Appendix E

Data Analysis Methods for Aquifer Tests

This appendix presents details of the analysis methods applied to the four constant-rate pumping tests (described in Section 2.6) performed in the Spokane Valley and in North Spokane. The appendix first discusses the calculations necessary to account for partial penetration effects, which have substantial influence on the drawdown data collected from certain wells. The appendix then discusses the calculation procedures used to derive transmissivity values from the aquifer test data. Also included in this appendix are attachments summarizing each aquifer test showing a site layout sketch, a brief summary of what occurred during testing, and hydrographs showing water level data.

E.1. Corrections for Partial Penetration

E.1.1. Definition of Partial Penetration Effects

Methods for analyzing aquifer test data and specific capacity data assume that groundwater flow in the vicinity of pumping wells and observation wells is horizontal (that is, there are no significant vertical flow components). For each of the four aquifer tests, each pumping well and observation well penetrates only the upper portion of the aquifer. Consequently, significant vertical flow occurs near a partially penetrating pumping well as water moves from the underlying aquifer into the well's open interval. Because water moves vertically from the aquifer formation through the open interval of a partially penetrating pumping well, a portion of the total drawdown in the well occurs as head losses due to partial penetration. These head losses arise because this mechanism for moving water into the well is less efficient than for a fully penetrating well, which obtains a greater proportion of its yield from horizontal flow into the well screen. Consequently, the drawdown in a partially penetrating well is greater than the drawdown in a fully penetrating well.

Because aquifer test data and specific capacity data collected in an unconfined aquifer are analyzed under the assumption of horizontal flow, the drawdown data from pumping wells must be adjusted to remove the artificial drawdown induced by the partially penetrating nature of the well. The drawdown data at observation wells must also be adjusted if the observation well is sufficiently close to the pumping well to be influenced by vertical flow. The adjustment of drawdown data for partial penetration effects uses methods originally developed by Butler (1957) and presented by Walton (1962).

E.1.2. Corrections for Aquifer Tests

Drawdown data collected during four aquifer tests are adjusted at selected wells to remove effects of partial penetration of both the pumping and observation wells. The adjustment method consists of identifying which wells require adjustment, followed by calculations of the drawdown adjustment factor.

During the data analysis procedure, additional evaluations were made to determine whether adjustments were also required for well casing storage effects or ambient changes in groundwater elevations. Based on these analyses, no adjustments were required to the drawdown data.

E.1.2.1. Wells Requiring Adjustment for Partial Penetration Effects

Identification of which wells required adjustment is made by calculating the approximate distance r_{pp} from the pumping well beyond which the effects of partial penetration are negligible:

$$r_{pp} = 2m\,(P_h/P_v)^{1/2}$$

where:
- m = initial aquifer saturated thickness (feet)
- P_h = horizontal hydraulic conductivity (ft/day)
- P_v = vertical hydraulic conductivity (ft/day)

Using a value of 3 for P_h/P_v and aquifer thicknesses of 400 feet at the Vera #2-1 and CID #11 sites, 450 feet at the CID #4 site, and 200 feet at the NSID #3 location, the values of r_{pp} are as follows:

Vera #2-1 test and CID #11:	$r_{pp} = (2 \times 400)\,(3)^{1/2}$	= 1,385 feet
CID #4 test:	$r_{pp} = (2 \times 450)\,(3)^{1/2}$	= 1,560 feet
NSID #3 test:	$r_{pp} = (2 \times 200)\,(3)^{1/2}$	= 690 feet

Based on these calculations, adjustments of drawdown data are required for all pumping and observations wells monitored during the four tests.

E.1.2.2. Calculation of Correction Factors

The partial penetration effects are corrected using Table 1 of Walton (1962), which requires defining the values of the following variables for each well:

$$r/m\,(P_h/P_v)^{1/2}$$

$$r_e / m$$

$$\alpha = L / m$$

$$s = C_p\, s_{pp}$$

where: r = distance between pumping well and observation well (feet)

$r_e =$ virtual radius of the cone of depression (assumed 1,000 feet for unconfined aquifers)

$\alpha =$ fractional penetration (percent of aquifer's saturated thickness penetrated by well's open interval)

L = length of open interval

$s =$ drawdown in equivalent fully penetrating well (feet)

$s_{pp} =$ observed drawdown in partially penetrating well (feet)

$C_p =$ partial penetration correction factor (for adjusting measured drawdown)

Table E-1 summarizes the calculation of the correction factors for the observation wells requiring adjustments to measured drawdown data.

Drawdown data from each pumping well were adjusted for partial penetration effects using Table 2 of Walton (1962). This procedure is identical to the procedure applied to observation well data from constant-rate pumping tests (Table 1 of Walton, 1962); the only differences are in the tabulated values of the correction factors. Table E-1 also shows the calculations of the correction factors for the pumping wells.

E.2. Transmissivity Calculations

Available drawdown and recovery data from the four aquifer tests were analyzed using methods and derivations consistent with Cooper-Jacob (1946) for unconfined aquifers. Particular analytical derivations included using time-drawdown, time-recovery, distance-drawdown, and specific capacity relationships. Time-drawdown analyses involve plotting drawdown versus elapsed pumping time (logarithmic scale). Time recovery plots consist of drawdown versus a ratio of the time since pumping began to the time since pumping has stopped on a logarithmic scale. Distance-drawdown analyses involve plots of drawdown at one particular time for several wells at differing distances from the pumping well (logarithmic scale).

Transmissivity values are estimated from specific capacity data using the following relationship (Driscoll, 1986, page 1021):

$$T = 2000*Q / s$$

where T = transmissivity (gallons/day/foot)

Q = pumping (gpm)

s = drawdown (feet), corrected for partial penetration effects

Specific transmissivity calculations are presented in the attachments included for each of the four aquifer tests. Table E-2 summarizes the ranges in transmissivity calculated.

Table E-1: Partial Penetration Correction Factors for SAJB Aquifer Test Observation Wells

Aquifer Test	Observation Well	r (feet)	m (feet)	r_e/m	Penetration Depth below water table (ft)	Penetration as a Percentage of Aquifer Saturated Thickness	$(r/m)(P_h/P_r)^{1/2}$ (a)	Correction Factor: Interpolated from Table 1 of Walton (1962) (b)	Correction Factor: Interpolated from Table 2 of Walton (1962) (b)	Correction Factor: Selected Value (c)
Vera #2	Vera #2-1	0.9	400	2.5	170	42%	0.004		0.5	0.5
	Vera test well	16	400	2.5	155	39%	0.069	0.2		0.2
North Spokane	NSID #3	1.9	200	5.0	65	33%	0.016		0.5	0.5
	NSID #2	170	200	5.0	65	33%	1.472	0.99		0.9
CID #11	CID #11A	1	400	2.5	135	34%	0.0043		0.3	0.3
	SAJB #3	59	400	2.5	40	10%	0.255	0.55		0.5
CID #4	CID #4B	0.75	450	2.2	130	29%	0.0029		0.3	0.3
	SAJB #1	90	450	2.2	30	7%	0.346	0.65		0.6

Notes:
(a) Assumes Ph/Pv = 3 and a well radius (r) of 0.5 feet for each well.
(b) Walton, William C. 1962. *Selected Analytical Methods for Well and Aquifer Evaluation.* Illinois State Water Survey Bulletin 49. Sixth printing.
(c) Selected values are generally lower than values estimated from Table 1 and 2 (Walton, 1962) to avoid underestimating aquifer transmissivity.

Table E-2: Transmissivity and Hydraulic Conductivity Summary

Aquifer Test	Location	Data Analysis Methods	Estimated Transmissivity Range (ft2/day)	Estimated Saturated Thickness (ft)	Estimated Hydraulic Conductivity (ft/day)
Vera #2	Valley, Sullivan and Broadway	Distance-drawdown	380,000	400	950
No SPK Irr Dist.	North Spokane, Francis and Market	Time-drawdown, time-recovery Specific capacity	100,000 - 700,000	200	500 - 3,500
CID #11	East Farms, Idaho Road and Wellesley	Distance-drawdown Specific capacity	800,000 - 1,700,000	400	2,000 - 4,200
CID #4	Valley, near Barker and Mission	Distance-drawdown Specific capacity	1,900,000 - 2,500,000	450	4,200 - 6,200

Vera Water and Power Well #2-1 Aquifer Test

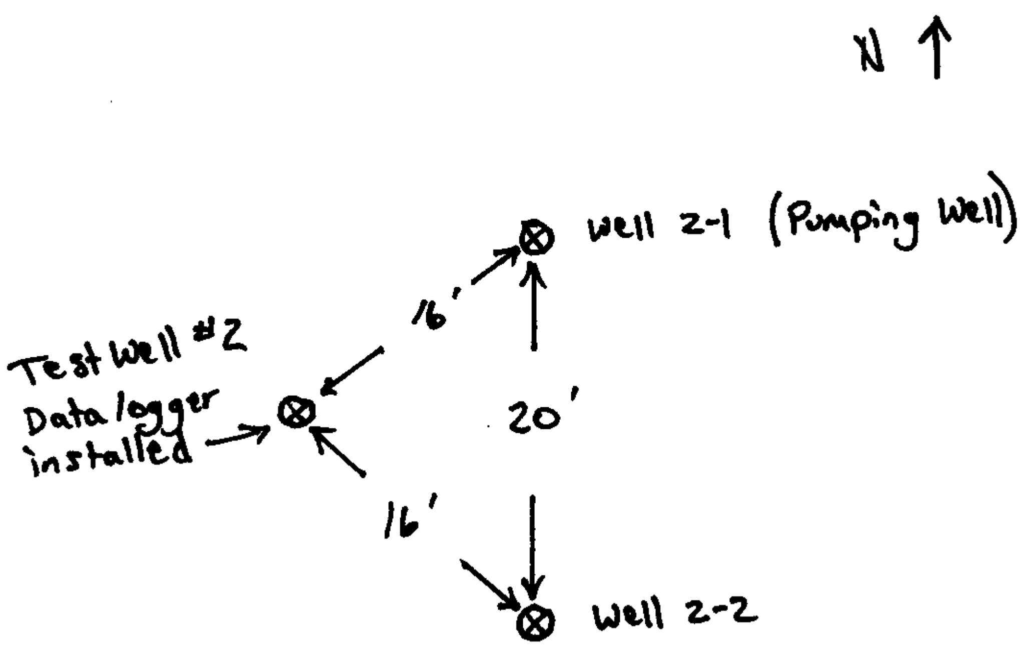
June 10, 1997

Background monitoring: Data logger and pressure transducer installed in test well #2 on June 6, 1997. Water levels showed a declining trend of approximately 0.15 feet per day. Water levels in test well #2 also showed drawdown and recovery responses to pumping from Well #2-1 and/or Well #2-2.

