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ABSTRACT

Separate aquifer tests were conducted in two aquifers which may be affected by TVA's proposed uranium mining operation near Burdock, South Dakota. In April 1979, a constant-discharge test was conducted in the Chilson member of the Lakota formation which comprises the principal ore body and an aquifer of regional importance. The hydraulic properties of both the Lakota (Chilson) aquifer and the overlying Fuson shale aquitard were determined. A second test was conducted in July 1979 in the Fall River aquifer which overlies the Fuson. The hydraulic characteristics of the Fall River aquifer and a second estimate of the Fuson aquitard properties were obtained from the test. The test results indicate that the two aquifers are hydrologically connected via (1) general leakage through the Fuson shale, and (2) direct pathways, probably in the form of numerous old (pre-TVA) unplugged exploration boreholes.

The hydraulic properties of the Fall River, Fuson and Lakota units obtained from the aquifer test analyses were incorporated into a computer model of the site geohydrologic system. These parameters were refined in a calibration process until the model could reproduce the drawdown responses observed during the Lakota aquifer test. Results indicate the transmissivity and storativity of the Lakota (Chilson) aquifer are approximately 1400 gallons per day per foot (gpd/ft) and 1.0×10^{-4}, respectively. The Fall River aquifer has an estimated transmissivity of 400 gpd/ft and a storativity of about 1.4×10^{-5}. The hydraulic conductivity of the Fuson aquitard is estimated at approximately 10^{-3} foot per day. The specific storativity of the Fuson was not measured but is assumed to be about 10^{-6} feet $^{-1}$.

INTRODUCTION

This report describes the aquifer testing program conducted at the proposed uranium mine site in Burdock, South Dakota. The purpose of the program was to determine the hydrogeologic conditions in the mining area in order to predict mine dewatering requirements and impacts.

The Fall River formation and the Chilson member of the Lakota formation comprise the principal aquifers in the vicinity of the proposed mine. These aquifers are separated by the Fuson shale member of the Lakota formation which acts as an aquitard. The uranium deposits to be mined lie within the Chilson unit.

Two unsuccessful aquifer tests were conducted at the site prior to those described in this report. The first test was conducted at the Burdock test well in February 1977. Pumping took place from both the Fall River and Lakota aquifers during the 14-day test. The test results were invalidated by questionable well discharge measurements and by mechanical difficulties with a deep-well current meter used to measure the quantity of water pumped from each aquifer. A second test lasting three days was performed in November 1977. Pumping was restricted to the Lakota aquifer during the test in order to determine the potential for leakage through the Fuson shale from the overlying Fall River aquifer. The results of the test were inconclusive because (1) five observation wells used in the test were subsequently found to be improperly constructed and (2) pressure gauges used to monitor pumping response at several wells malfunctioned during the test.

The problems associated with the two earlier tests were corrected for the tests described in this report. The defective observation wells were pressure sealed with cement grout and replaced with properly constructed wells. More reliable instrumentation for monitoring potentiometric heads in observation wells was used in subsequent tests.

HYDROGEOLOGY

Regional Setting

The proposed mine site is located in the northwestern corner of Fall River County, South Dakota, less than one mile southeast of the community of Burdock. Geologically, the site is situated on the southwest flank of the Black Hills Uplift (see Appendix, Figure 1). The stratigraphy of the region consists of a sequence of rocks ranging in age from Precambrian to Recent which crop out peripherally to the Black Hills. The Precambrian rocks crop out near the center of the Black Hills, and progressively younger rocks crop out to the southwest. Surficial rocks in the site area range in age from lower Cretaceous to Recent. A generalized stratigraphic column for the site is shown in Table 1.

The major structural features of the region are the southwesterly-trending Dewey and Long Mountain structural zones. Faults, fractures and breccia pipes in these zones are believed to affect the ground-water water regime.

Aquifers

The principal aquifers in the region are the alluvial deposits associated with the Cheyenne River and its major tributaries, the Fall River formation, the Lakota formation, the Sundance formation, and the Pahasapa (or Madison) formation. Except for the alluvium, these aquifers crop out peripherally to the Black Hills where they receive recharge from precipitation. Ground-water movement is in the direction of dip, radially from the central Black Hills. In most instances, ground water in these aquifers is under artesian conditions away from the

TABLE I : GENERALIZED STRATIGRAPHIC COLUMN FOR SITE REGION (FROM KEENE, 1973)

PERIOD	FORMATION NAME	SYMBOL	COLUMN	LITHOLOGIC DESCRIPTION	THKNS. IN FEET	HYDROLOGIC CHARACTERISTICS
Quaternary	Alluvium	Qal		Gravel, sand, and silt floodplain deposits. Alluvial terraces and windblown material.	1-30	Good to excellent aquifer along floodplains; terraces generally non-productive except for scattered springs.
Cretaceous	Pierre Fm.	Kp		Dark gray shale, weathering brown or buff and containing many fossiliferous concretions. Scattered concretions which form "teepee buttes". Black fissile shale, cone-in-cone concretions.	1000+	Relatively no value as an aquifer; locally large diameter wells in stream valleys may yield small amounts of highly mineralized water during wet seasons.
	Niobrara Fm.	Kn		Gray calcareous shale, weathering yellow and impure chalk with Ostrea Congesta.	100-225	No known wells.
	Turner sand Carlile Fm. Wall Creek sand	Kcr		Light gray shale with large concretions. Gray shale with thin sandstone layers. Bed of impure limestone. Thin sandstone.	520-540	Relatively impermeable; possible small yields from Turner and Wall Creek sands.
	Greenhorn Lms.	Kg		Thin bedded hard limestone, weathering creamy white, contains Inoceramus Labiatus.	50	Too thin and dense to be an aquifer.
	Belle Fourche Fm. Mowry Shale Graneros Group Newcastle sand Skull Creek Shale	Kgs		Light gray shale, bentonite, large concretions. Light gray siliceous shale. Thin brown-to-yellow sandstone. Black shale	870	Newcastle sand may yield water, permeability is variable.
	Fall River Fm.	Kfr		Interbedded red-brown massive sandstone and Carbonaceous shales.	30-165	Largest producer in the area. Yields up to 60 gpm of highly mineralized water (flow). Water quality generally poor, sometimes yields hydrogen sulfide.
	Fuson Shale Minnewasta Lms. Lakota Fm.	Klk		Gray-to-purple shale, thin shales. Light gray massive limestone. Coarse, hard, cross-bedded sandstone, buff-to-gray, coal beds locally near base.	0-180 0-25 130-230	Relatively good aquifer from the lower Chilson member, up to 30 gpm artesian flow
	Morrison Fm.	Km		Green-to-maroon shale, thin sandstone.	0-125	No known wells, possible aquifer
Jurassic	Unkpapa Fm.	Ju		Fine grained, massive, vari-colored sandstone.	0-240	No known wells, possible aquifer
	Sundance Fm.	Jsd		Alternating beds of red sandstone and red-to-green marine shales.	250-450	Produces small amounts of water from the sands suitable for domestic use.
Triassic ?	Spearfish Fm.	℞s		Red silty shale, limestone, and anhydrite near the top. Redbeds. Gypsum locally near the base.	400	Poor producer, small yields of sulfate water
Permian	Minnekahta Lms.	Cmk		Pale brown, to gray dense, crystalline limestone.	50	Locally secondary fracture porosity
	Opeche Fm.	Co		Red thinly bedded sandstones and shales, purple shale near top.	100	No known wells
? Pennsylvanian	Minnelusa Fm.	Cml		Converse sand, red-to-yellow cross bedded sand. Red marker, thin red shale near middle. Leo sands, series of thin limestones. Dolomite at bottom with basal laterite zone.	755-1040	Permeability variable; tremendous flows of warm mineralized water recorded near the perifery of the Black Hills. Excellent potential.
Mississippian	Pahasapa Fm.	Cps		Massive, light colored dolomite and limestone, cavernous in upper 100 feet	165-465	Most promising aquifer in the area. The 2 wells in this aquifer produce large amounts of water suitable for domestic use
Precambrian	Metamorphic and igneous rocks	PC		Granite, schists, quartzite, and slates.	---	No potential.

outcrop area, and water flows from numerous wells in the area at ground surface.

The Fall River and Lakota formations which form the Inyan Kara Group are the principal aquifers in the region. The alluvium is used locally as a source of domestic and stock water. The Sundance formation is used near its outcrop area in central and northwestern Fall River County. The Pahasapa (Madison) formation is locally accessible only by very deep wells and is the source for five wells in the city of Edgemont.

The Fall River and Lakota aquifers are of primary concern because of the potential impact of mine dewatering on the numerous wells developed in these aquifers in the vicinity of the mine. At the proposed mine site, the Fall River consists of approximately 120 feet of interbedded fine-grained sandstone, siltstone and carbonaceous shale. The Fall River aquifer is overlain by approximately 250 feet of the Mowry and Skull Creek shales unit, which act as confining beds. Twenty-six domestic and stock-watering wells are known to be developed in the Fall River formation within a four-mile radius of the mine site. Many of these are flowing at the surface.

The Fall River formation is underlain by Fuson shale member of the Lakota formation. Thickness of the Fuson is on the order of 60 feet in the site vicinity. The Fuson acts as a leaky aquitard between the Fall River and Lakota aquifers. A physical examination of undisturbed core samples of Fuson indicates that the shale itself has a very low permeability. However, aquifer tests suggest a direct connection through the Fuson which may be the result of some as-yet-unidentified structural features or old unplugged exploration holes.

The Chilson member of the Lakota formation is the second most widely used aquifer in western Fall River County, as the source for some 23 wells within a four-mile radius of the mine site. It is also the uranium-bearing unit to be mined. The Chilson consists of about 120 feet of consolidated to semi-consolidated, fine-grained sandstone and siltstone. It is underlain by the Morrison formation consisting of inter-bedded shale and fine-grained sandstone. Regionally, the Morrison is not considered an aquifer. Under conditions of groundwater withdrawal from the Chilson, the Morrison is expected to act as an aquitard.

Recharge to the Fall River and Lakota aquifers is believed to occur at their outcrop areas. Bowles (1968) has theorized that re-charge to these aquifers may also be derived from the upward movement of ground water along solution collapses and breccia pipes from the deeper Minnelusa and Pahasapa aquifers. The solution collapse and breccia pipe features lie within the Dewey and Long Mountain structural belts.

AQUIFER TEST DESIGN

The objective of the aquifer testing program was to obtain sufficient quantitative information about local hydrogeologic conditions to enable prediction of mine dewatering requirements and impacts to both the Fall River and Lakota aquifers. Since the two aquifers involved are separated by the Fuson aquitard, two distinct pumping tests were required to obtain the necessary information about each formation: one test in which the Lakota aquifer was pumped, and another in which pumping was limited to the Fall River aquifer. During both tests ground-water levels were monitored in observation wells developed in each of the three formations. Data obtained from these tests were then analyzed to obtain estimates of the hydraulic properties of the aquifers and aquitard.

The Burdock test well was constructed approximately 600 feet north of the proposed mine shaft. Total depth of the well is 559 feet. The well is screened in both the Fall River and Lakota aquifers as shown in Figure 2.

Fifteen observation wells were constructed within an approximate one-mile radius of the pumping well as indicated in Figure 3. Seven of these wells are developed in the Fall River formation, five in the Lakota, and three in the Fuson. In addition, there is a single well developed in the Sundance formation located approximately one mile from the test well. This well was not constructed specifically for the aquifer tests, but was monitored periodically during the Lakota aquifer test. Construction details for these wells are given in Table 2.

TABLE 2. Observation Well Construction Details

Well No.	Total Depth (feet)	Casing Diameter (inches)	Depth Interval of Open Borehole or Well Screen (feet)	Distance From Pumped Well (feet)
B-10LAK	550	4	510-550	195
B-10FU	395	4	377-395	255
B-10FR	350	4	300-350	177
B-1LAK	570	4	525-570	405
B-1FU	440	4	420-440	350
B-1FR	376	4	334-376	373
B-11LAK	550	4	504-550	618
B-11FR	360	4	315-360	620
B-9LAK	545	1	503-545	1540
B-9FR	293	1	251-293	1540
B-7LAK	441	1	399-441	2507
B-7FR	252	1	210-252	2540
Sundance Well	880	7 7/8	666-780	4763

Inasmuch as water levels in each hydrogeologic unit will respond differently during pumping tests, it is important that each observation well reflect the potentiometric head in the intended uncased borehole interval. Several observation wells used in previous tests were suspected of leaking along the grout seal placed in the annular space between well casing and borehole wall. As a result, special precautions were taken to ensure proper construction of the observation wells used in the present tests. A geophysical device known as a cemeton logging probe was used to check the continuity of the cement grout seal in each well after construction. All were found to be properly sealed.

The so-called ratio-method of multiple-aquifer test analysis (Neuman and Witherspoon, 1973) requires that the response of water levels in both the pumped and unpumped aquifers and in the interven-ing aquitard be monitored during the test. Water level responses in these units must be measured in wells located at approximately the same radial distance from the pumped well. To obtain the necessary data, two groups of observation wells were constructed, each group having one well developed in the Fall River, one in the Fuson, and one in the Lakota (Chilson member). The B-10 group was located approximately 200 feet northeast of the pumping well, while the B-1 group was located approximately 375 feet to the southwest. These well groups were located close to the pumped well to ensure response in the aquitard and in the unpumped aquifer, if such responses were to occur at all. The remaining well groups (B-7, B-9 and B-11 series) contain only Fall River and Lakota wells.

Under natural conditions, the test well and all monitor wells except for those of the B-7 group flow at ground surface if not capped. The two previous tests conducted at the site indicated that observation wells in the pumped aquifer located close to the pumping well would become non-flowing at some point during the test. Thus, pressure sensing devices would be required during the early part of the test and depth measuring techniques during later periods. To ensure adequate data records, each flowing well was equipped with two pressure measuring devices. Malfunctions of several pressure gauges on previous tests pointed out the need for a back-up pressure measuring device.

Three types of pressure sensors were used: mercury manometers, electronic pressure transducers, and mechanical pressure gauges. The B-1 and B-10 observation well groups were equipped with mercury manometers and pressure transducers. As the closest wells to the pumping center, the data from these wells are most important in the multiple aquifer analysis and warrant the best instrumentation. Pressure transducers from all wells were wired to a central terminal and could be monitored frequently during the tests. Each well in groups B-9 and B-11 was equipped with a mercury manometer and a mechanical pressure gauge. Electric probes were used to measure water levels in the non-flowing wells of the B-7 group. These devices were also used to measure water levels in other wells which became non-flowing during pumping tests. Potentiometric head in the pumped well was measured with a mercury manometer, an air line and an electric probe.

LAKOTA AQUIFER TEST

Several months prior to the Lakota test, a pneumatic packer was set within the Fuson section of the test well to prevent communication between the Fall River and Lakota aquifers through the well. A submersible pump was set below packer to restrict pumping to the Lakota aquifer. Well-head valves on the test well and other artesian observation wells were closed to prevent flow in order to bring the ground-water system into equilibrium before testing.

Hydrographs for the test well and observation wells prior to test are shown in Figures 4 and 5. These hydrographs typify the basic relationship between the potentiometric heads in the Fall River, Fuson and Lakota, i.e., heads are highest in the Lakota, lowest in the Fall River, and at an intermediate position within the Fuson. The irregular readings recorded during January and February 1979 were due to depressurization of the aquifers during the installation of instrumentation and new wells. The pre-test ground-water level configuration in the Lakota aquifer on April 18 is shown in Figure 6.

