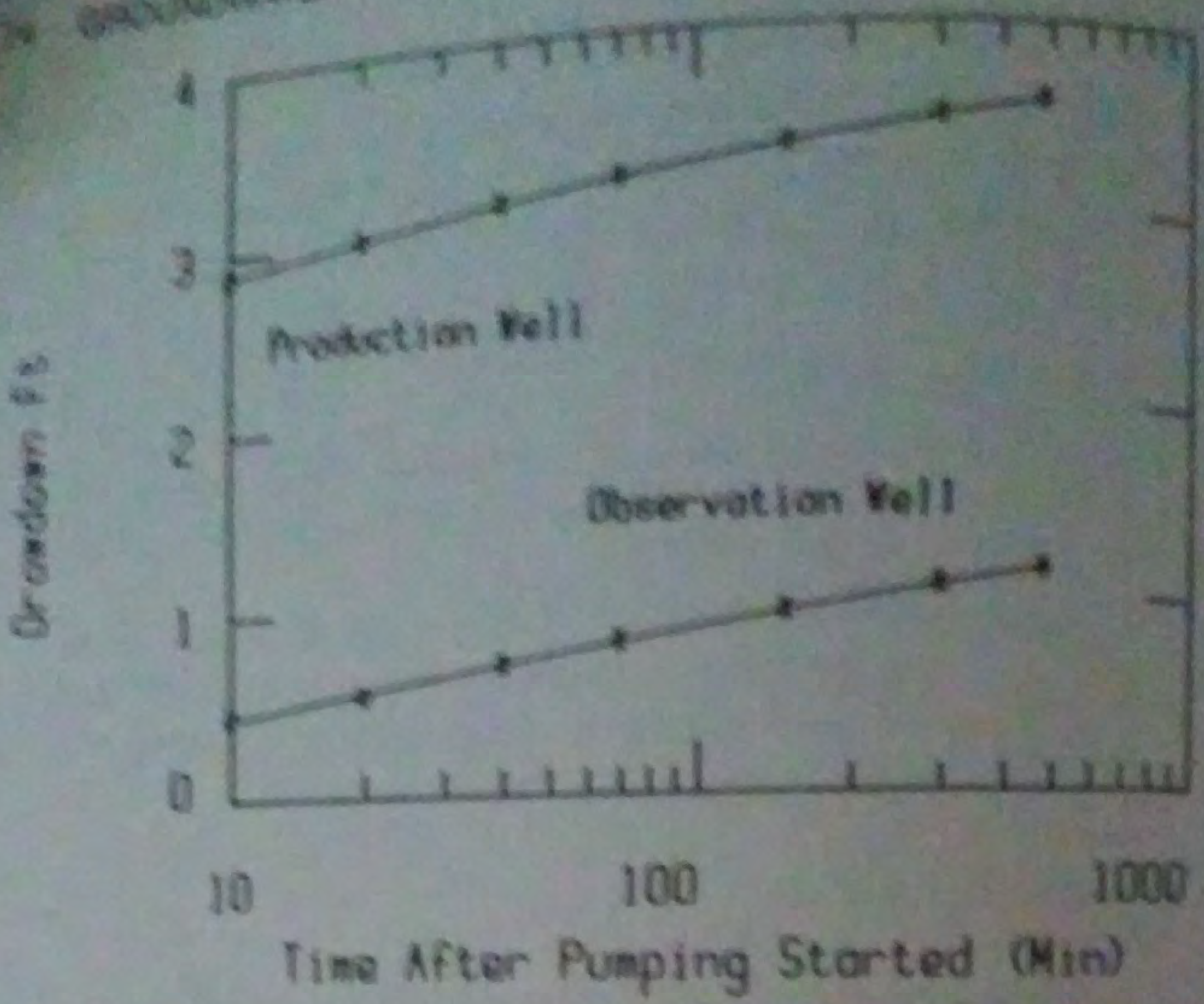

Figure 3.8. Time-drawdown graphs for Example Problem 3.7.

ity using the straight line matching method and microcomputer program PT6.

The slopes of the straight lines through both time-drawdown graphs are 0.42 ft; the zero-drawdown intercept for OBS-1 is 0.824 minute. Values of aquifer transmissivity and storativity calculated with Equations 3.39 and 3.40 are 31,429 gpd/ft and 1×10^{-4}, respectively. Aquifer storativity cannot be calculated from production well data because the effective radius and well loss coefficient for the production well are unknown. According to Equation 3.38, u was ≤ 0.02 before the first water level measurement was made in the production well and 24 minutes after pumping started in OBS-1. The time-drawdown graphs for the two wells are presented in Figure 3.8.

A 3-day pumping test was conducted with a production well and three observation wells in a water table aquifer system in Example Problem 3.8. The production and observation wells fully penetrate the aquifer. The production

Table 3.8. Database for Example Problem 3.8

Distance from Production Well to Observation Well (ft)	Drawdown (ft)
50	.81
100	.54
250	.23

well constant discharge rate was 100 gpm. The thickness of the aquifer is 50 ft and the radius of the production well was 0.33 ft. A lake hydraulically connected to the aquifer system (source of recharge) is located 100 ft from the production well. All observation wells are on a line through the production well and parallel to the lake shore. Distances from the production well to OBS-1, OBS-2, and OBS-3 are 50, 100, and 200 ft, respectively. The temperature of the surface water is 54°F. Distance-drawdown data for the end of the test are presented in Table 3.8. Calculate the aquifer transmissivity and specific yield and the lakebed induced infiltration rate.