Testing: Pumping began at approximately 8:30 a.m. and concluded at 4:45 p.m. The pumping rate during the testing ranged from approximately 2,400 to 2,650 gpm and average approximately 2,500.

Problems Encountered: No access ports available in pumping well or well #2-2 to measure water levels.

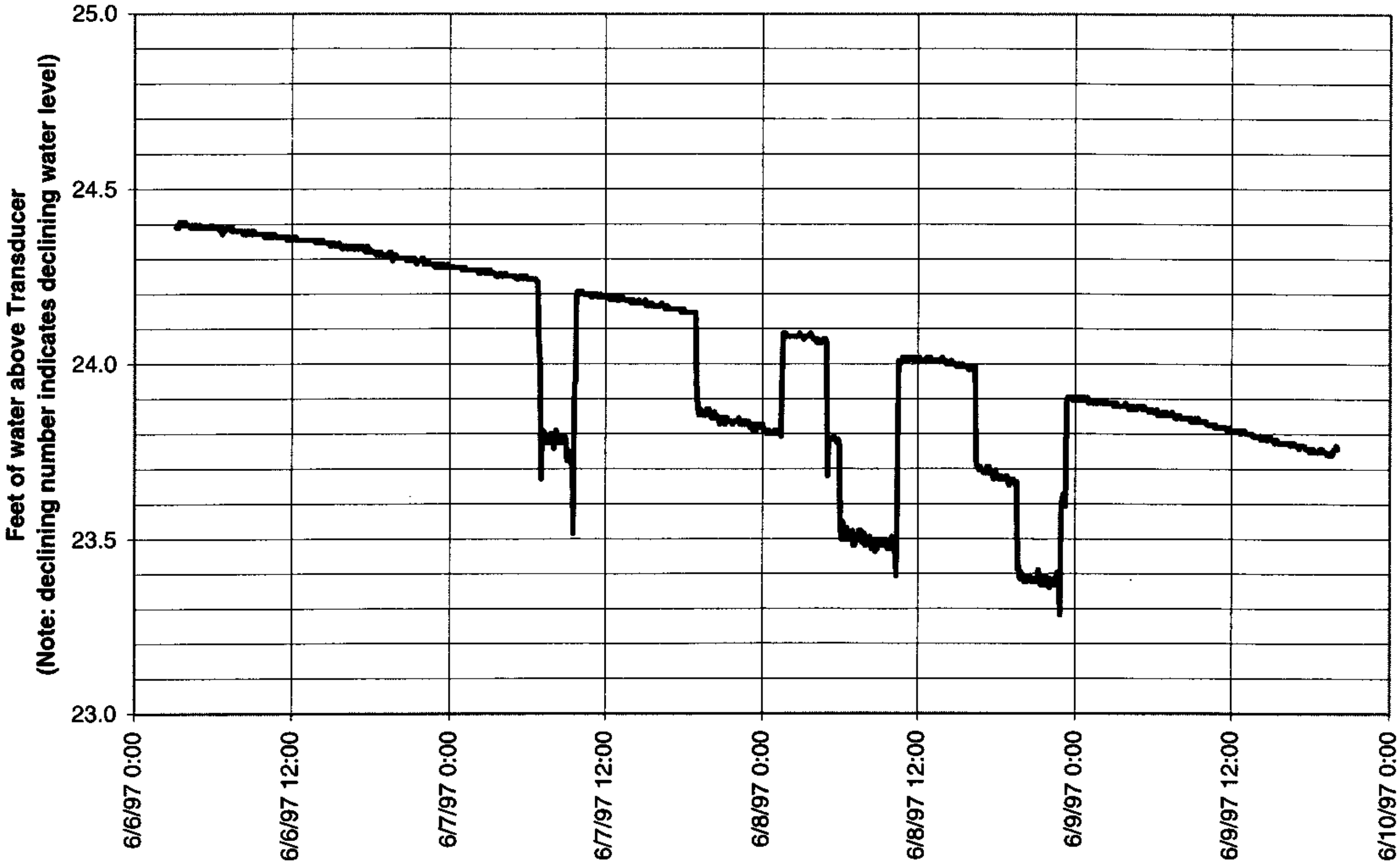
Site Sketch:



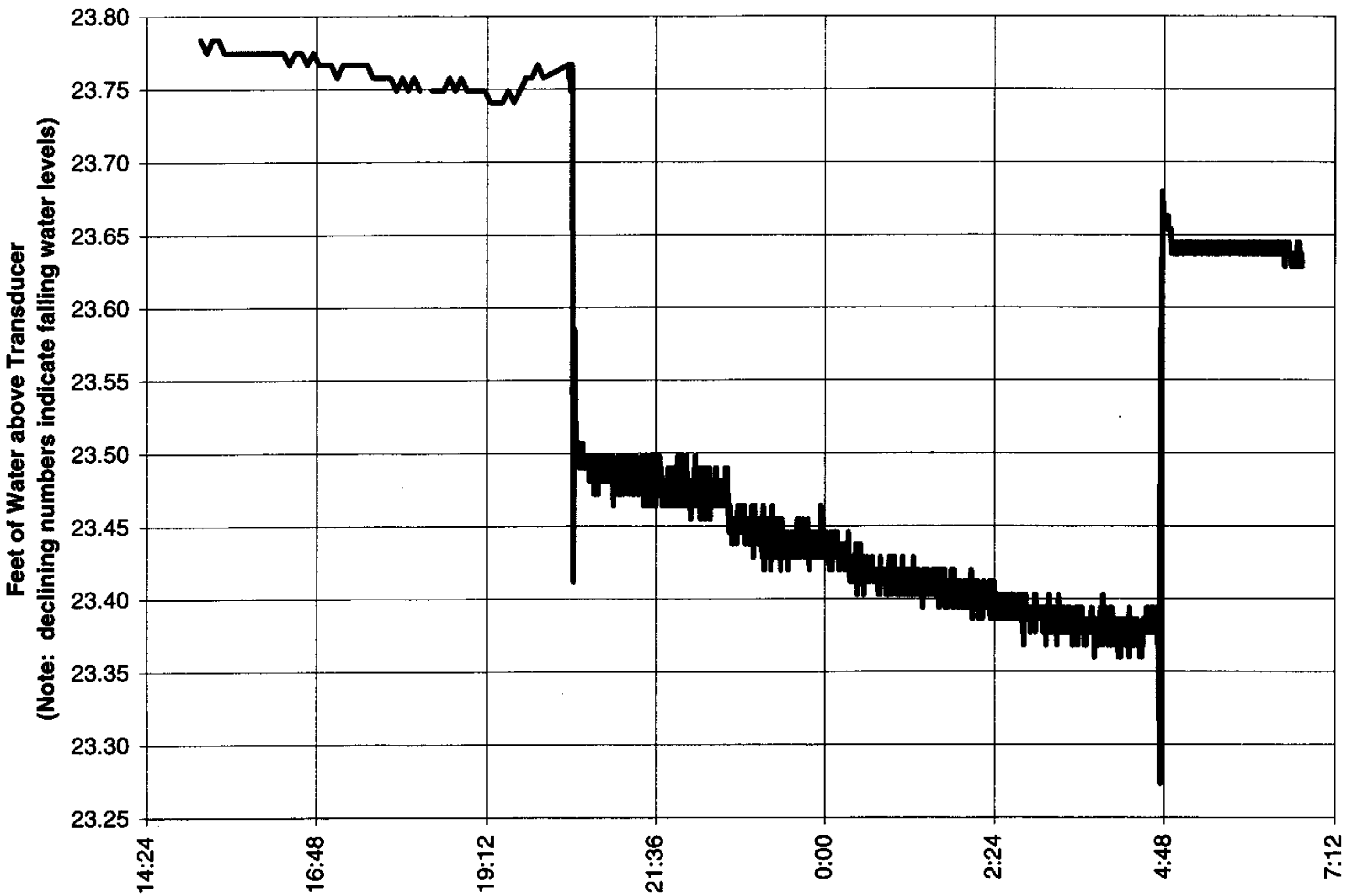
Screened Intervals

Well 2-1	210 - 265
Well 2-2	210 - 265
Test Well 2	229 - 249

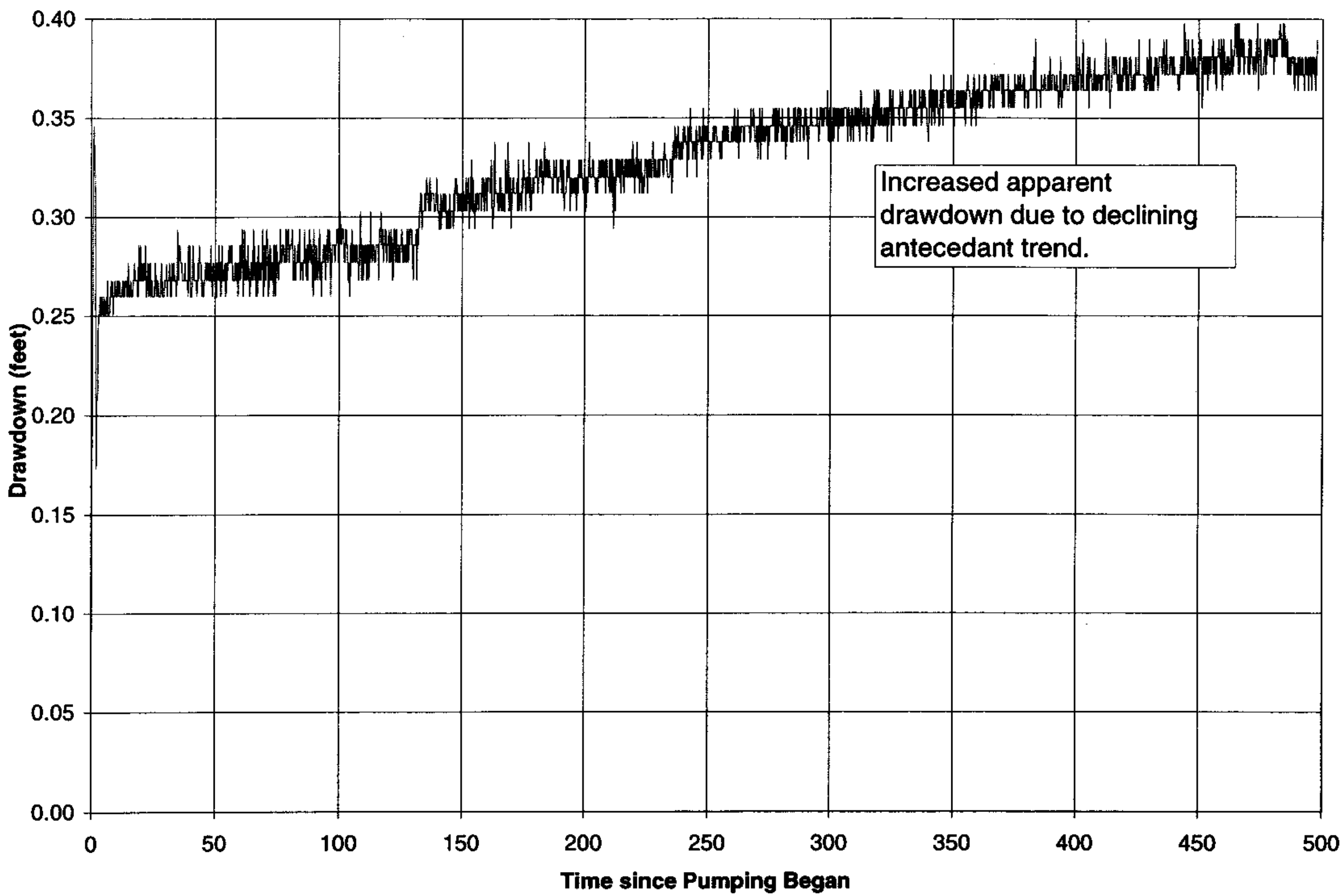
Water Levels in Test Well #2
Prior to Aquifer Testing