Test Procedures and Results

A constant-discharge aquifer test was initiated at 1300 hours on April 18, 1979. Discharge from the well was pumped via pipeline to a stock-watering pond located approximately 0.75 miles from the test well. Pumpage was measured with an in-line flow meter and with an orifice plate and manometer device at the end of the discharge line. The pumping rate varied little during the test ranging from 201 to 205 gpm and averaging 203 gpm. The pumping phase of the test lasted for

73 hours (3.04 days) and was followed by a 30 day period of recovery measurements.

Figure 7 shows a semilogarithmic graph of drawdown (s) versus time (t) for the pumping well (Lakota aquifer). Erratic readings during the first 200 minutes of the test are the result of problems with the airline equipment, and are not due to discharge variations. These difficulties were subsequently corrected, but in general airline measurements are believed to be accurate only to within about ±2 feet.

Semilog graphs for the observation well groups are shown in Figures 8 through 12. Note that a slight initial increase in hydrostatic pressure is indicated in the Fall River and Fuson wells of the B-10 and B-1 well groups. This anomalous trend is more pronounced in the Fuson wells than in the Fall River wells and persists for approximately 90 minutes in B-10FU. The response is believed to be due to an increase in pore pressure resulting from deformation of the matrix of these formations.[1] In any case, the anomalous trend was recorded by both the pressure transducers and mercury manometers, and is not the result of measurement error.

The Jacob straight-line method (see Walton, 1970, pp. 130-133) was applied to the semilog graphs for the Lakota wells to obtain the values of transmissivity (T) and storativity (S) presented in Table 3. In the case of the closer observation wells, two straight-line

[1]During the early stages of pumping, water removed from the Lakota in the immediate vicinity of the well causes compaction of the aquifer. This, in turn, may cause the overlying strata to flex slightly in the area where the underlying support of the Lakota has been reduced. The resulting deformation in the overlying formations causes compressive forces which temporarily increase pore pressures in these materials. Subsequently, the effect of pumping-induced depressurization is transmitted through the overlying materials, gradually lowering the hydrostatic pressure.

TABLE 3. Lakota Aquifer Properties

Well No.	r (ft)	Jacob Method T_e (gpd/ft)	Jacob Method S_e --	Jacob Method T_ℓ (gpd/ft)	Jacob Method S_ℓ --	Theis Method T_e (gpd/ft)	Theis Method S_e --	Theis Method T_ℓ (gpd/ft)	Theis Method S_ℓ --	Recovery Method T_e (gpd/ft)	Recovery Method T_ℓ (gpd/ft)
PW-LAK	0.67	1980	--	1260	--	--	--	--	--	--	--
B-10LAK	195	2680	7.6×10^{-5}	1370	3.5×10^{-4}	2530	8.4×10^{-5}	1660	1.6×10^{-4}	2060	1300
B-1LAK	405	2140	4.4×10^{-5}	1340	1.2×10^{-4}	2120	4.8×10^{-5}	1550	8.4×10^{-5}	1970	1240
B-11LAK	620	--	--	--	--	2530	1.1×10^{-4}	1530	1.5×10^{-4}	--	1250
B-9LAK	1540	--	--	--	--	--	--	1370	1.3×10^{-4}	--	1290
B-7LAK	2507	--	--	--	--	--	--	1760	6.5×10^{-5}	--	1500
Average:		2270	6.0×10^{-5}	1320	2.4×10^{-4}	2390	8.1×10^{-5}	1570	1.2×10^{-4}	2015	1270

NOTE: Subscript "e" denotes an aquifer parameter determined using early drawdown (or recovery) data. Similarly, subscript "ℓ" denotes a parameter computed from late data.

solutions were possible: one using the early data and another using the late data. Note that data for wells B-7L, B-9L and B-11L cannot be analyzed by the Jacob method because data do not satisfy the criterion that $r^2S/4Tt \leqq 0.01$ (consistent units), where r is the distance between the pumped well and the observation well.

Logarithmic graphs of drawdown data for all observation wells are given in Figures 13 through 17. Theis curve-matching techniques (Walton, 1970, pp. 209-211) were applied to the Lakota curves to obtain T and S estimates for the Lakota aquifer. As with the Jacob analyses, two curve-match solutions were possible: one using the early, steeply-rising portions of the s-t curves, and another using the later data. Both solutions are given in Table 3.

A semilogarithmic graph of distance versus drawdown (Figure 18) was constructed by plotting the final drawdown in each Lakota well versus its radial distance from the pumped well. The Jacob straight-line techniques were applied to these data to obtain T and S values for the Lakota of 1780 gpd/ft and 7.7×10^{-5}, respectively. However, this type of analysis is applicable only to nonleaky aquifer systems. Since leakage obviously occurred during the test, the results are considered unreliable.

Contour maps of the final drawdown in the Lakota and Fall River aquifers at the end of the test are shown in Figures 19 and 20, respectively. The drawdown cone in both aquifers is slightly elongated in a northwesterly direction. This is probably an indication of anisotropic transmissivity, with the transmissivity in the direction parallel to the axis of elongation being somewhat greater than that in the direction normal to the axis of elongation. The principal direction of transmissivity parallels the strike of a regional fracture-joint set, suggesting a possible explanation for the observed drawdown configuration.

Following the pumping phase of the test, water level recovery measurements were made at all observation wells for a period of 30 days. Attempts were also made to monitor recovery in the pumped well using an airline. However, data collected were highly erratic suggesting a malfunction of the airline equipment. Semilogarithmic graphs of residual drawdown versus t/t' (ratio of time since pumping started to time since pumping stopped) for the observation wells are shown in Figures 21 through 25. Lakota graphs were analyzed using Jacob straight-line techniques to obtain the estimates of transmissivity presented in Table 3. Again, two straight-line fits are possible for the closer Lakota wells. Both are given in Table 3.

Interpretation of Test Results

The drawdown trends recorded in the observation wells indicate some important qualitative information about hydrogeologic conditions at the proposed mine site, in addition to providing a basis for determining hydraulic properties of materials. The relative response of the Fall River, Fuson and Lakota formations as reflected in the B-10 and B-1 groups (Figures 13 and 14), is not typical of the response that would be expected in an ideal leaky multiple aquifer system. Ideally, the s-t curve for the intervening aquitard lies between the curves for the pumped and unpumped aquifers. That is, in a logarithmic plot of s-t data the aquitard (Fuson) curve would lie below the curve for the pumped aquifer (Lakota), and above the curve for the unpumped aquifer (Fall River). However, "ideal" trends are not evident in the observed data until after 300 minutes of pumping in the case of the B-10 group, and not until after 2000 minutes in the case of the B-1 group. The fact that a greater pumping response is observed in Fall River formation than in the Fuson during the early part of the test indicates that direct (though restricted) avenues through the Fuson must exist. This condition was suspected before the test, and is believed to be the result of numerous old, unplugged uranium exploration boreholes in the test site vicinity. The shift to a more ideal relationship among the s-t curves exhibited during the latter part of test possibly indicates that general leakage through the Fuson itself has caught up with leakage through the open boreholes.

The leakage condition which is apparent in the response of the Fuson and Fall River wells is not evident in the Lakota well data. Under ideal conditions, the rate of drawdown in the Lakota observation wells would be expected to gradually decrease and perhaps even level off completely for some period of time. However, the opposite effect is noted in Lakota s-t plots, particularly the semilog graphs for B-10 LAK and B-1 LAK (Figures 8 and 9). The rate of drawdown increases in the latter stages of pumping which might indicate decreasing transmissivity of the Lakota aquifer in the site vicinity. The decrease in transmissivity may be due to aquifer thinning or possibly a facies change to less permeable materials. In any case, it is suspected that the leakage effects in the Lakota drawdown data are masked by the conflicting effect of a decreasing transmissivity in the site vicinity.

In general, the agreement between the Theis and Jacob analyses of s-t data is good. T values computed using early drawdown data average 2390 gpd/ft using the Theis method, and about 2270 gpd/ft using the Jacob method. Early data storativities are also in good agreement averaging 6.0×10^{-5} for the Jacob method and 8.1×10^{-5} for the Theis method. The T values computed from the late data (T_ℓ) are significantly lower than those determined from the early data, whereas late storativities are larger. The Jacob method yields T_ℓ values which average 1320 gpd/ft and storatitivies averaging 2.4×10^{-4}. The Theis method produced an average T_ℓ of 1570 gpd/ft and an average S_ℓ of 1.2×10^{-4}. The late Theis T values are somewhat higher than the Jacob T's because the Theis method gives some consideration to the earlier data which the Jacob method does not. Transmissivities estimated by the recovery data average 1270 gpd/ft, and are in close agreement with the late Jacob results, although slightly lower.

Ordinarily, in selecting representative T and S for the pumped aquifer in a leaky multiple aquifer system, more emphasis would be placed on the early data collected in the pumped aquifer at the pumped well and closest observation wells. These data are considered least affected by leakage. However, because of the apparent decrease in transmissivity of the Lakota aquifer during the latter stages of the test, it is believed that Lakota parameters computed from the late data are more representative of aquifer properties under a long-term pumping situation such as mine dewatering. On this basis the average transmissivity of the Lakota is estimated to be 1400 gpd/ft and the average storativity 1.8×10^{-4}.

FALL RIVER AQUIFER TEST

Following completion of recovery measurements associated with the Lakota aquifer test, pumping equipment in the Burdock well was rearranged for the Fall River test. A submersible pump was set within the Fall River section of the well and the pneumatic packer reset below the pump in the Fuson section of the well in order to restrict pumping to the Fall River. A preliminary test of the pump and other equipment lasting less than one hour was conducted on May 29. Unexpectedly, the Fall River aquifer was capable of yielding only about 10 gpm on a sustained basis. Since other Fall River wells in the region yield up to 40 gpm, it was assumed that either the well screen was encrusted or the well was not fully developed, or both. An unsuccessful effort was made to develop the well by pumping. A television camera was subsequently lowered into the well to examine the well screen. Little or no encrustation was observed on the screen. Ultrasonics were used in the well to remove any existing encrustation but the yield of the well was not improved. The low productivity of the well is, therefore, attributed to locally poor water-bearing characteristics of the Fall River formation.

Test Procedures and Results

A constant discharge test commenced at 1100 hours on July 24. Water levels in all geologic units were stable prior to the test, as there was no pumping activity in the site vicinity since the completion of well development on July 3. Discharge was measured with an in-line flowmeter, and checked with a 55-gallon container and stopwatch.

During the test the pumping rate varied from 7.6 to 10.4 gpm, and averaged 8.5 gpm. Ground-water levels were monitored in all observation wells shown in Figure 3. The constant discharge test was terminated at 1200 hours on July 26 after 49 hours of pumping. Subsequently, ground-water level recovery measurements were made for a period of six days.

Semilog graphs of drawdown data recorded at the pumped well and observation well groups B-1, B-10 and B-11 are shown in Figures 26 through 29, respectively. No graphs are presented for B-11LAK or the B-7 and B-9 groups as there was no measureable drawdown in these wells. Except for B-11FR, these graphs exhibit a typical straight-line drawdown trend during the first part of the test, followed by a gradual decrease in slope towards the end of the test. This slope change is the result of leakage from adjacent formations, and/or an increase in aquifer transmissivity at some distance from the pumped well. The Jacob method was applied to the semilog graphs to obtain the transmissivity and storativity values shown in Table 4. The T_e and S_e values were obtained using early drawdown data recorded during approximately the first 500 minutes of the test. T_l and S_l values were computed from data recorded after about 1000 minutes. The only reliable estimates are considered to be those computed for B-1FR and B-10FR. Drawdown data for the pumped well is affected by wellbore storage which is significant in this test because of the relatively low pumping rate. The pumped well drawdown data may also be affected by low well efficiency. The semilog plot for B-11FR cannot be analyzed by the Jacob method because the criterion that $r^2S/4Tt \leqq 0.01$ is not satisfied for any of the data.

TABLE 4. Fall River Aquifer Properties

		Jacob Method				Theis Method		Recovery Method	
Well No.	r (ft)	T_e (gpd/ft)	S_e --	T_ℓ (gpd/ft)	S_ℓ --	T_e (gpd/ft)	S_e --	T_e (gpd/ft)	T_ℓ (gpd/ft)
PW-FR	0.67	16.(?)	--	--	--	--	--	11(?)	--
B-10FR	177	140.	$1.8x10^{-5}$	410.	--	150.	$1.7x10^{-5}$	80.	340.
B-1FR	373	150.	$0.8x10^{-5}$	420.	--	150.	$1.1x10^{-5}$	90.	350.
B-11FR	618	--	--	--	--	--	--	--	--
Average:		145	$1.3x10^{-5}$	415.	--	150.	$1.4x10^{-5}$	85.	345.

Logarithmic graphs of drawdown data for the pumped well and observations well groups B-10, B-1 and B-11 are presented in Figures 30 through 33, respectively. Theis curve-matching techniques were applied to the Fall River curves to obtain the aquifer properties given in Table 4.

Semilog recovery curves for the pumped well and well groups B-10, B-1 and B-11 are shown in Figures 34 through 37, respectively. Again, properties computed from the pumped well recovery data are invalidated by well-bore storage effects. Separate estimates of transmissivity obtained from early and late phases of the recovery data are given in Table 4.

Interpretation of Fall River Aquifer Test Results

There is good agreement between the early Jacob and Theis results for B-1FR and B-10FR. These analyses indicate an average T_e of about 150 gpd/ft and an average S_e of approximately $1.4x10^{-5}$. Application of the Jacob method to the late drawdown data yields an average T_l of 415 gpd/ft. No meaningful storativity values could be computed from the late data. The T_e values computed by the recovery method are considerably lower than those computed by the other two methods and are believed to be unrealistic. The T_l values derived from the recovery analyses compare reasonably well with the Jacob late drawdown results.

The computed transmissivity and storativity values are representative of the aquifer only within the relatively small area influenced by the pumping test. The yield of the test well is substantially less than that of several other wells in the region. The difference in well yields suggests that the Fall River aquifer is less permeable in the mine site vicinity than in certain surrounding areas. The aquifer parameters computed from the early drawdown and recovery data are believed to be representative of the aquifer in the immediate vicinity of the test wells. Parameters obtained from analysis of the late data are probably more representative of regional aquifer characteristics.

FUSON AQUITARD PROPERTIES

The hydraulic properties of the Fuson aquitard were estimated using an analytical technique known as the "ratio method" developed by Neuman and Witherspoon (1973). The method requires (1) a knowledge of the transmissivity and storativity of the pumped aquifer; (2) drawdown data for the pumped and unpumped aquifers and the aquitard measured in wells located at approximately the same radial distance from the pumped well; and (3) the vertical distance between the aquifer-aquitard boundary and the perforated section of each aquitard well (Z). The method yields a value of aquitard hydraulic diffusivity, α', equal to K'_V/S'_S, where K'_V is the vertical hydraulic conductivity of the aquitard and S'_S is the specific storativity of the aquitard. To determine K'_V or S'_S from α', either K'_V or S'_S must first be known. In the following analyses a value of $S'_S = 10^{-6}$ ft^{-1} is assumed for the Fuson aquitard. Experience indicates that specific storativities of geologic materials do not vary over as wide a range as do hydraulic conductivities. For this reason, and considering the difficulty and expense of obtaining an accurate measure of S'_S over the site vicinity, it appears justifiable to assume a value of S'_S typical of similar geologic materials.