The slope of the straight line through the distance-drawdown graph is 0.90 ft and the aquifer transmissivity calculated with Equation 3.41 is 58,667 gpd/ft. The aquifer specific yield calculated with microcomputer program PT7 is 0.05. Lake depletion at the end of the test was calculated to be 84 gpm with microcomputer program PT8. The distance from the production well to the recharging image well simulating lake induced infiltration was calculated with Equation 3.43 to be 400 ft. Thus, the effective line of recharge is 200 ft from the production well or 100 ft offshore. Drawdowns between the lake shore and the effective line of recharge ranged from 0.42 to 0.01 ft and average 0.05 ft within the area of influence of pumping according to microcomputer program PT9. Drawdown was appreciable 1000 ft up and down the lake shore. The area of lakebed induced infiltration was 200,000 sq ft. The lakebed induced

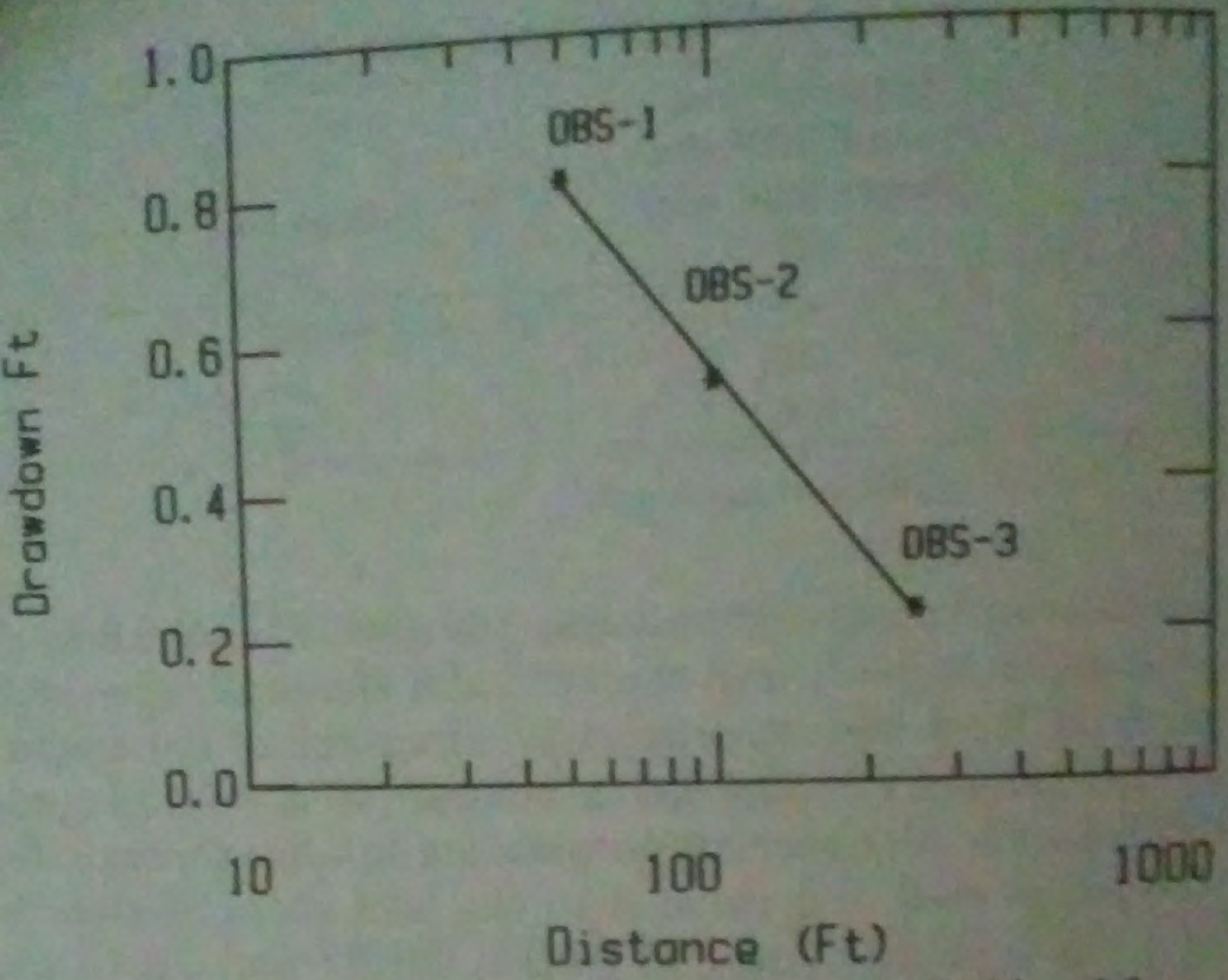

Figure 3.9. Distance-drawdown graph for Example Problem 3.8.

infiltration rate is 26,460 gpd/acre based on Equation 3.44 and the lakebed induced infiltration rate per foot of head loss beneath the lakebed is 529,200 gpd/acre/ft based on Equation 3.45. The lakebed induced infiltration rate per foot of head loss would be 763,033 gpd/acre/ft if the temperature of the surface water were 79°F (see Equation 3.46). Calculations made with Equations 1.1 and 1.3 indicate that well storage impacts were negligible with r_c = 0.1 ft after 1 minute of pumping and delayed gravity yield impacts were negligible with P_V/P_H = 1/10 before the end of the test. The distance-drawdown graph is presented in Figure 3.9.