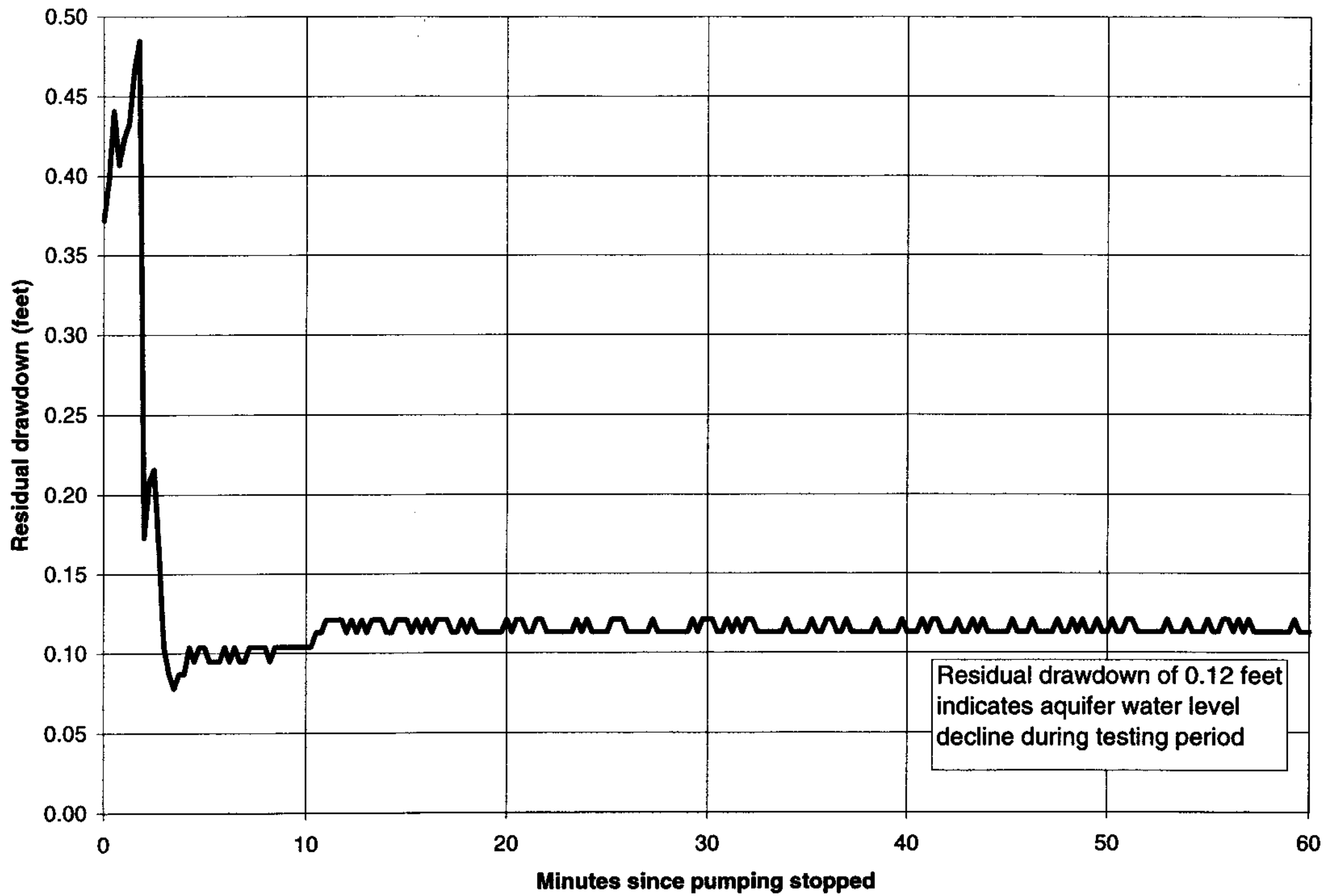
Water Levels in Vera Test Well #2
Day of AquiferTest



Drawdown in Test Well #2 During Aquifer Testing



Recovery in Vera Test Well #2 Following Pumping



Notes: Instantaneous drawdown and recovery in test well #2 preclude curve matching techniques.

Drawdown in test well = 0.26 feet

Drawdown in Pumping well #2-1 = ?

→ Specific capacity data from #2-1 during installation (1994) indicated 1.25 feet of drawdown after 1 hour of pumping at 2500 gpm.

Assume similar conditions current.

Therefore

drawdown in pumping well = 1.25 feet
" in test well #2 = 0.26 feet

Apply partial penetration factors of 0.5 and 0.2 respectively and drawdown =

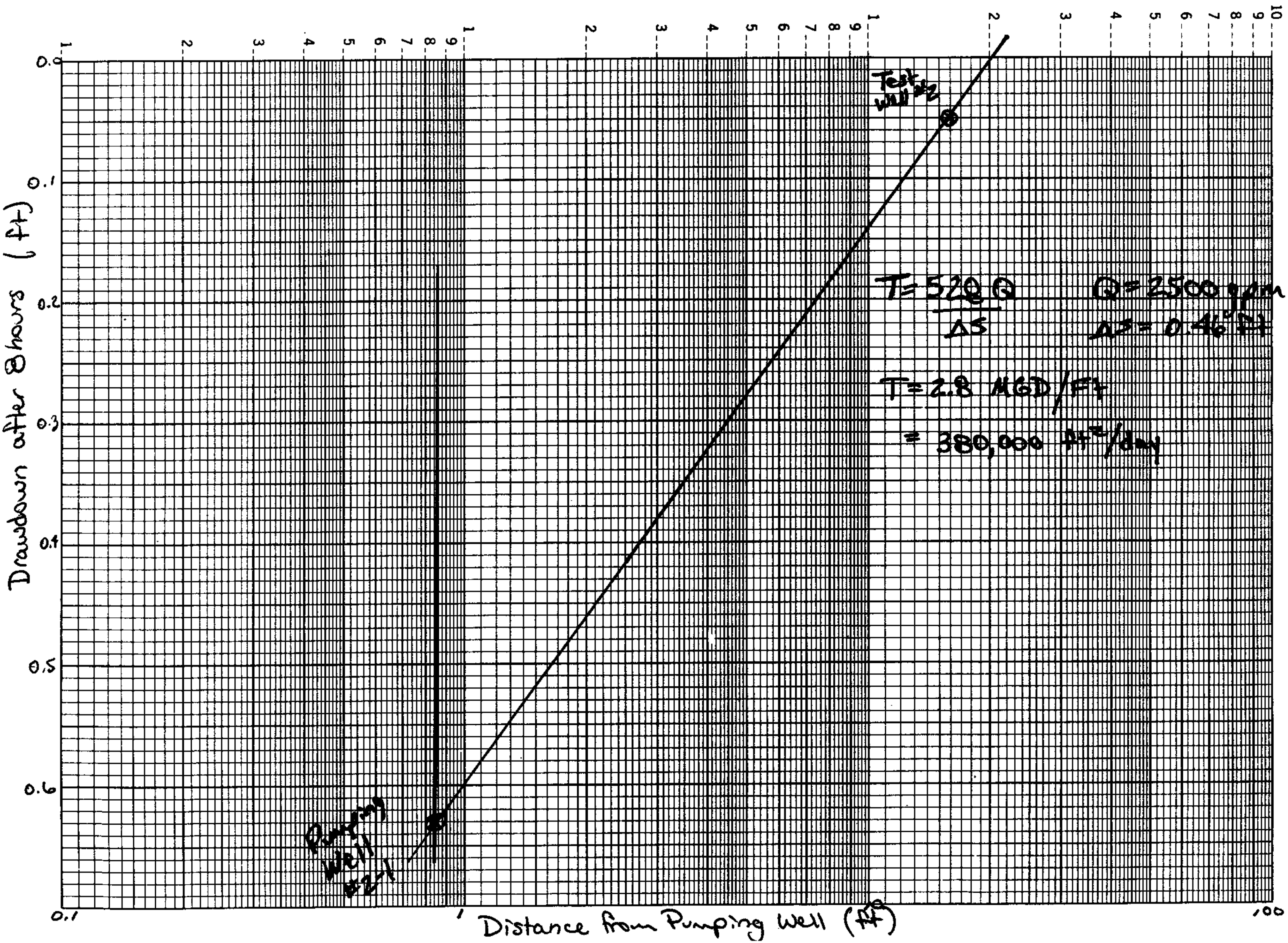
0.63 pumping well
0.05 observation well

Do distance-drawdown calculation.