The first step in the analysis is to compute a value of s'/s at a given radial distance from the pumped well, r, and at a given time, t. Next a value of t_D (dimensionless time for the aquifer equal to tT/r^2S) is determined. The values of s'/s and t_D are used to compute a value for t'_D (dimensionless time for the aquitard equal to $K't/S'_SZ^2$) using a family of type curves given in Figure 3 of Neuman and Witherspoon (1973). The vertical hydraulic conductivity of the aquitard K'_V is then obtained from the following equation:

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$$K'_v = t'_D Z^2 S'_s/t \quad (1)$$

Since separate pumping tests were conducted in the Lakota and Fall River aquifers, it is possible to calculate two independent values of K'_v for each well group. Fuson aquitard properties computed by the ratio method along with certain pertinent parameters used in the calculations are presented in Table 5.

Note that since the Fall River, Fuson and Lakota observation wells in each well group do not lie at exactly the same radial distance from the pumped well, an average radial distance r_{avg} is used in the calculations. The r_{avg} values shown in Table 5 were obtained by averaging the radial distance for the pumped aquifer observation well and the radial distance for the aquitard observation well. Also note that the column labeled "Time Interval" represents the time interval during which K'_v values were computed. Generally, three or four values of K'_v were computed at specific times within this interval. These values were then averaged to obtain the K'_v values shown in Table 5.

The vertical hydraulic conductivity of the Fuson ranges from about 10^{-4} ft/d at the B-1 well group to about 10^{-3} ft/d at the B-10 well group. The agreement between the conductivities computed at each well group site for both tests is good. The reason for the order of magnitude difference between the conductivities at the different well sites is unknown, but may be related to errors caused by differences in the radial distances of observation wells--these differences being somewhat greater for the wells of the B-10 group.

TABLE 5. Fuson Aquitard Properties

Test	Well Group	$r_{avg.}$ (ft)	Z (ft)	Time Interval (min.)	K'_v (gpd/ft^2)	K'_v (ft/d)
Lakota	B-10	225	28	100-393	$2.0x10^{-2}$	$2.7x10^{-3}$
	B-1	378	11	100-393	$1.0x10^{-3}$	$1.3x10^{-4}$
Fall R.	B-10	216	25	100-300	$4.8x10^{-3}$	$6.6x10^{-4}$
	B-1	362	40	1200-2350	$1.3x10^{-3}$	$1.8x10^{-4}$

The magnitudes of computed conductivities are slightly higher than expected on the basis of the physical characteristics of the Fuson, although they are still within reason. The presence of open boreholes may have caused a more rapid drawdown response in the Fuson monitor wells than would have occurred otherwise. As a result, the calculated K'_V values are probably larger than the actual conductivity of the Fuson shale. The calculated K'_V values are, however, probably smaller than the effective K'_V of the aquitard in the areas where it is breached by open boreholes.

COMPUTER MODEL SIMULATIONS

The hydraulic properties estimated for the Fall River, Fuson and Lakota formations were incorporated into a computer model of the site geohydrologic system. Simulations of the Lakota aquifer test were performed to see if the model could reproduce the drawdown responses observed during the test. An acceptable match between the measured and computed responses would indicate the validity of the estimated formation properties, and thus enhance the credibility of the model for predicting mine dewatering requirements and impacts.

A finite element numerical model developed by Narasimhan et al. (1978) was used for the aquifer test simulations. The aquifer/well-field system was modeled in three dimensions using axial symmetry. The hydraulic properties of the Fall River, Fuson and Lakota formations obtained from the aquifer test analyses were used as initial input data (see Table 6). Uniform properties were assumed for each hydrogeologic unit. The shale units which lie above the Fall River formation and those which lie below the Lakota were assumed to be impermeable in the model. All simulation comparisons were made for the Lakota aquifer test. The Lakota test stressed a larger portion of the multiple aquifer system than did the Fall River test, and more closely approximates the flow regime expected during mine dewatering.

A comparison of the measured and computed results for the initial simulation run are shown in Figure 38. In general, the agreement between the computed and observed drawdown graphs for the Lakota aquifer are good. However, there are large discrepancies in the Fall River and Fuson responses.

TABLE 6. Parameters Used In Computer Simulations

	Initial Parameters					Final Parameters				
Formation	T (gpd/ft)	S (--)	K_v (ft/d)	K_v/K_h (--)	Ss (ft^{-1})	T (gpd/ft)	S --	K_v (ft/d)	K_v/K_h --	Ss (ft^{-1})
Fall River	150.	$1.4x10^{-5}$	$5.6x10^{-2}$	1/3	$1.2x10^{-7}$	400	$1.4x10^{-5}$	$4.6x10^{-2}$	1/10	$1.2x10^{-7}$
Fuson	0.13	$6.0x10^{-5}$	$1.7x10^{-4}$	1/3	$1.0x10^{-6}$	0.45	$6.0x10^{-5}$	$1.0x10^{-3}$	1/1	$1.0x10^{-6}$
Lakota (Chilson)	1400.	$1.8x10^{-4}$	$5.0x10^{-1}$	1/3	$1.5x10^{-6}$	1400.	$1.0x10^{-4}$	$1.5x10^{-1}$	1/10	$8.3x10^{-7}$

Several attempts were made to improve the match between the computed and observed drawdown responses by trial-and-error adjustment or calibration of model parameters. The most reliable parameters, such as the computed Lakota and Fall aquifer coefficients, were only slightly altered in the calibration process, whereas the least reliable parameters, including the ratio of vertical to horizontal permeability and the Fuson properties, were allowed to vary over a wider (though reasonable) range. The hydraulic properties within each hydrogeologic unit were assumed to be uniform throughout the calibration process.

The set of hydraulic parameters yielding the best agreement between measured and observed drawdown data is given in Table 6. The final parameter set differs only slightly from the original. The largest changes were made in the K_v/K_h terms which were unknown to begin with; and in the Fuson hydraulic conductivity which was increased by a factor of five. Both the early and late Fall River T values computed from the aquifer test analyses (150 and 415 gpd/ft, respectively) were tested during model calibration. The drawdown response of the model was found to be relatively insensitive to the value of T used. A transmissivity of 400 gpd/ft is included in the final parameter set as it is believed to be more characteristic of the aquifer regionally.

The match between the measured and computed drawdown responses, shown in Figure 39, is considered acceptable in light of the fact that uniform aquifer-aquitard properties were used in the model. The apparent discrepancies are believed to be due to the heterogeneity and anisotropy of the actual system. The departures which occur during the early phase of the simulation appear large, but are not significant.

The ability of the model to predict the long-term response of system is more important. Thus, more significance is attached to the agreement between the simulated and observed results for the latter part of the test which, in most cases, is quite good. The final set of aquifer-aquitard properties are considered to represent a valid basis for future predictive modeling.

SUMMARY AND CONCLUSIONS

The aquifer test results indicate that the Fuson member of the Lakota formation is a leaky aquitard separating the Fall River and Lakota aquifers. The hydraulic communication between the two aquifers observed during the tests is believed to be the result of (1) general leakage through the primary pore space and naturally occurring joints and fractures of the Fuson shale, and (2) direct connection of aquifers via numerous old unplugged exploratory boreholes. Whereas, the former leakage mechanism is a regional characteristic of the Fuson, leakage caused by borehole short-circuiting is probably limited to the relatively small area of intensive uranium exploration in the Burdock vicinity.

The Lakota (Chilson) aquifer has an estimated transmissivity of approximately 1400 gpd/ft and a storativity of about 1.0×10^{-4}. These properties are representative of the Lakota in the area affected by the pumping test, and are consistent with what is known or suspected about the aquifer regionally. The transmissivity and storativity of the Fall River aquifer are estimated at approximately 400 gpd/ft and 1.4×10^{-5}, respectively. Test results indicate that the transmissivity of the Fall River may be considerably less than 400 gpd/ft in the immediate vicinity of the test site. However, the selected transmissivity value is more consistent with regional aquifer characteristics.

The hydraulic conductivity of the Fuson aquitard is estimated at approximately 10^{-3} ft/d. The specific storativity of the Fuson was not measured but is assumed to be about 10^{-6} ft^{-1}. If open boreholes are present at the test site as suspected, the computed hydraulic conductivity is probably higher than the true conductivity of the shale, yet lower than the effective conductivity of the aquitard where short-circuited by open boreholes. For this reason, the selected aquitard conductivity of 10^{-3} ft/d should provide a conservative estimate of mine dewatering impacts. Outside of the relatively small area where the aquitard is breached by boreholes, leakage between the two aquifers will be governed by the true conductivity of the shale which is probably on the order of 10^{-4} ft/d or less.

The hydraulic properties of the Fall River, Fuson and Lakota (Chilson) formations computed from aquifer test data were incorporated into a computer model of the site geohydrologic system. These parameters were refined through repeated simulations of the Lakota aquifer test until the model could reproduce the drawdown responses observed during the test. The agreement between the observed and computed responses indicates the validity of the aquifer-aquitard properties, and should enhance the credibility of future predictive models using these parameters.

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2. Keene, J. R., "Ground-water Resources of the Western Half of Fall River County, South Dakota." Rept. of Inv. No. 109, S. D. Geol. Survey, 1973.

3. Narasimhan, T. N., S. P. Neuman, and P. A. Witherspoon, "Finite Element Method for Subsurface Hydrology Using a Mixed Explicit-Implicit Scheme," Water Resources Research, Vol. 14, No. 5, 1978.

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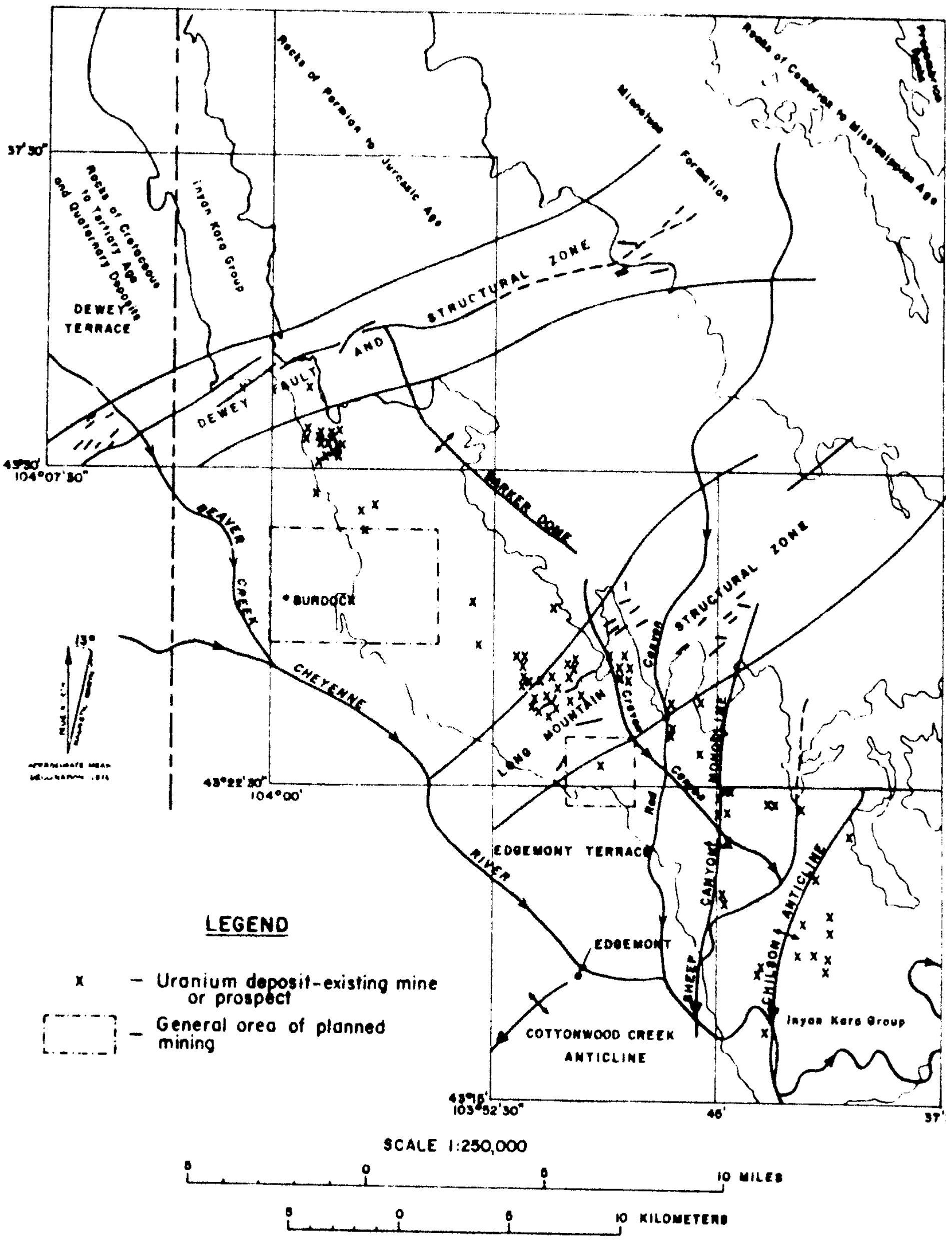
APPENDIX



(MODIFIED FROM PLATE 4 - USGS PROFESSIONAL PAPER 763)

Figure 1 : Generalized Geologic Map of Site Region

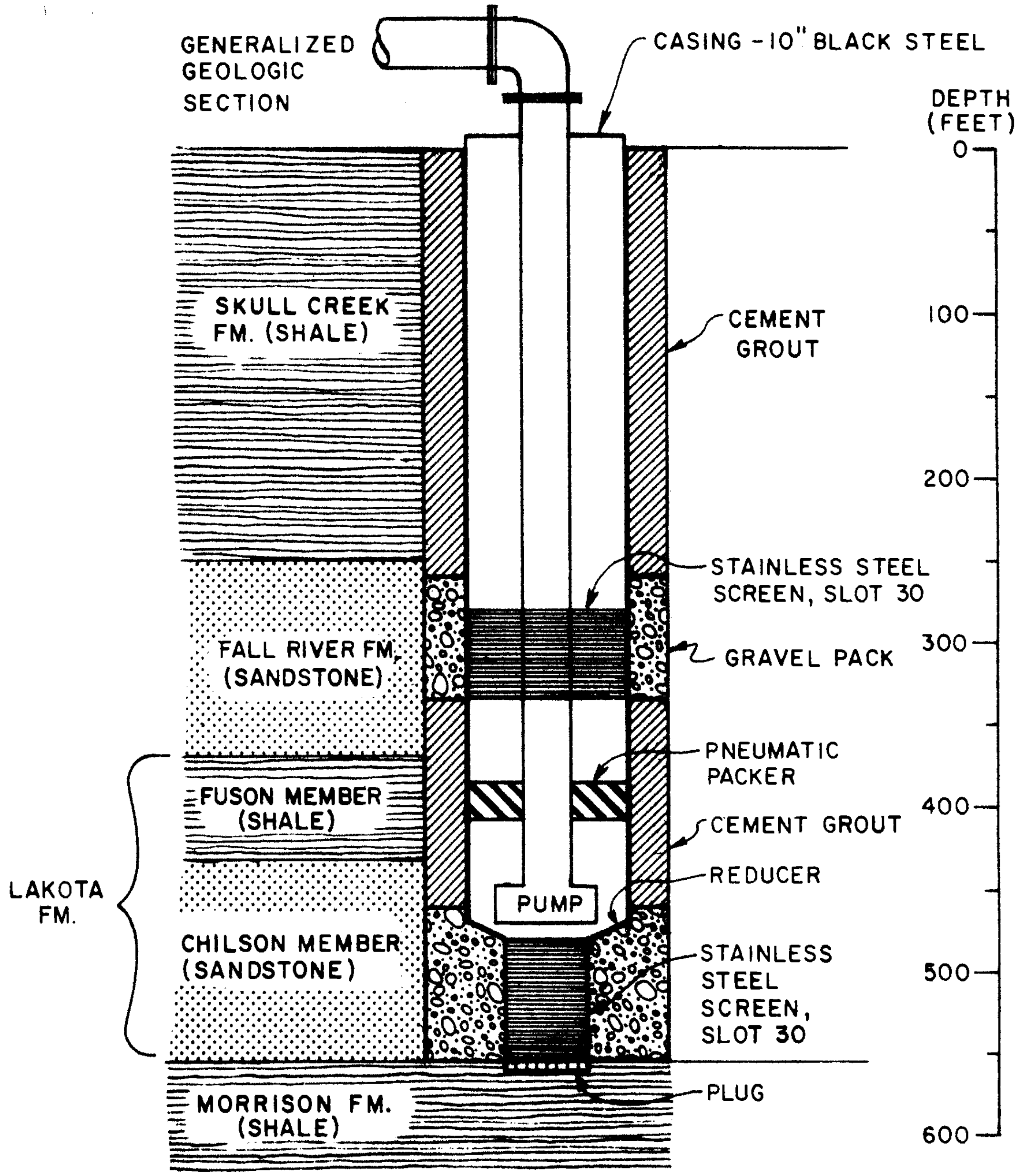


Figure 2 : Burdock Well Profile

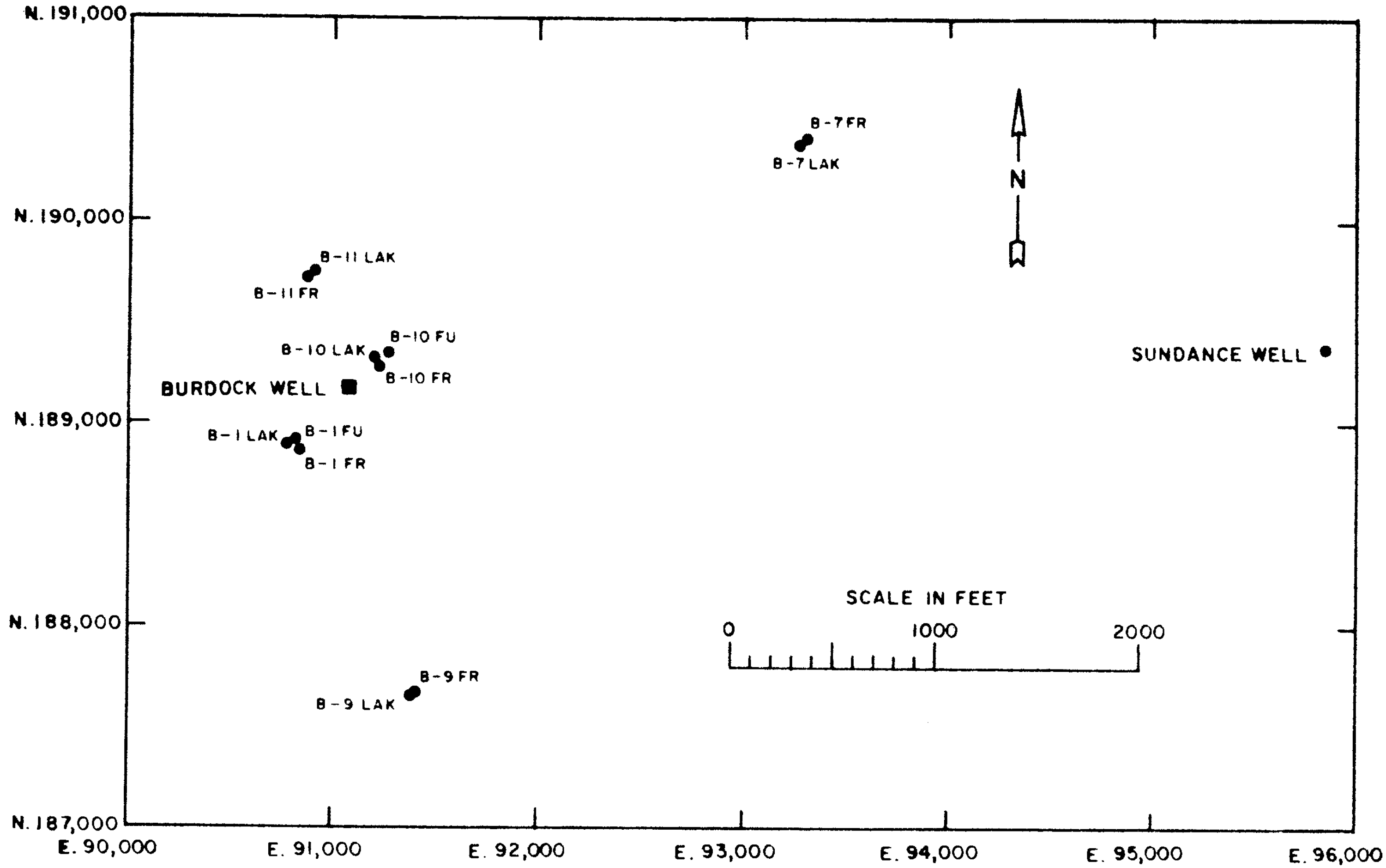


Figure 3 : Well Location Map

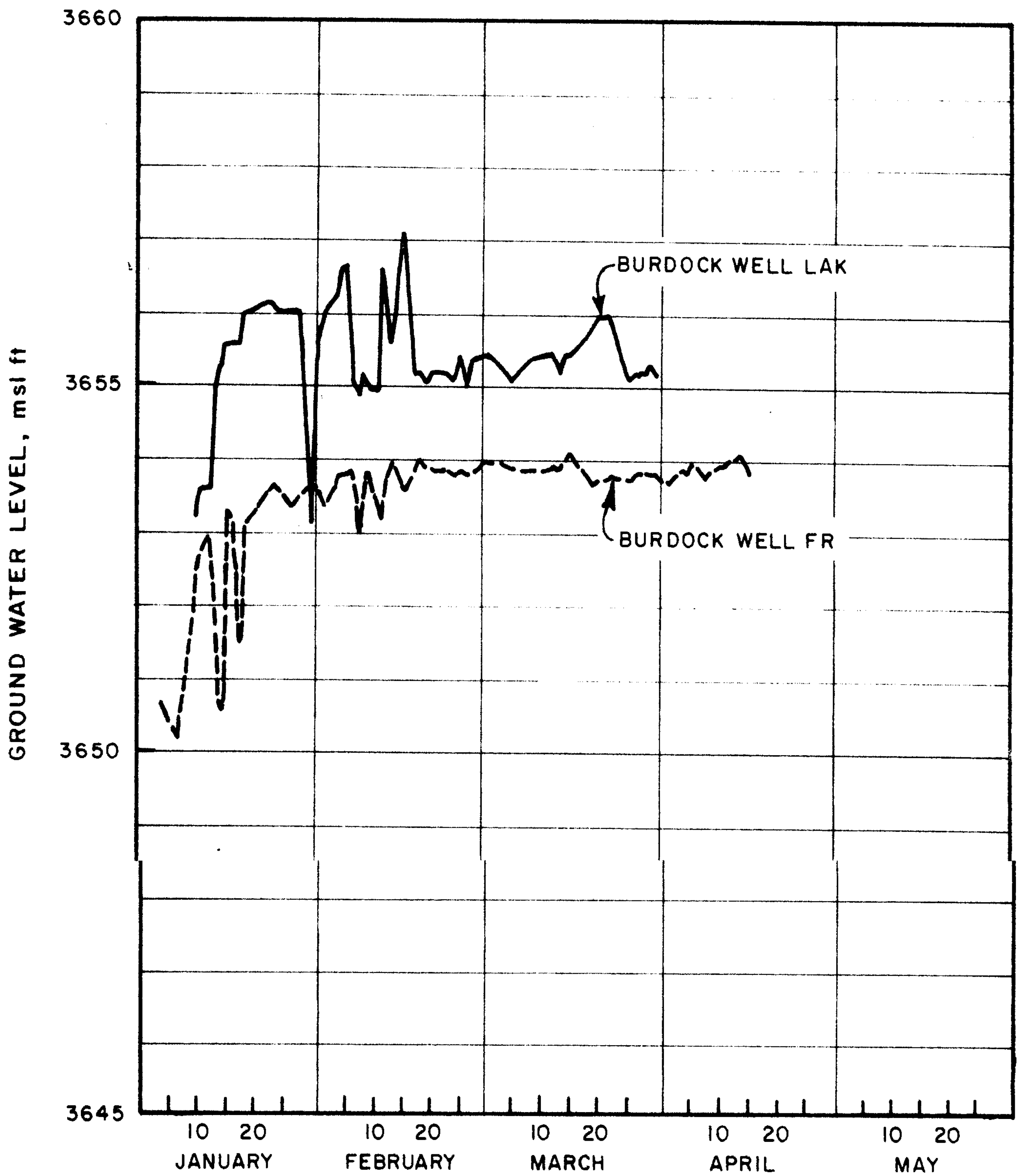


Figure 4 : Hydrographs for Burdock Test Well, January 1 through April 17, 1979

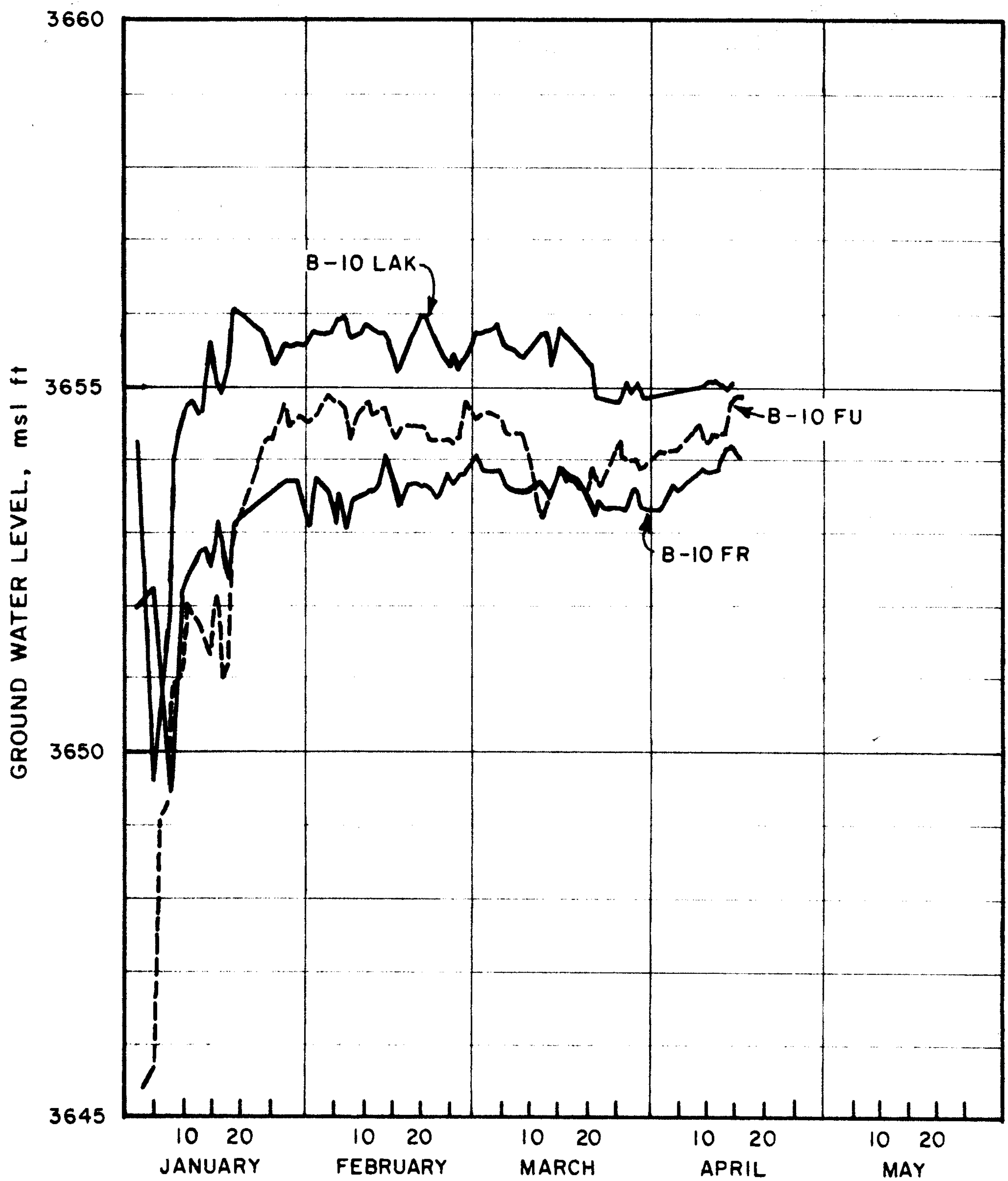


Figure 5 : Hydrographs for B-10 Observation Well Group, January 1 through April 17, 1979