$T = 380,000\ ft^2/day$ $K \cong 1000\ ft/day$

From estimated specific capacity data, $T = 1,100,000\ ft^2/day$

This assumes pumping well is 100% efficient. If it is 80% effiecient, then $T \simeq 500,000\ ft^2/day$


Test Well #2
Pumping Well #2-1
T = 528 Q / ΔS
Q = 2500 gpm
ΔS = 0.46 ft
T = 2.8 MGD/Ft
= 380,000 ft²/day
Drawdown after 8 hours (ft)
Distance from Pumping Well (ft)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.1
1
10
100

North Spokane Irrigation District (NSID) Well #3 Aquifer Test

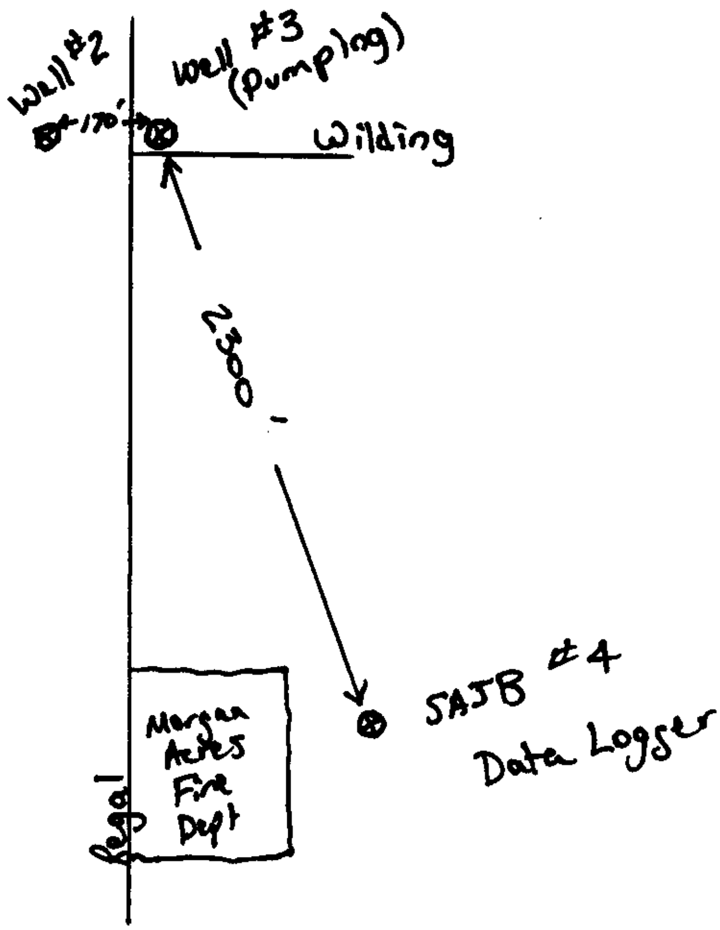
July 16, 1997

Background monitoring: Data logger and pressure transducer installed in SAJB #4 monitoring well located at the Morgan Acres Fire Dept. on July 11, 1997. Water levels showed a declining trend of approximately 0.1 feet per day. Water levels in SAJB #4 generally showed steady decline throughout the day until early in the morning when water levels typically leveled-off through mid-day. No was no apparent direct evidence suggesting water level responses in this well to pumping occurring at the NSID well field located approximately 2,300 feet north-northwest.

Testing: Pumping began at NSID Well #3 at approximately 9:30 a.m. and concluded at 4:00 p.m. The pumping rate during the testing averaged approximately 800 gpm during testing. Water levels were manually measured in the pumping well and at an idle backup well (Well #2) located 170 feet west (cross-gradient).

Problems Encountered: System capacity would only allow approximately 6.5 to 7 hours of pumping.

Site Sketch:



Screened Intervals
#2 unknown
#3 232-251
SAJB #4 183-213

Drawdown data and recovery data from the pumping well (Well #3) and drawdown data from Well #2 using data corrected for partial penetration suggest:

Transmissivity (T) ranges from approx. 240,000 ft^2/day to 700,000 ft^2/day

Assuming saturated thickness ~200 ft, then hydraulic conductivity (K) would range from 1200 - 3500 ft/day

*Insufficient data collected from observation well during recovery to provide analysis.

Specific Capacity data using pumping data only:

$$T = \frac{(2000)\ Q}{S}$$

$$= \frac{(2000)\ (800)}{2.02}$$

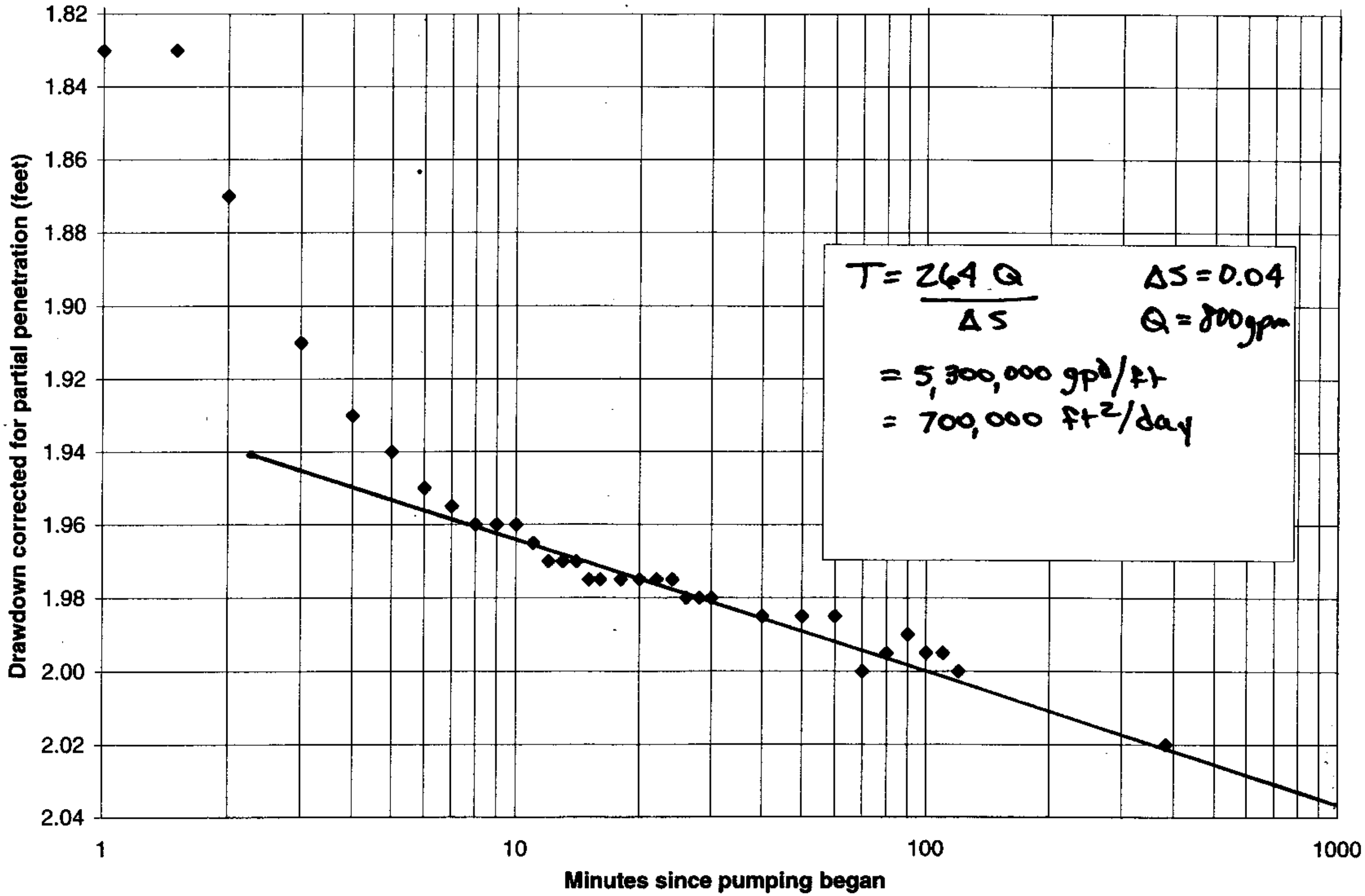
= 790,000 gpd/ft

100,000 ft^2/day

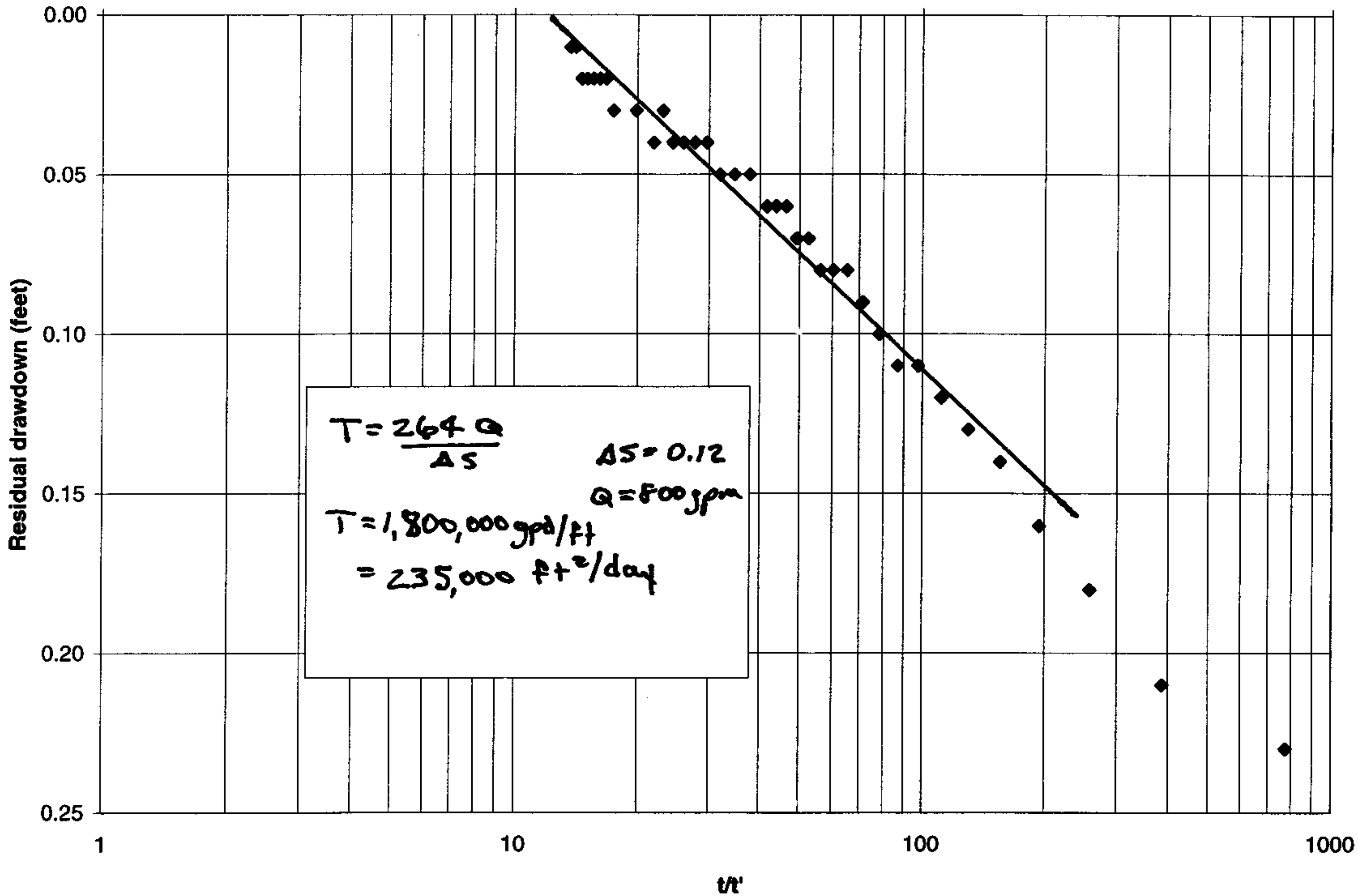
Therefore T range 100,000 to 700,000 ft^2/dy