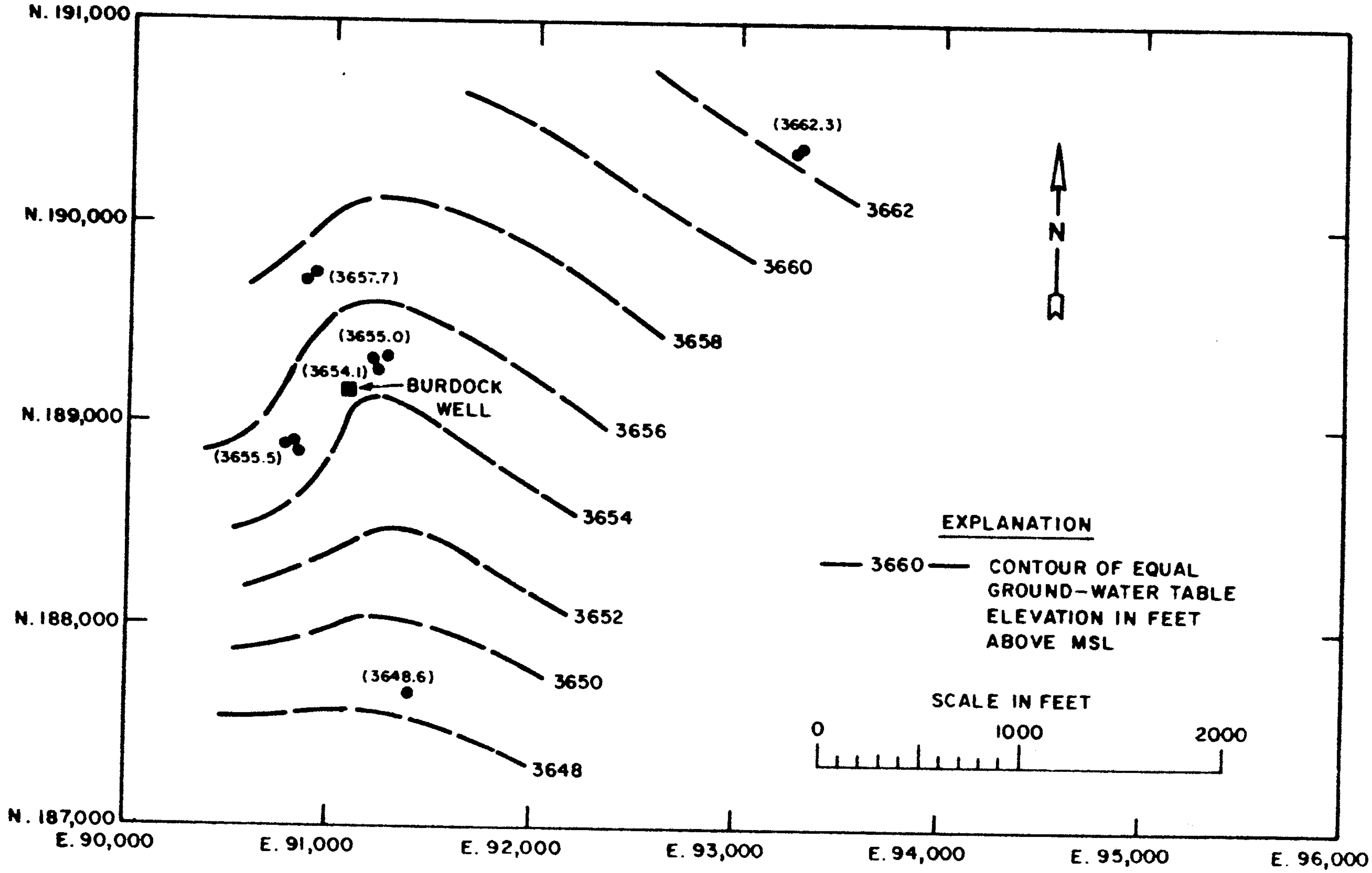


Figure 6 : Pre-Test Ground-Water Level Contour Map for Lakota Aquifer

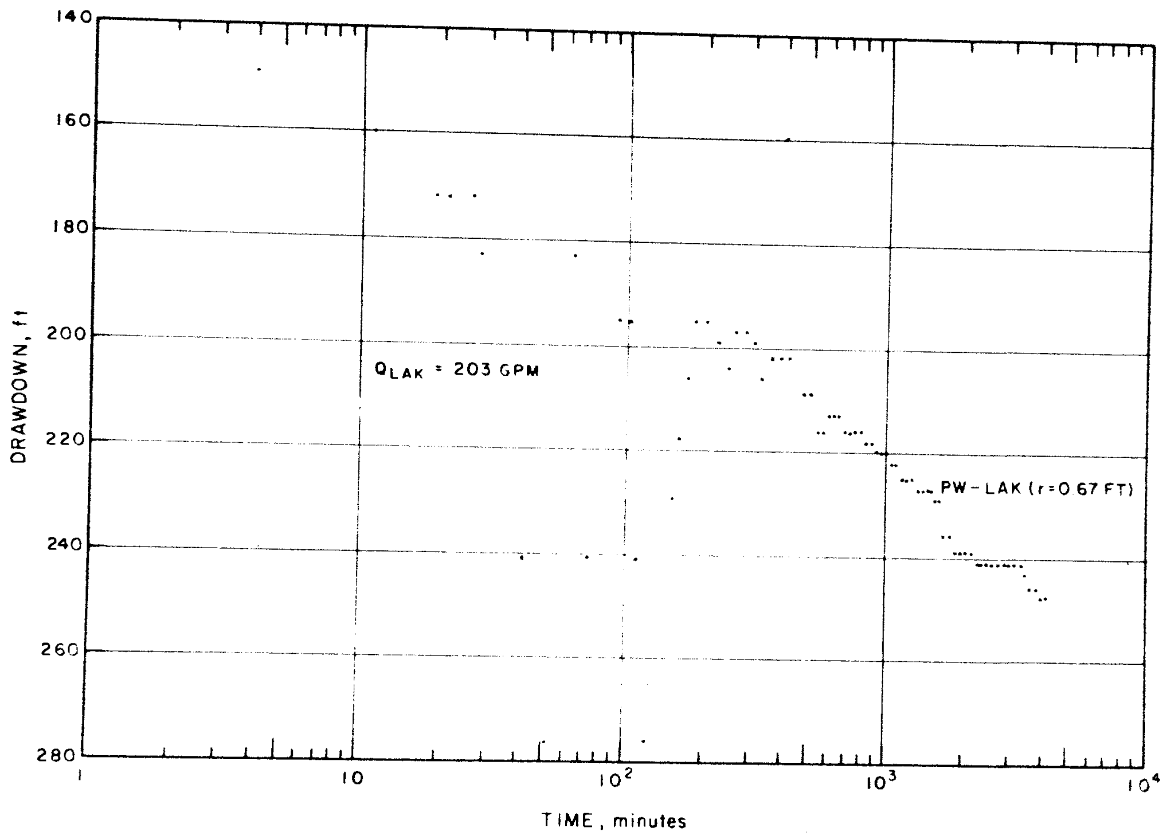


Figure 7: Semilogarithmic Graph of Drawdown for Pumped Well, Lakota Aquifer Test

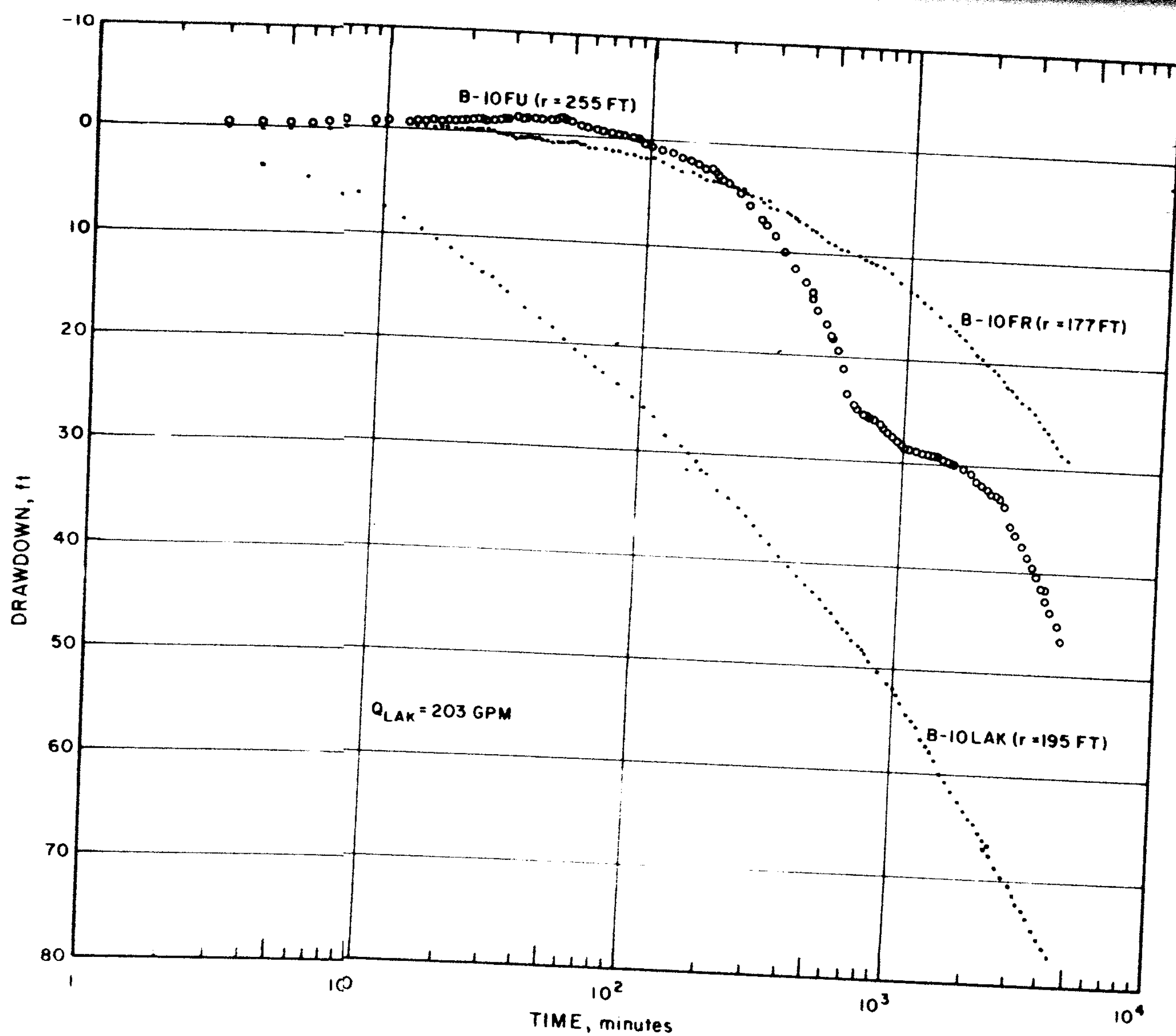


Figure 8 : Semilogarithmic Graphs of Drawdown for B-10 Observation Well Group, Lakota Aquifer Test

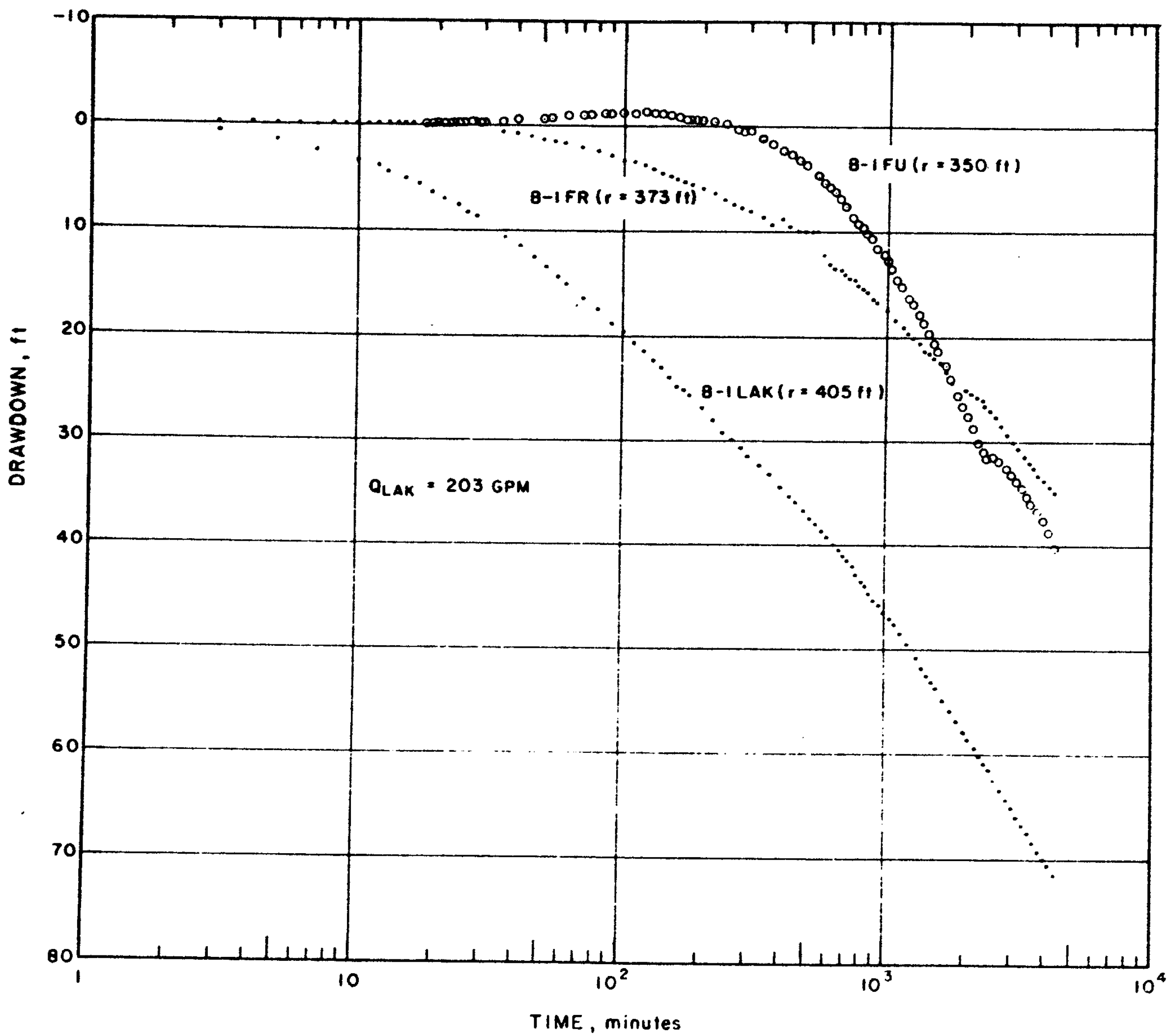


Figure 9: Semilogarithmic Graphs of Drawdown for B-1 Observation Well Group, Lakota Aquifer Test

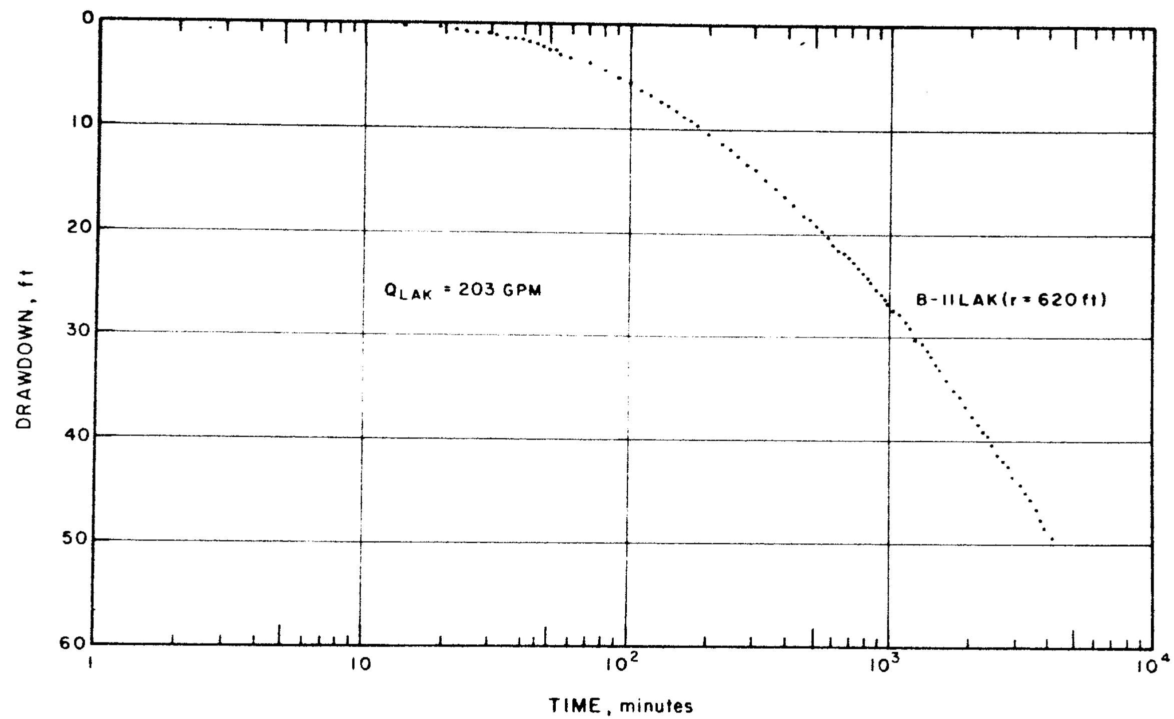


Figure 10: Semilogarithmic Graph of Drawdown for B-11 Observation Well Group, Lakota Aquifer Test

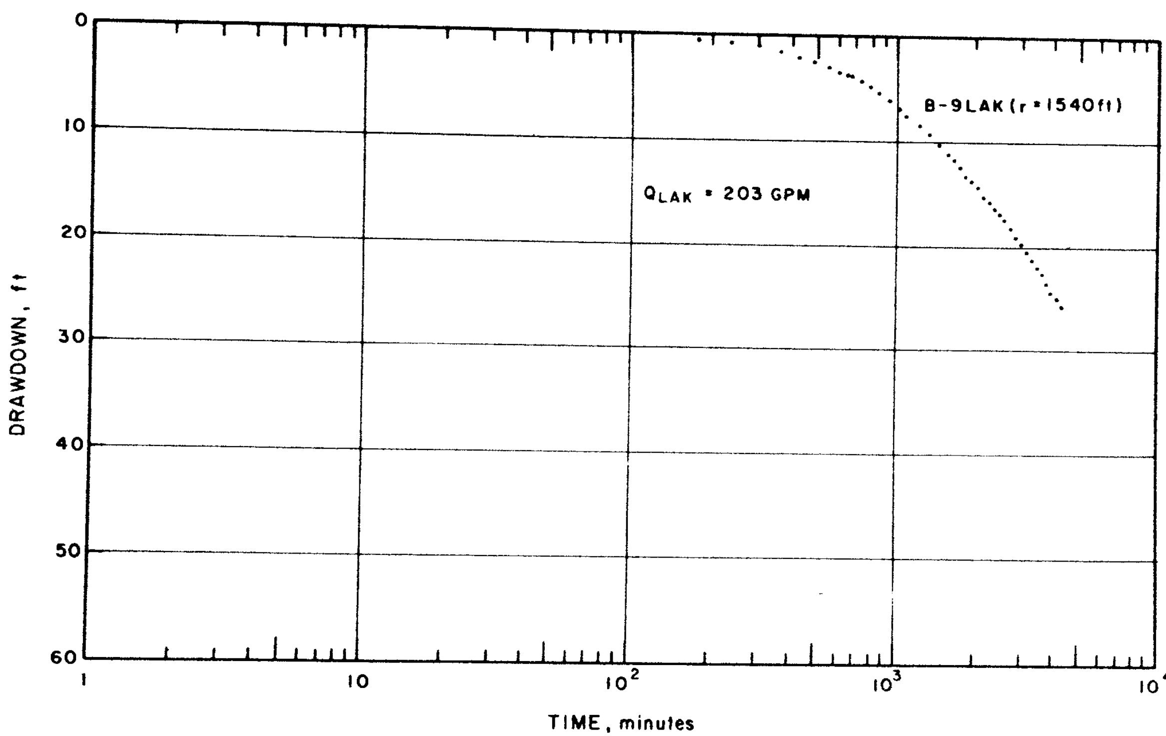


Figure 11: Semilogarithmic Graph of Drawdown for B-9 Observation Well Group, Lakota Aquifer Test

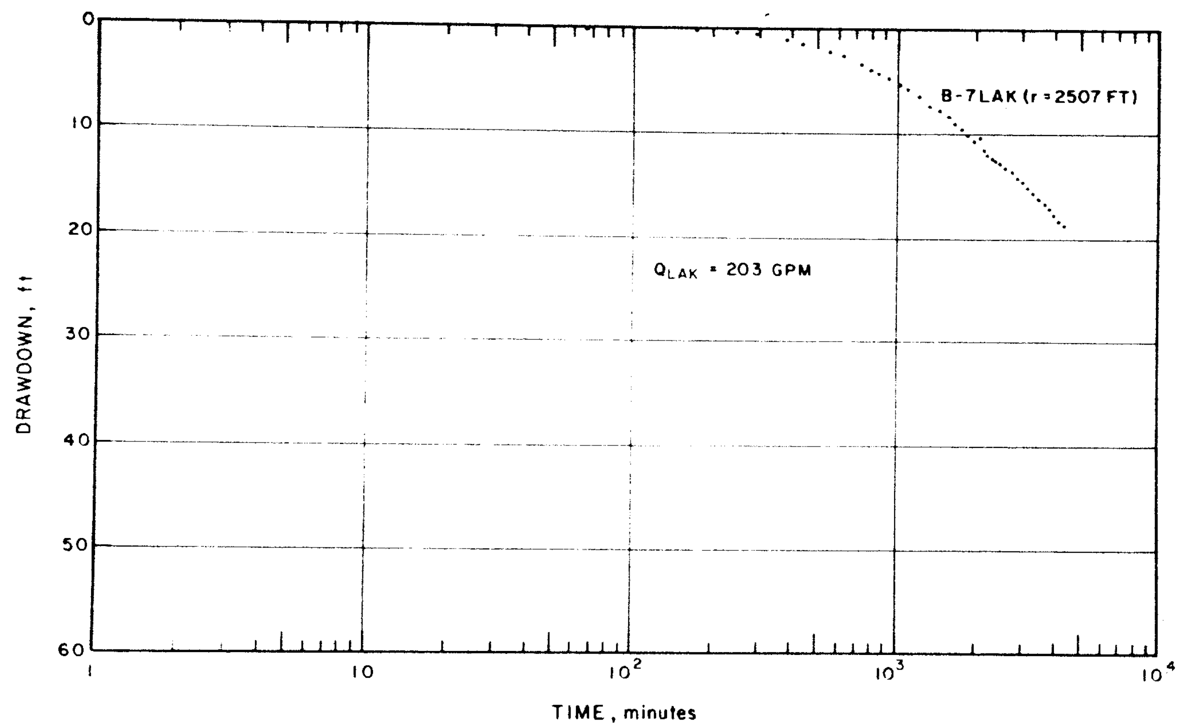


Figure 12: Semilogarithmic Graph of Drawdown for B-7 Observation Well Group, Lakota Aquifer Test

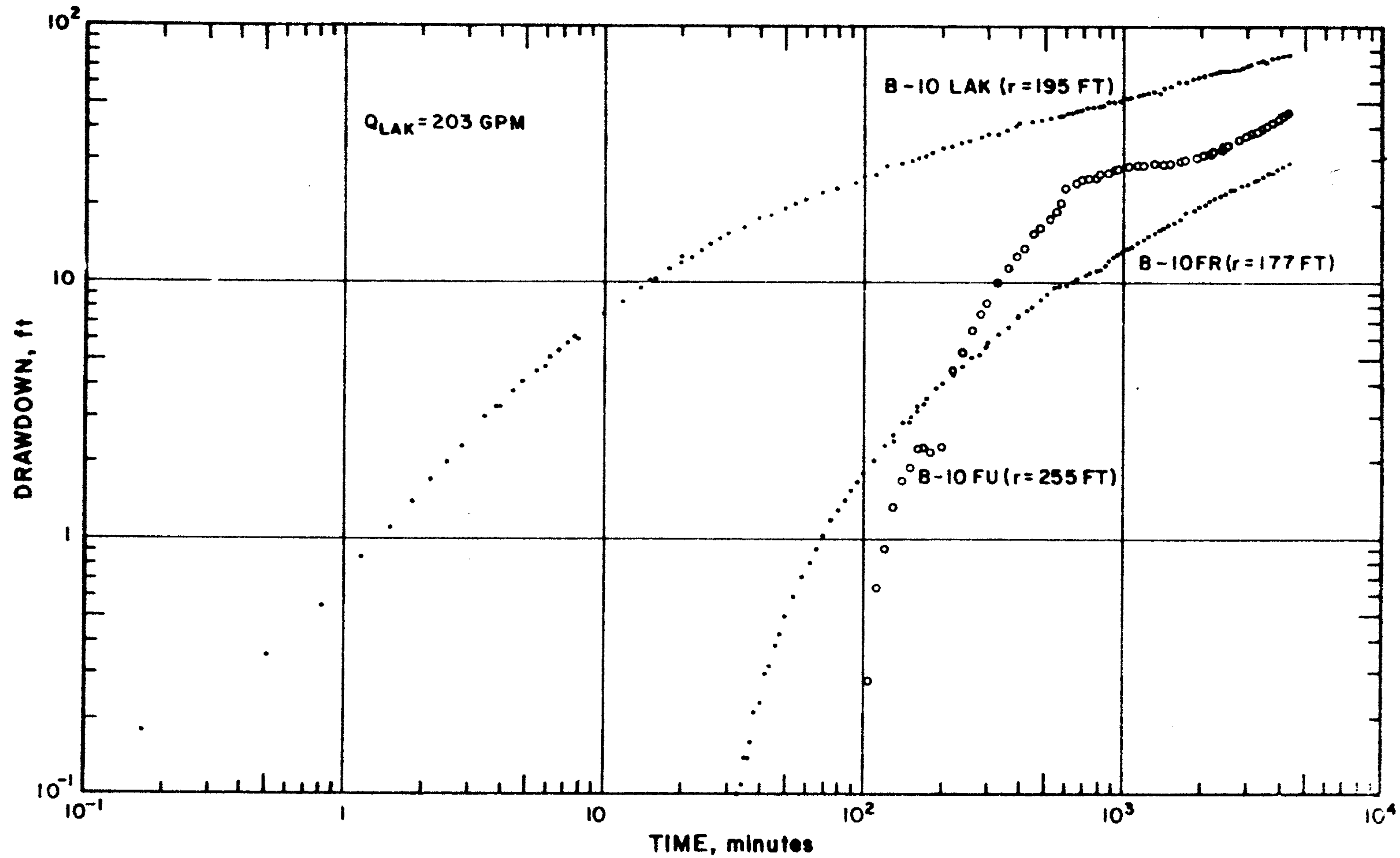


Figure 13 : Logarithmic Graphs of Drawdown for B-10 Observation Well Group, Lakota Aquifer Test

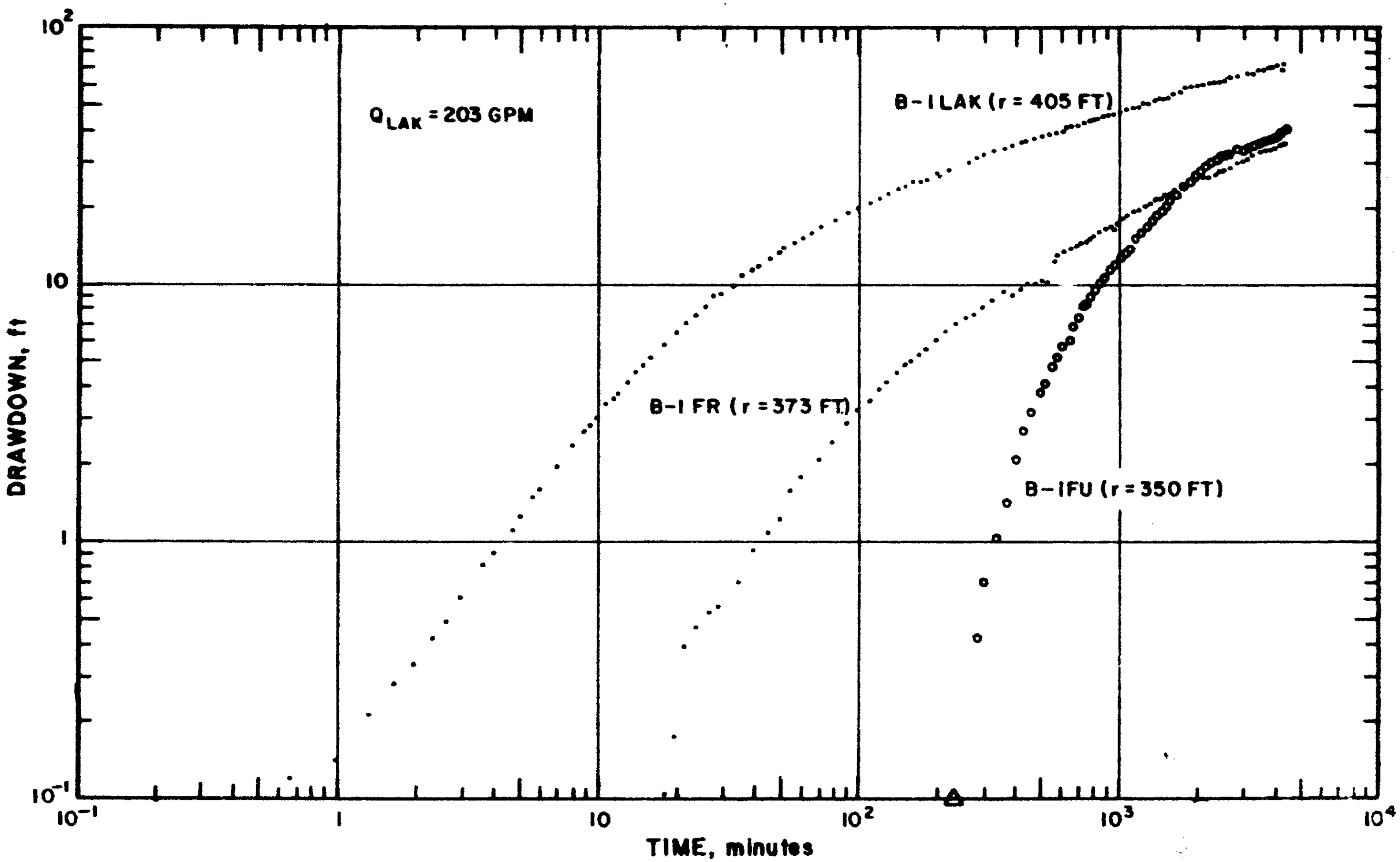


Figure 14 : Logarithmic Graphs of Drawdown for B-1 Observation Well Group, Lakota Aquifer Test