K would range 500 - 3500 ft/day

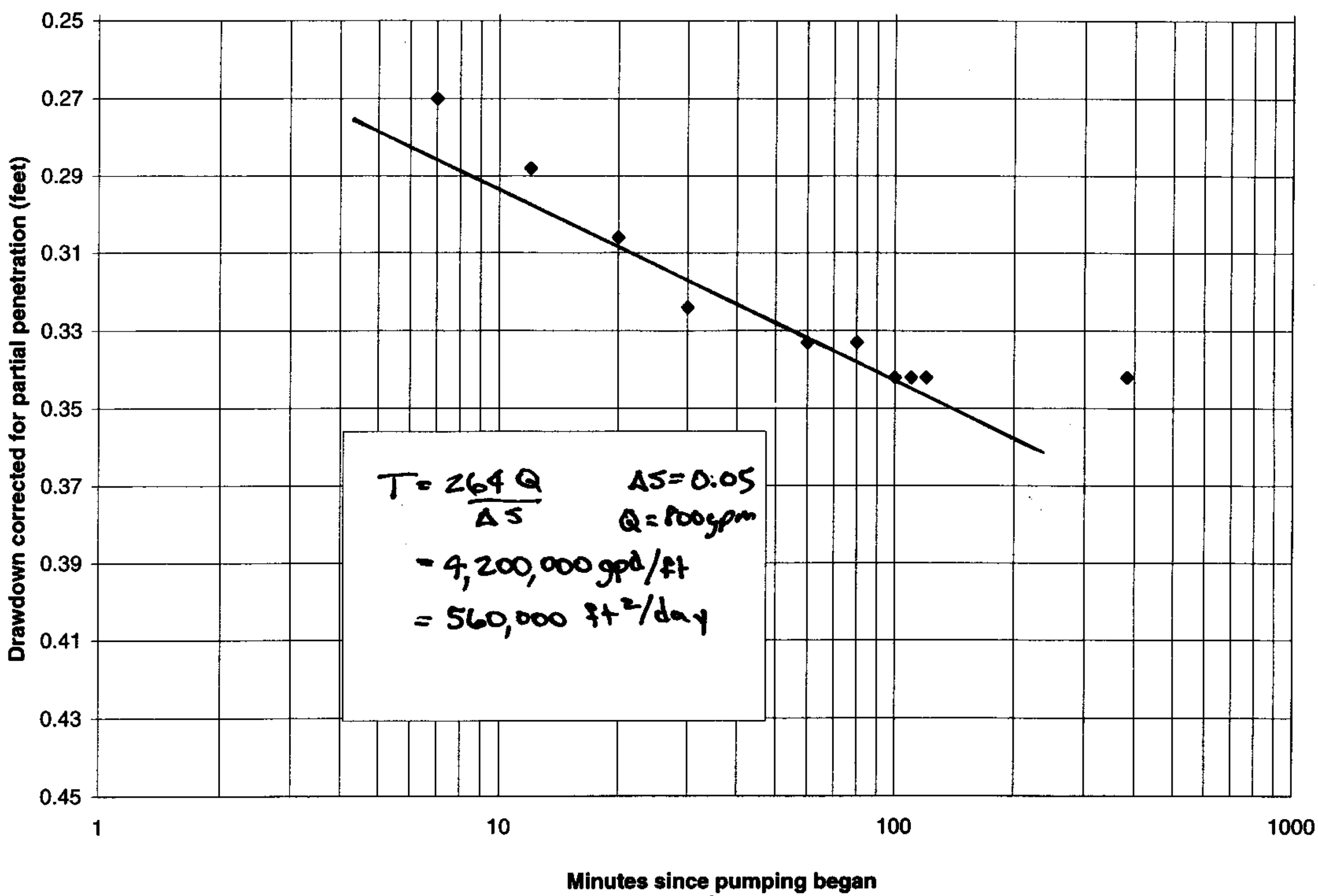
Drawdown in Pumping Well - NSID Well #3



NSID Well #3 Recovery Data



Drawdown in NSID Well #2



Consolidated Irrigation District (CID) Well #11A Aquifer Test

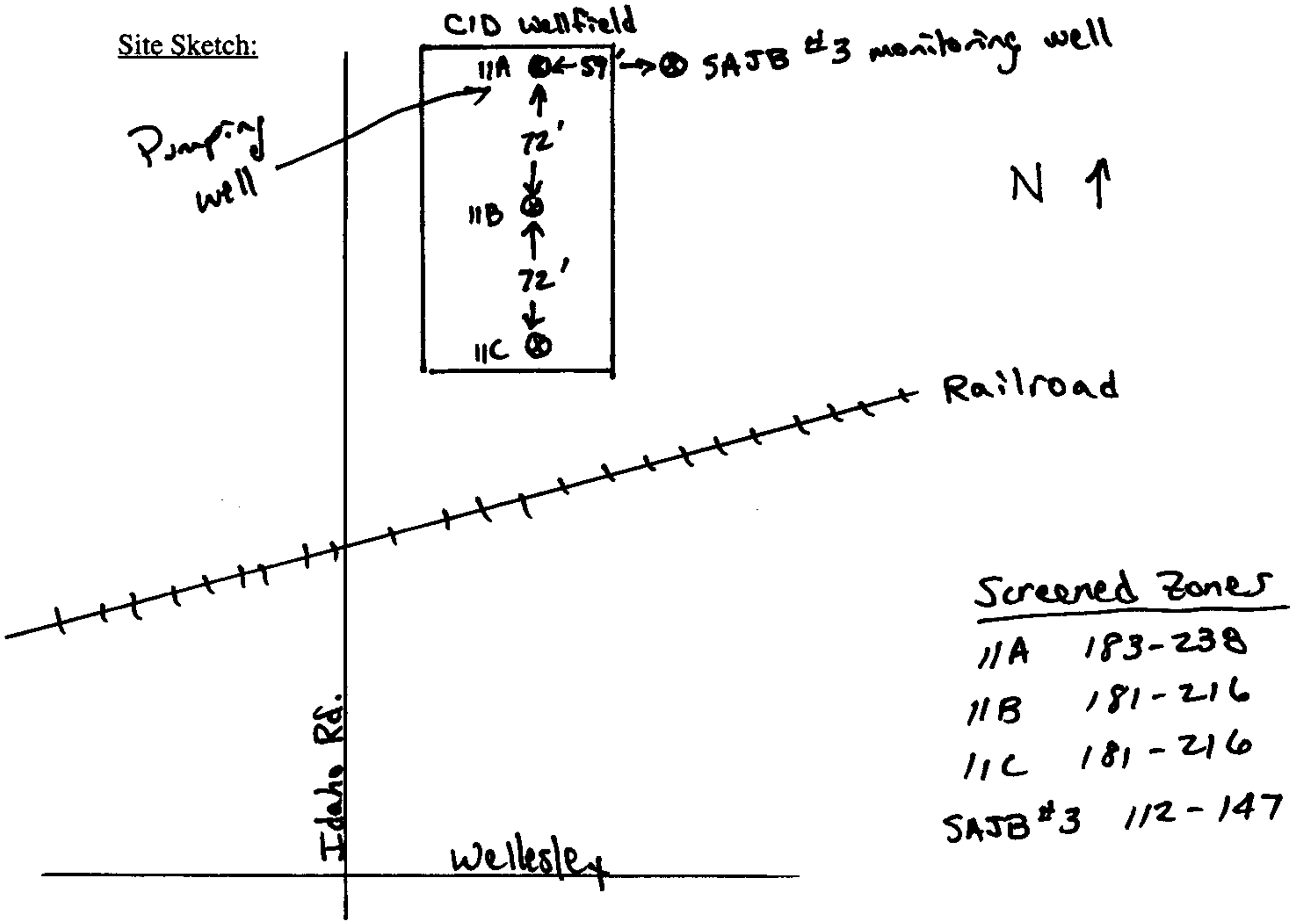
August 8, 1997

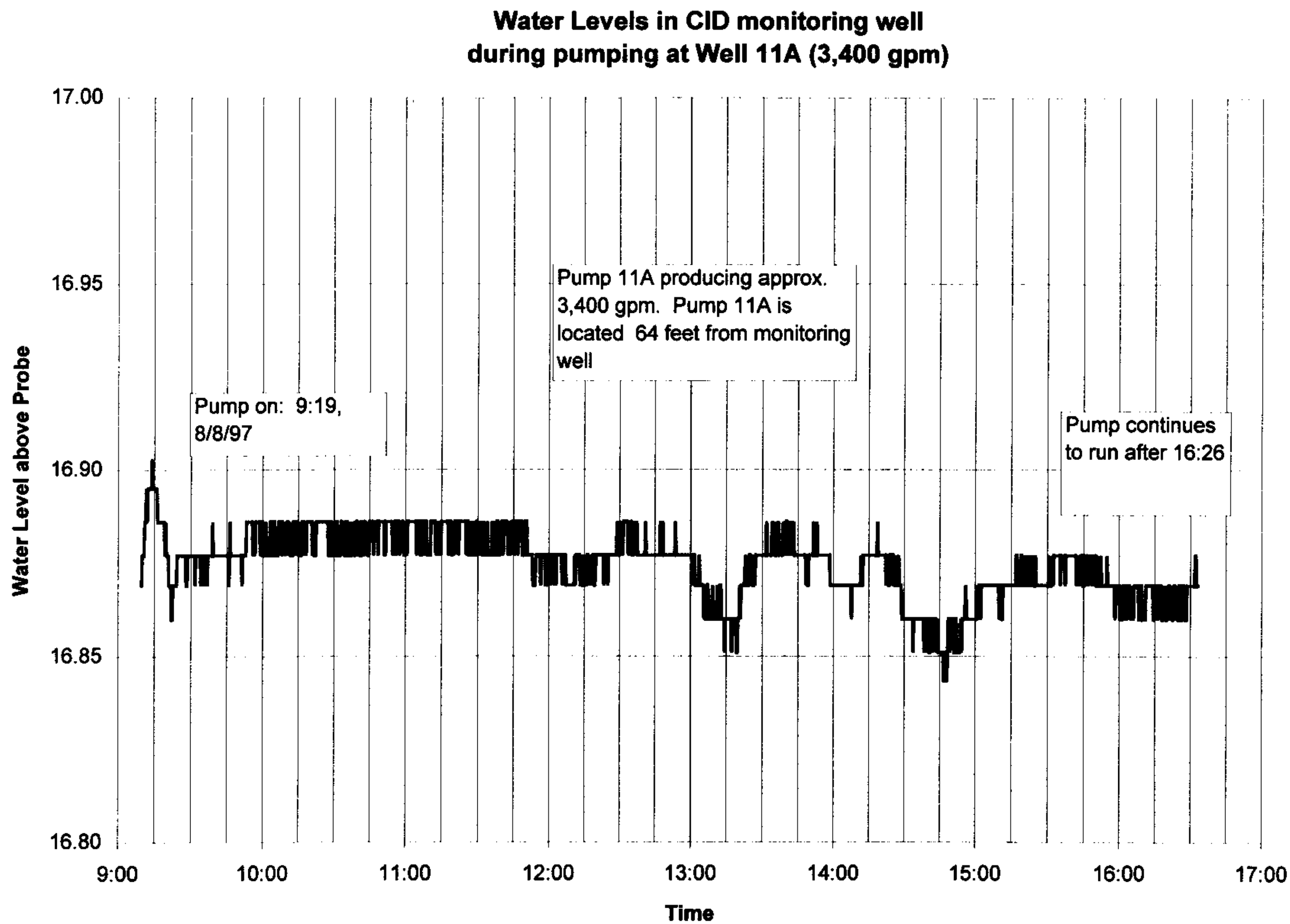
Background monitoring: Data logger and pressure transducer installed in SAJB #3 monitoring well on August 3, 1997. Water levels showed a declining trend of approximately 0.10 feet per day. Water levels in SAJB #3 monitoring well showed water level declines and recoveries in responses to pumping from the wellfield.

Testing: The pumping well (#11A) was shutdown at 6:30 a.m. To meet system demand, well #11C then began to cycle on and off. Pumping at well #11A began at approximately 9:20 a.m. and concluded at 4:20 p.m. The pumping rate (of well #11A) during the testing averaged approximately 3,400 gpm. During the 7-hour testing period, well #11C pumped 100,000 gallons during approximately 90 minutes of pumping.

Problems Encountered: Pumping well was offline for about 3 hours prior to testing, however, pumping occurred at well #11C during this period. During testing, pumping could not be controlled at well #11C as demand apparently was greater than what well #11A was producing. Airlines at wells #11B, and #11C did not provide reliable readings.

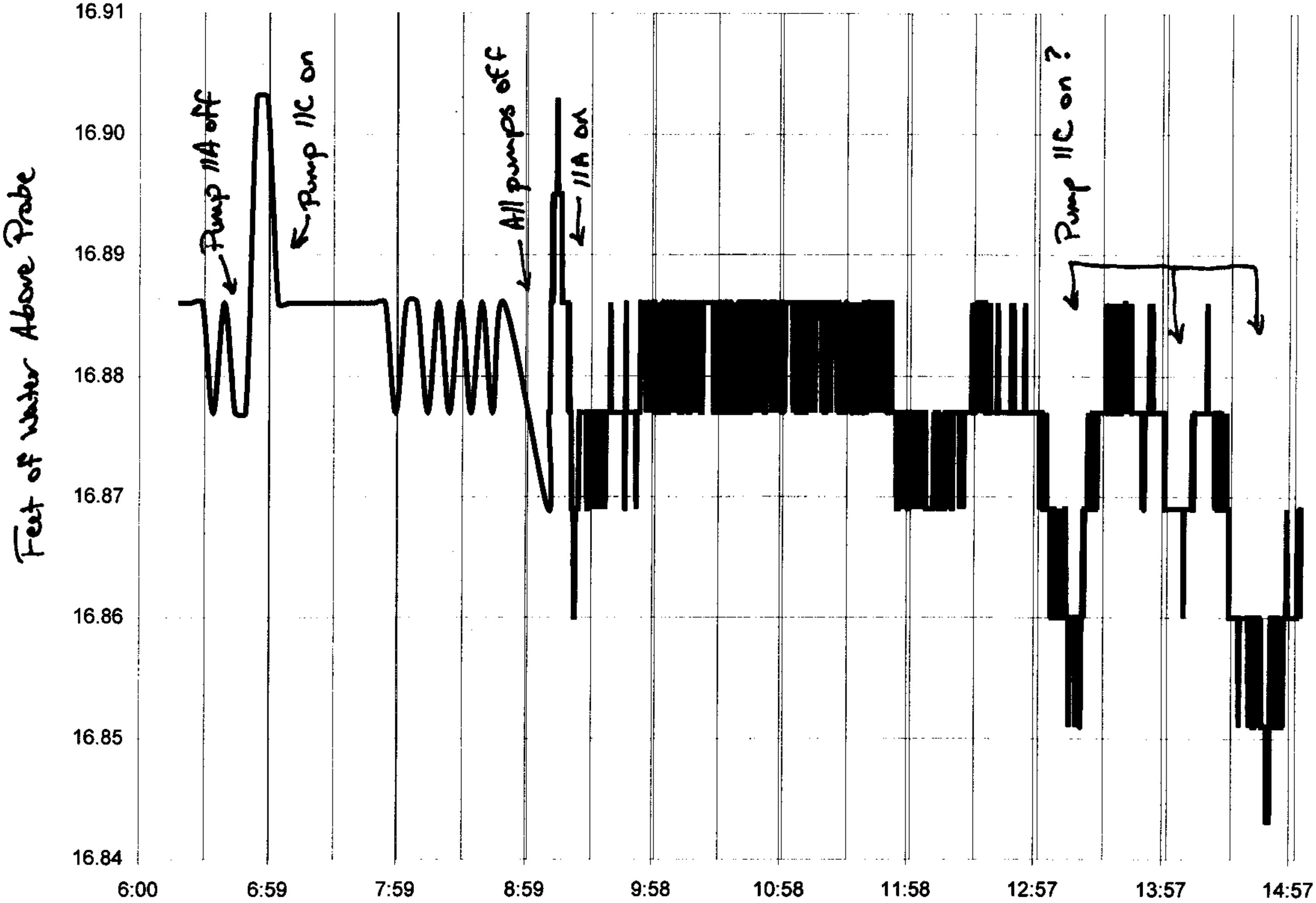
Site Sketch:

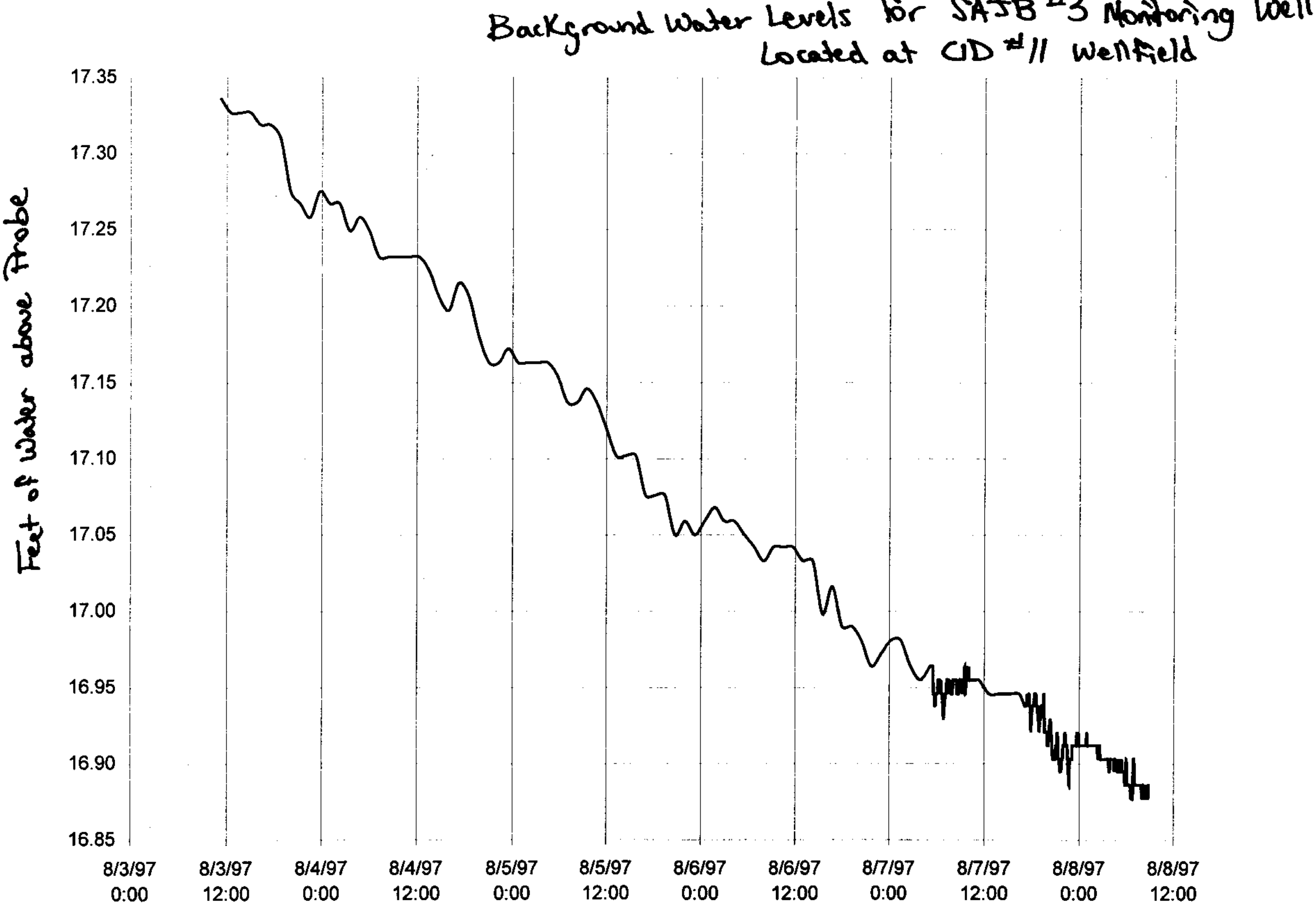



Water Levels in CID monitoring well
during pumping at Well 11A (3,400 gpm)
17.00
16.95
16.90
16.85
16.80
Water Level above Probe
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
Time
Pump on: 9:19, 8/8/97
Pump 11A producing approx. 3,400 gpm. Pump 11A is located 64 feet from monitoring well
Pump continues to run after 16:26

8-8 7am to 3 pm

SAJB #3 Water Levels




Background Water Levels for SAJB #3 Monitoring Well
Located at CID #11 Wellfield
Feet of Water above Probe
17.35
17.30
17.25
17.20
17.15
17.10
17.05
17.00
16.95
16.90
16.85
8/3/97 0:00
8/3/97 12:00
8/4/97 0:00
8/4/97 12:00
8/5/97 0:00
8/5/97 12:00
8/6/97 0:00
8/6/97 12:00
8/7/97 0:00
8/7/97 12:00
8/8/97 0:00
8/8/97 12:00

Notes: Small, but instantaneous drawdown in pumping well and in SAJB #3 (observation well). Pump at Well 11C cycled during testing providing some interference.