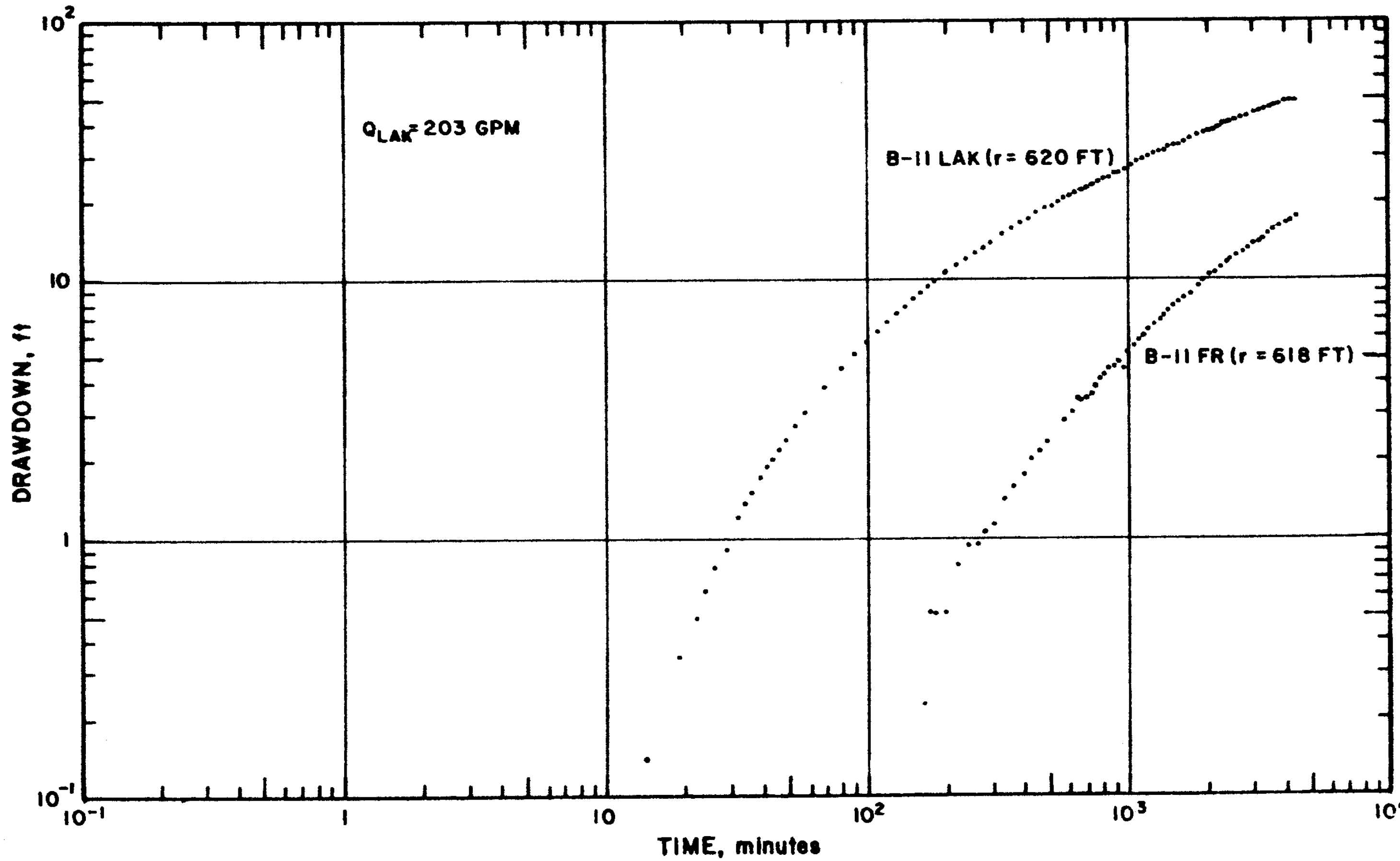


Figure 15: Logarithmic Graphs of Drawdown for B-11 Observation Well Group, Lakota Aquifer Test

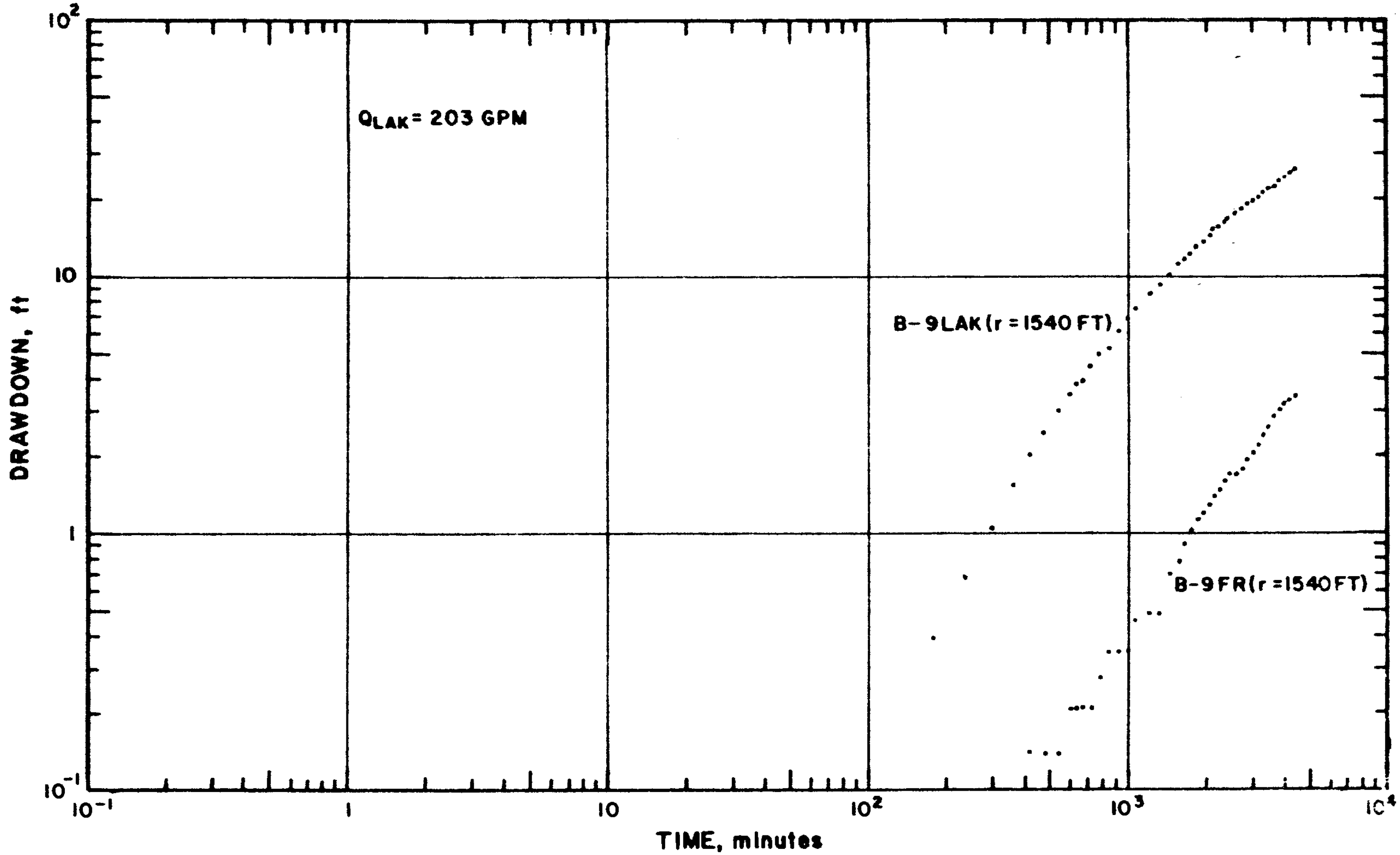


Figure 16 : Logarithmic Graphs of Drawdown for B-9 Observation Well Group, Lakota Aquifer Test

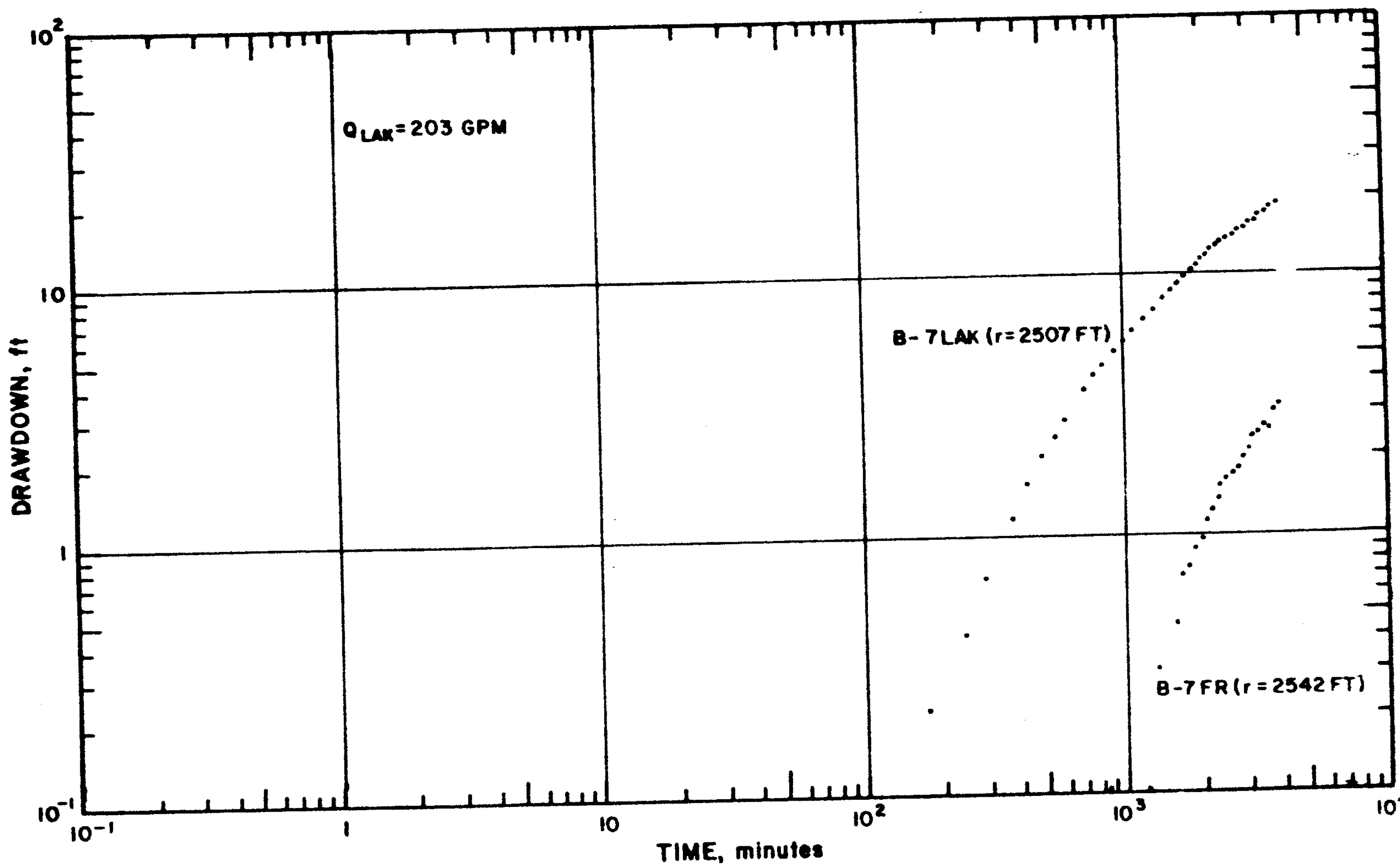


Figure 17 : Logarithmic Graphs of Drawdown for B-7 Observation Well Group, Lakota Aquifer Test

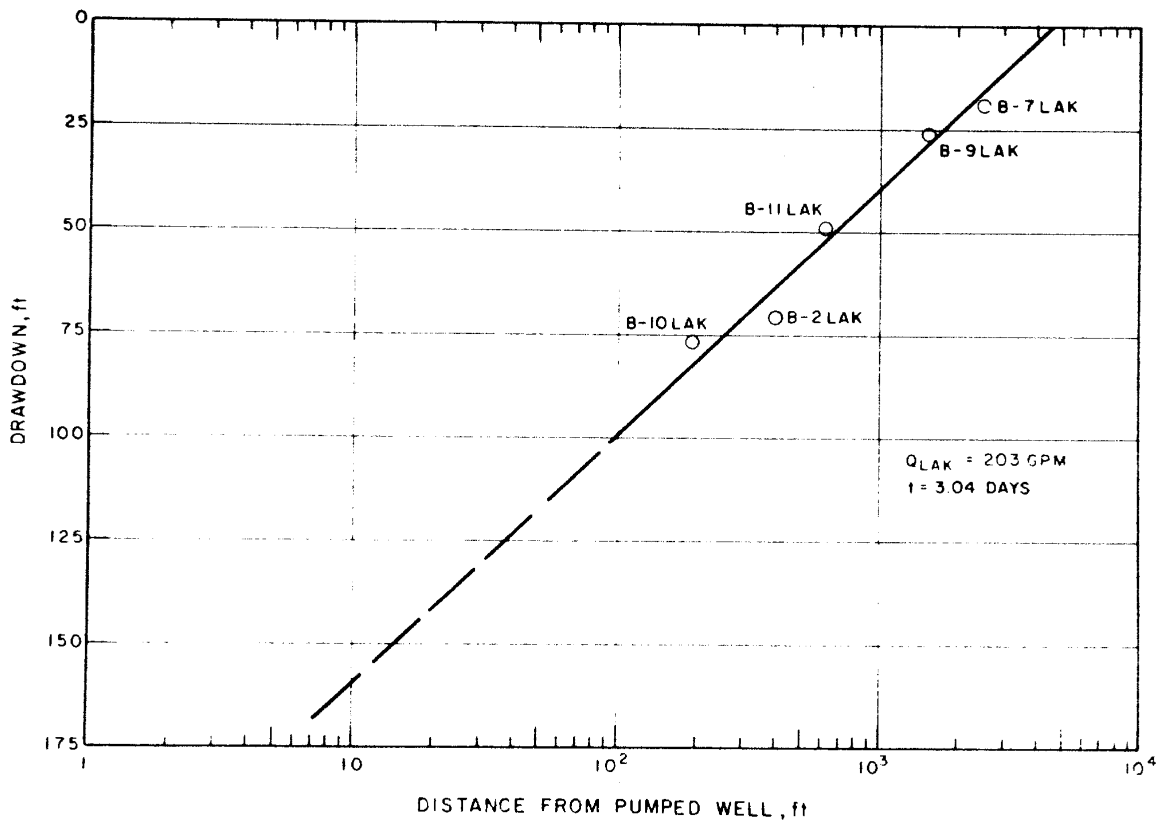


Figure 18: Semilogarithmic Graph of Distance vs. Drawdown at End of Pumping Test, Lakota Aquifer Test