	Observed Drawdown	Partial Penetration Effects Corrected Drawdown
Well 11A	1.8 ft	0.54
SAJB #3	0.03 ft	0.02

PP factors 11A = 0.3
SAJB #3 = 0.5

*Drawdown in well 11A based on airline readings

Do distance-drawdown plot of drawdown data

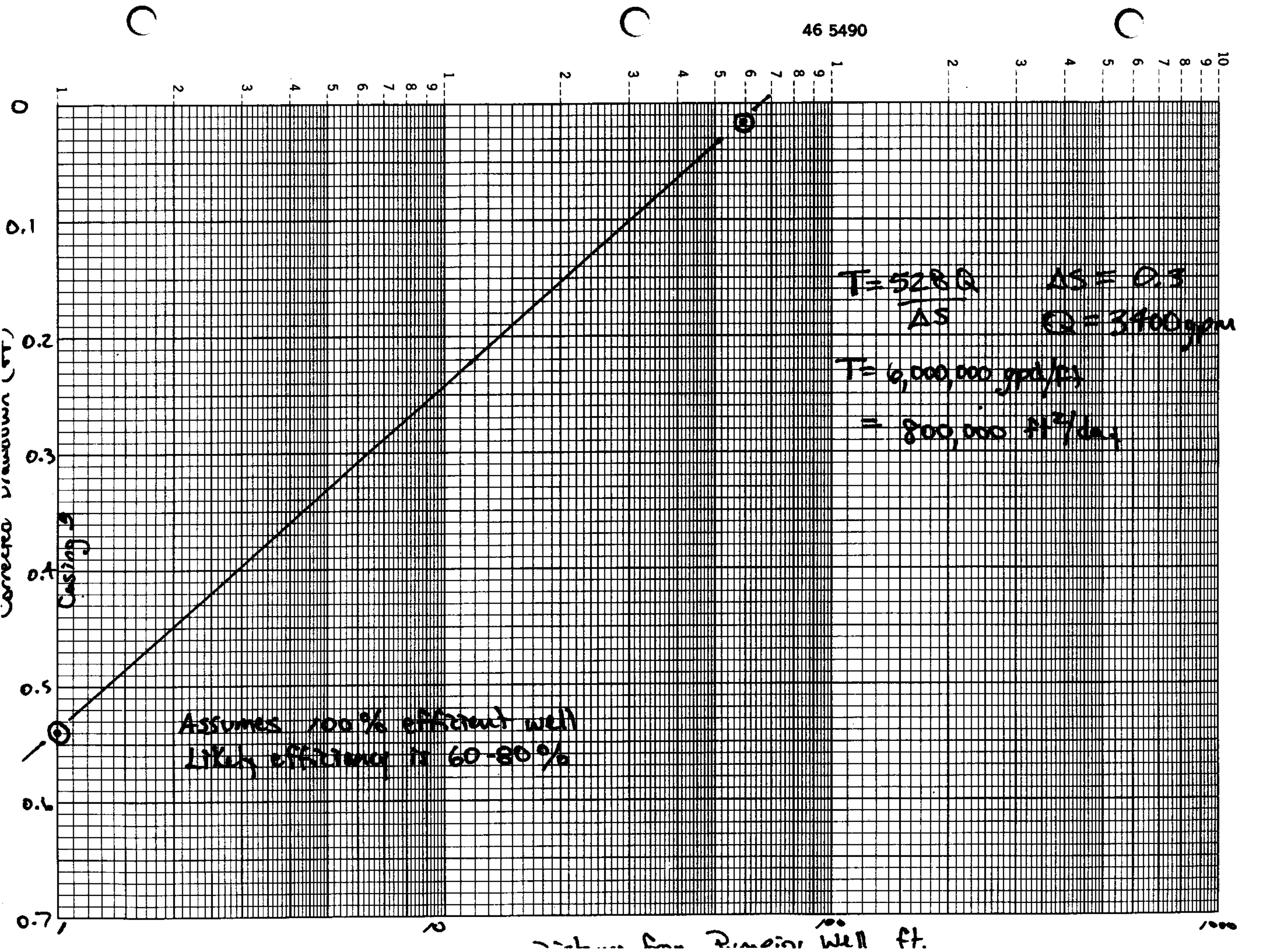
T = 6,000,000 gpd/ft
= 800,000 ft^2/day
- this likely underestimates T as this calculation assumes 100% efficiency in pumping well.

Specific Capacity Data

$$T = \frac{(2000)\,Q}{S}$$

$$= \frac{(2000)(3400)}{0.54}$$

= 12,600,000 gal/ft/day
= 1,700,000 ft^2/day


46 5490
T = 528 Q / ΔS
ΔS = 0.3
Q = 3400 gpm
T = 6,000,000 gpd/ft
= 800,000 ft²/day
Assumes 100% efficient well
Likely efficiency is 60-80%
Casing
Distance from Pumping Well ft.
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
1
10
100
1000

MONITORING WELL

DEPTH SOUNDER READING = 107.83'
DATA LOGGER READING = 16.869'
DATA LOGGER PROBE BELOW TOP OF PVC PIPE = 124.699'

8-8-97 8:50 AM (PUMPS B&C ON PUMP A OFF)

SOUNDER = 107.84'
DATA LOGGER = 16.865'

DEPTH TO PROBE = 124.705
(4:30pm, PUMP A ON, PUMPS B&C OFF)

PRODUCTION WELL # 11-A

DATE	TIME	P.S.I. GAUGE	FLOW METER	PUMP STATUS
8-8-97	9:15 AM	11.1 psi	517770.00	OFF
Δ1.8'	9:19.25 AM			START
	9:23.30	10.3 psi		ON
	9:32.00	10.28 psi		ON
	10:18.00	10.3 psi		ON
	4:26 pm	10.28 psi		ON
	4:27 pm		519755.00	ON

MW = 59' from 11A
MW = 93' from 11B
MW = 156' from 11C

PRODUCTION WELL # 11-B

DATE	TIME	DEPTH TO WATER (GAUGE)		FLOW METER	PUMP STATUS
8-8-97	9:18.30	104	Δ2.5'		ON (PUMP A IS OFF) (PUMP C IS ON)
	≈ 9:30	101.5			ON (PUMP A IS ON)
	10:20 AM	101		697606.00	OFF (PUMP A ON PUMP C OFF)
	4:20 pm	101.5		697606.00	OFF (PUMP A ON) (PUMP C OFF)

PRODUCTION WELL # 11-C

DATE	TIME	FLOW METER	PUMP STATUS
8-8-97	9:23.00 AM		PUMP TURNS OFF
	10:22 AM	838359.00	OFF (PUMP A IS ON) (PUMP B IS OFF)
	4:20 pm	838490.00	OFF (PUMP A IS ON) (PUMP B IS OFF)

Consolidated Irrigation District (CID) Well #4B Aquifer Test

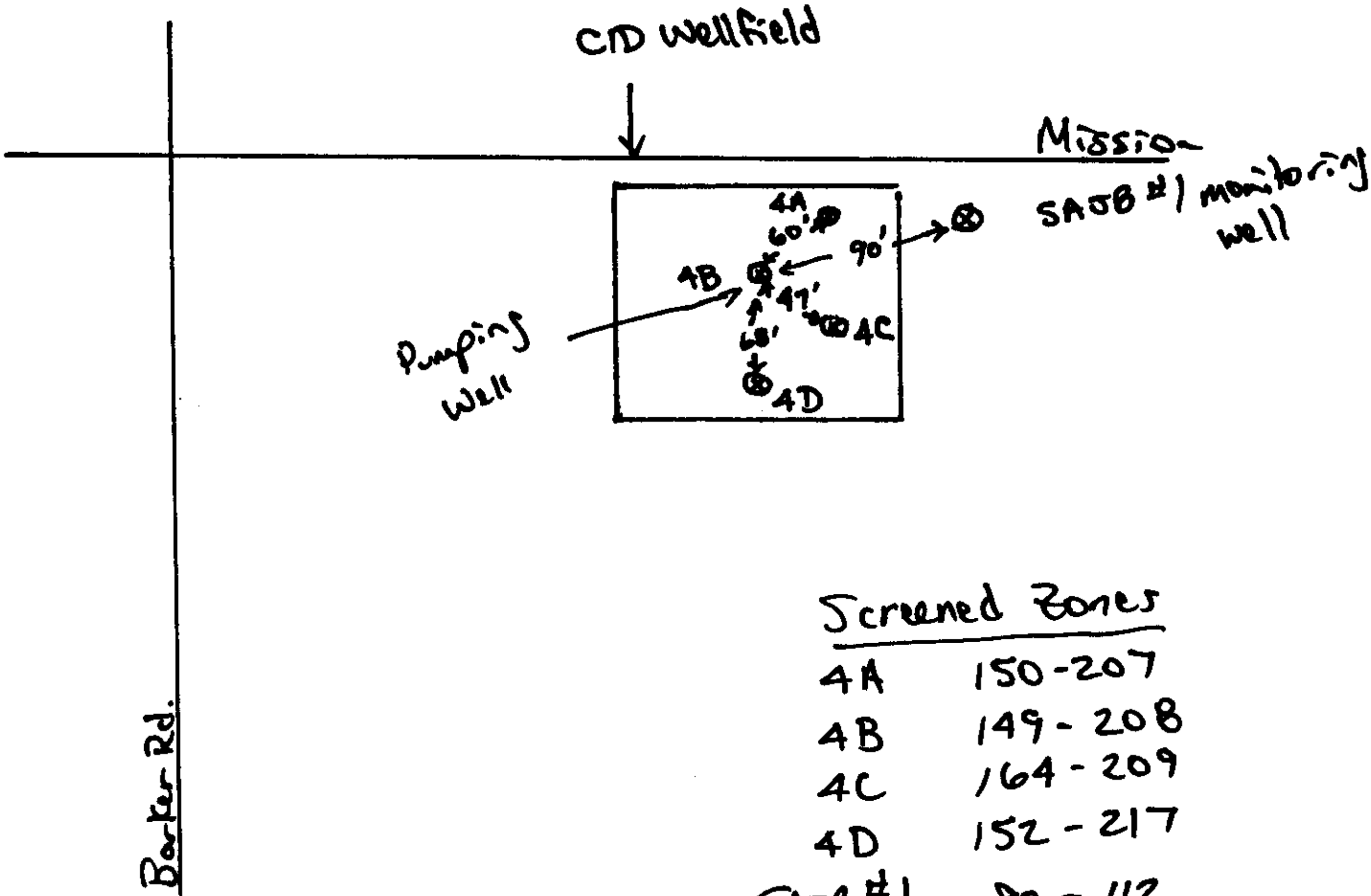
August 19, 1997

Background monitoring: Data logger and pressure transducer installed in SAJB #1 monitoring well on August 14, 1997. Water levels prior to pumping were relatively flat with a slight declining trend. Water levels after August 17, 1996 showed a declining trend of approximately 0.05 feet per day. Water levels in SAJB #3 monitoring well showed water level declines and recoveries (on the order of up to 0.05 feet) in responses to pumping from the wellfield.

Testing: The pumping well (#4B) was shutdown at 6:30 a.m. Pumping at well #4B began at approximately 9:50 a.m. Water level responses were monitored over a period of 4 hours, during which the pumping well (#4B) cycled on and off 4 times. These on-off cycles generally consisted of 35 to 40 minutes of pumping at a rate of 1,975 gpm followed by 20 minutes when the pump was off.

Problems Encountered: System demand would not allow the highest-capacity well (well #4A) to be pumped consistently. In fact, the system demand would only allow for periodic pumping of well #4B as described above. Airlines at wells #4B and #4C provide fairly reliable readings.

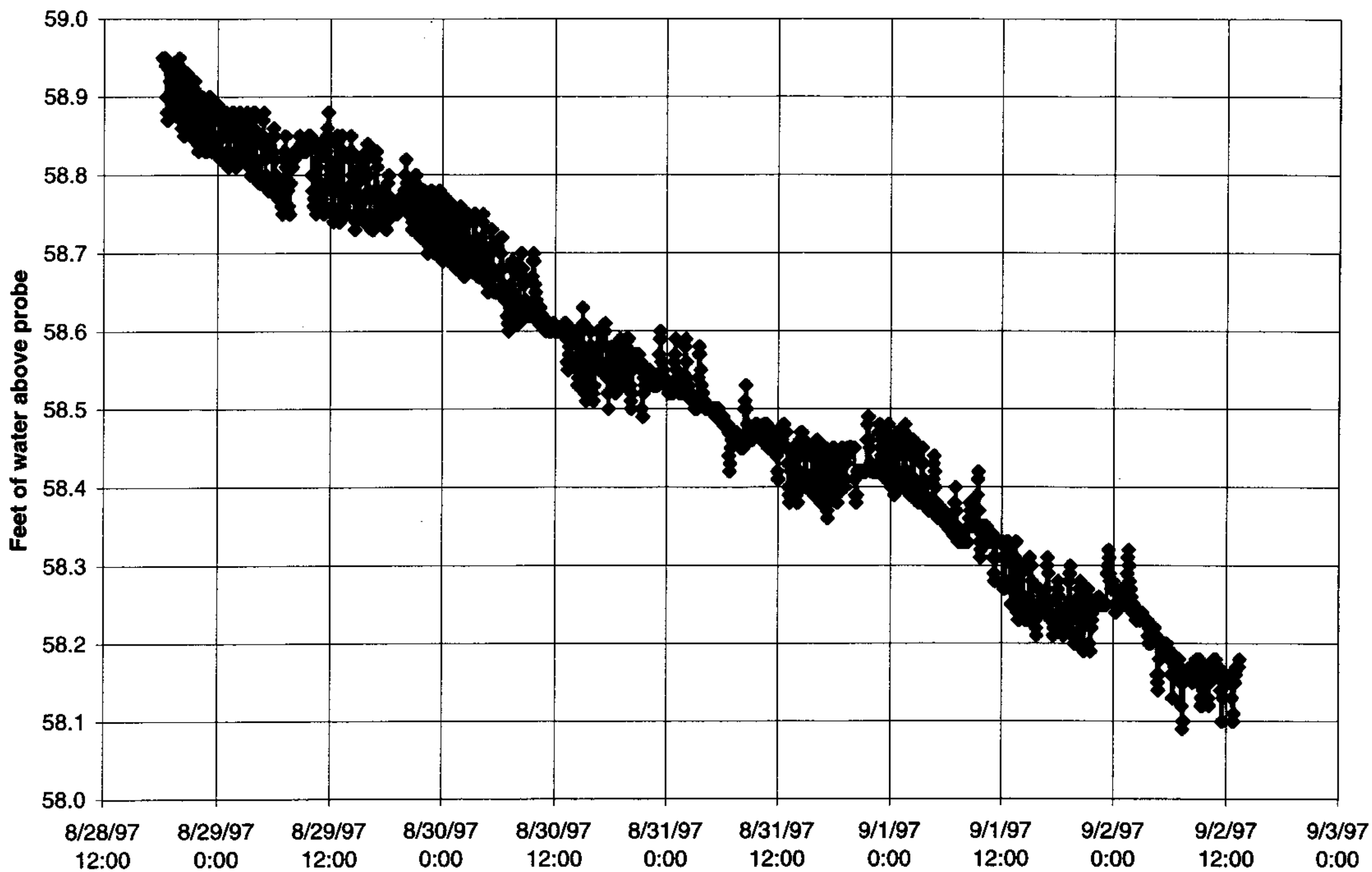
Site Sketch:



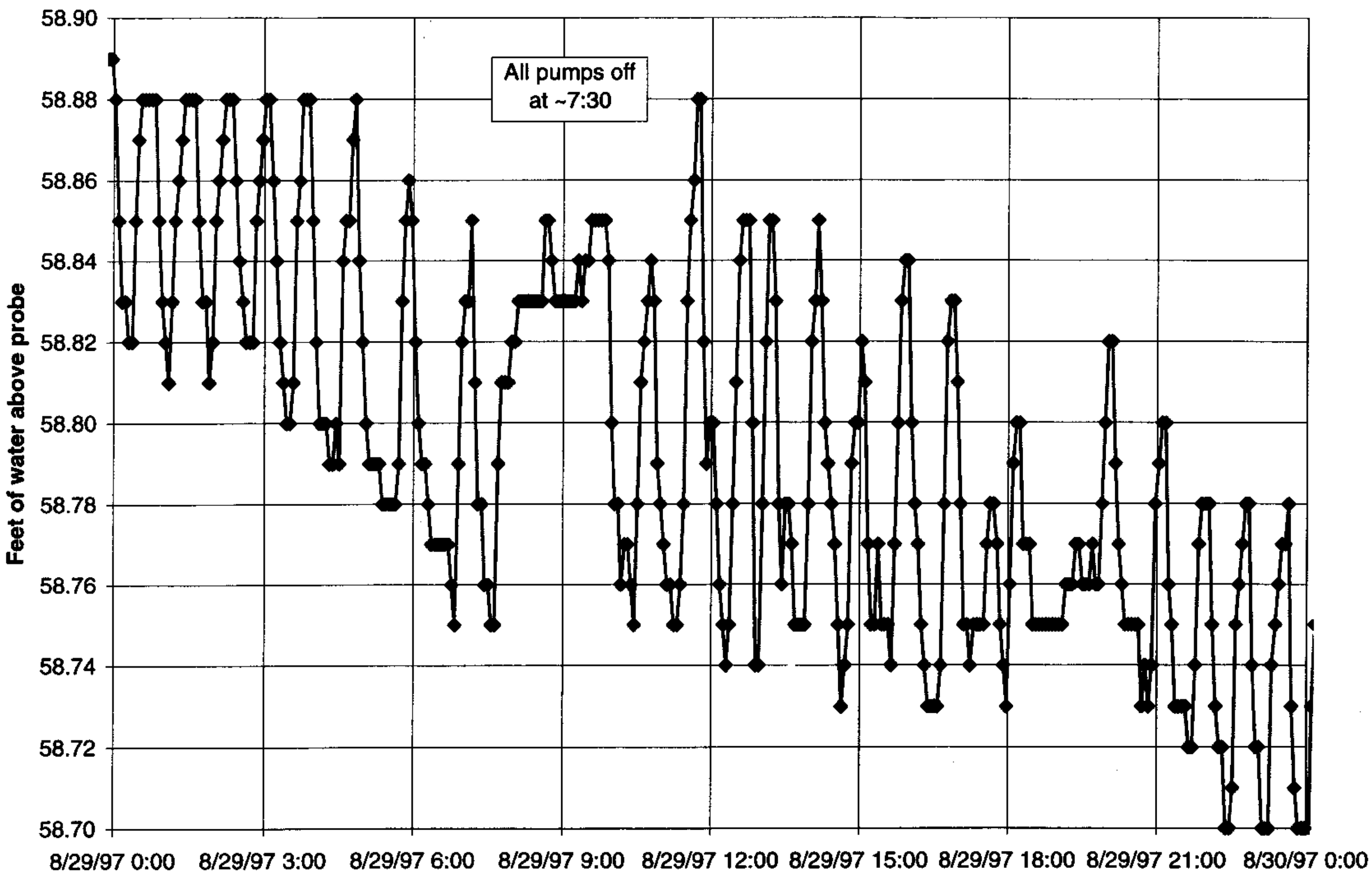
Screened Zones

4A	150-207
4B	149-208
4C	164-209
4D	152-217
SAJB #1	82-112

Water Level Changes in SAJB #1 Monitoring Well
8/28 through 9/2/97



Water Level Changes in SAJB #1 Monitoring Well
8/29/97



Notes:

Pumping well cycling on and off. The short durations of pumping do not allow for analyzing drawdown or recovery data for the observation well. Therefore, use distance-drawdown method of analysis.

Observed drawdown	Partial Penetration Factor	Corrected Drawdown
Well 4B pumping 0.7 ft	0.3	0.21
SAJB #1 0.1 ft	0.6	0.06

Do Distance-Drawdown Plot

$T = 1,900,000\ ft^2/day$

Specific Capacity Data

$T = \frac{(2000)\,Q}{S}$ $Q = 1975$, $S = 0.21$

= 18,800,000 gpd/ft

= $2,500,000\ ft^2/day$

T ranges = $1,900,000$ to $2,500,000\ ft^2/day$ aq. thickness ≈ 450

K = 4200 – 5,600 ft/day

Distance-Drawdown Data for CID #4B Aquifer Test