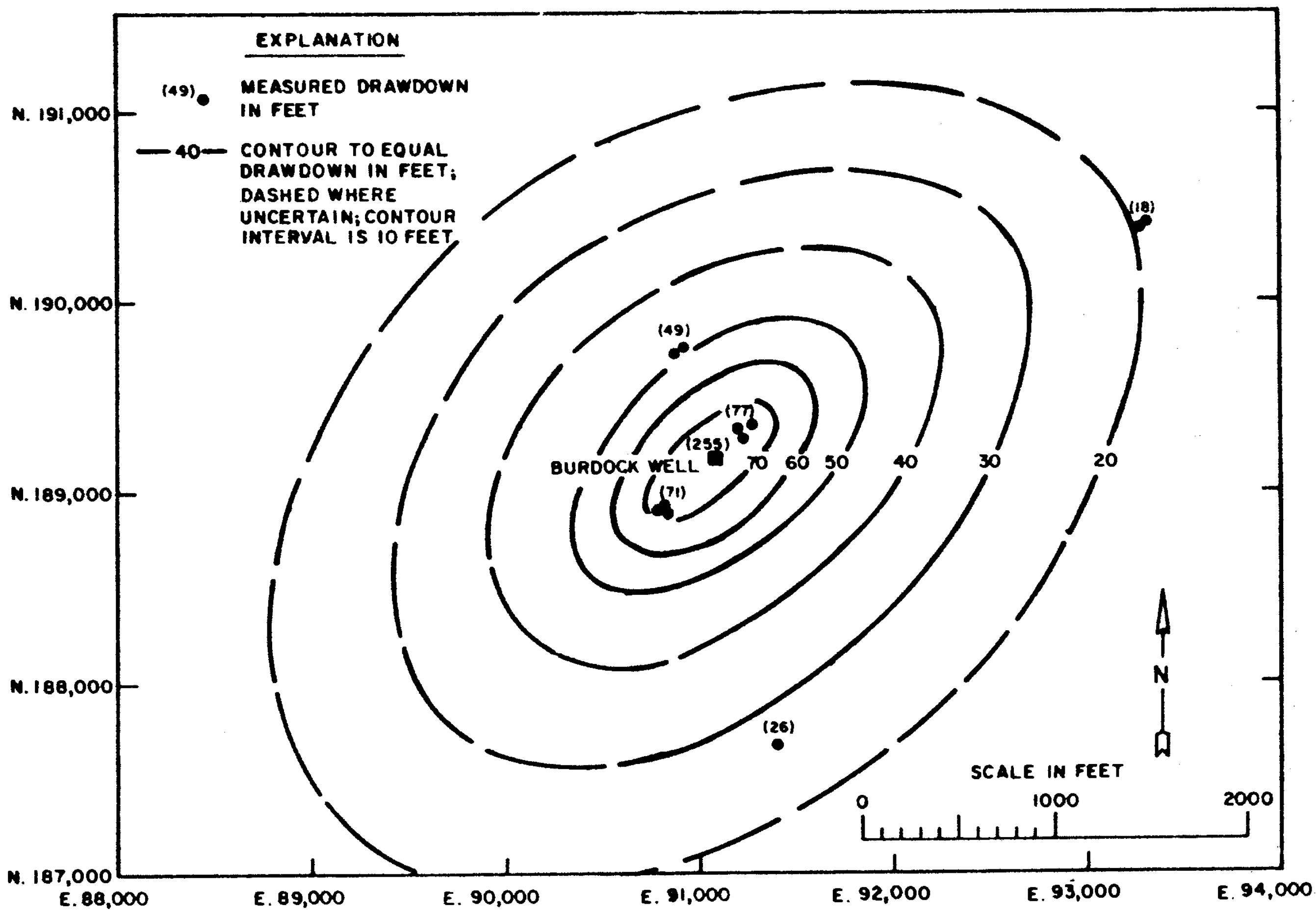


Figure 19 : Drawdown in Lakota Aquifer at End of Lakota Test

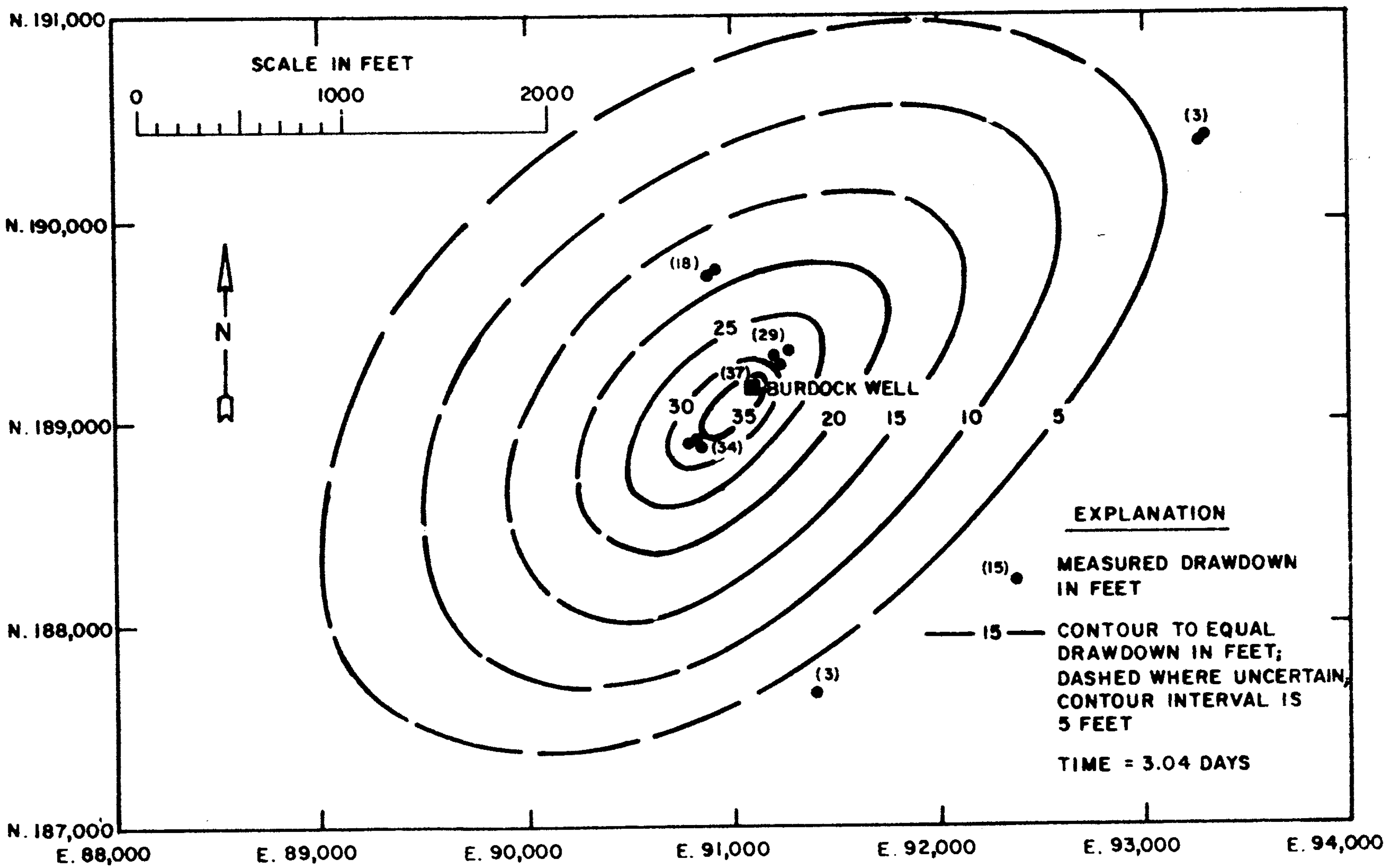


Figure 20 : Drawdown in Fall River Aquifer at End of Lakota Test

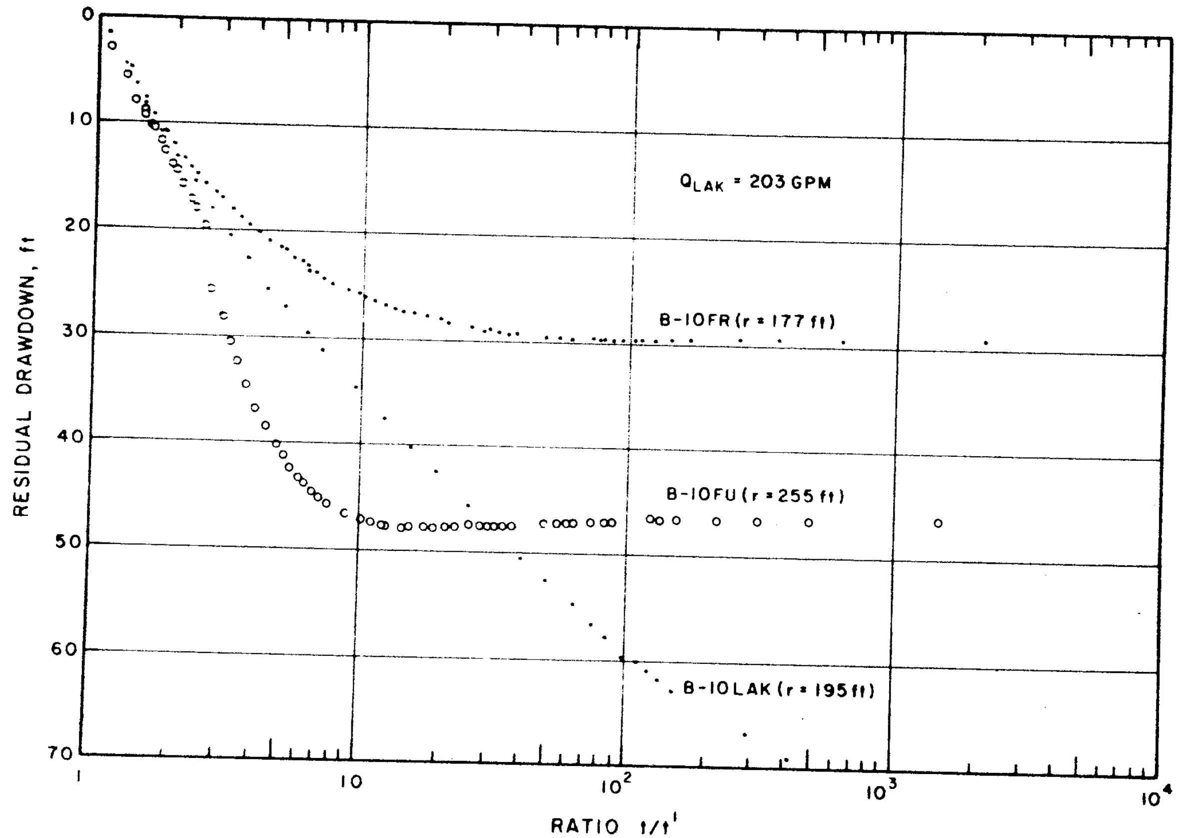


Figure 21: Recovery Graphs for B-10 Observation Well Group, Lakota Aquifer Test

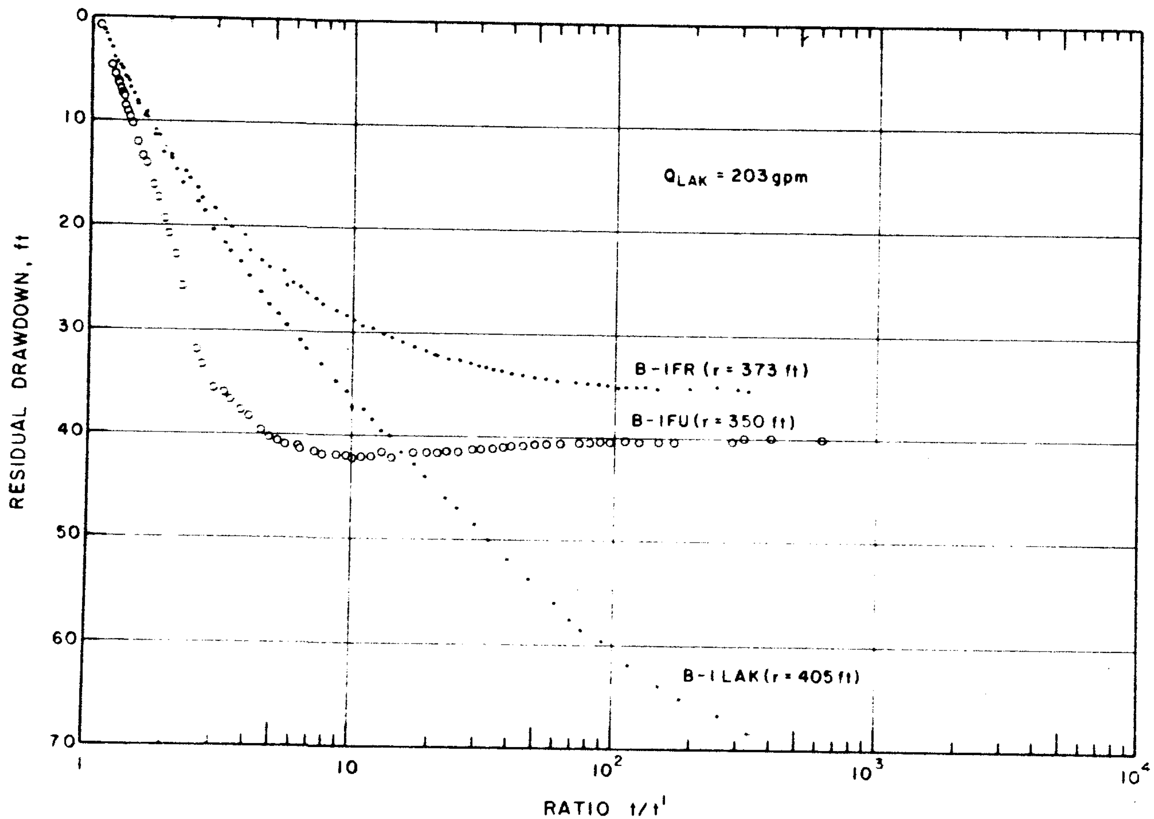


Figure 22 Recovery Graphs for B-1 Observation Well Group, Lakota Aquifer Test

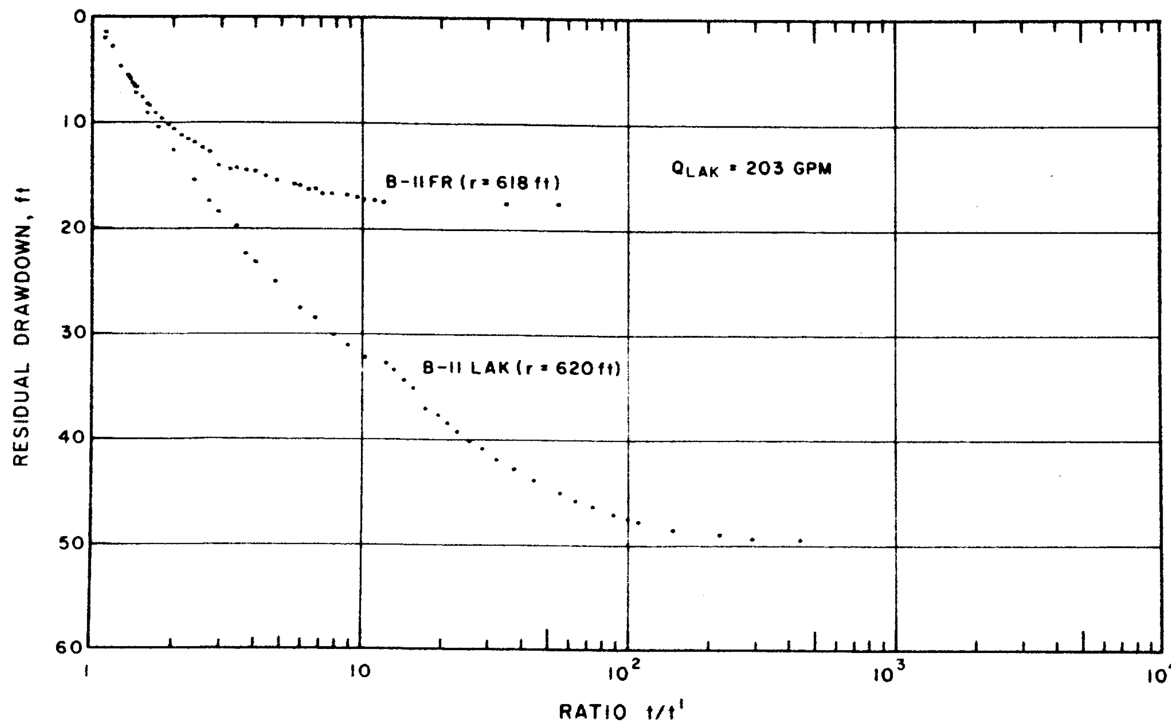


Figure 23: Recovery Graphs for B-11 Observation Well Group, Lakota Aquifer Test

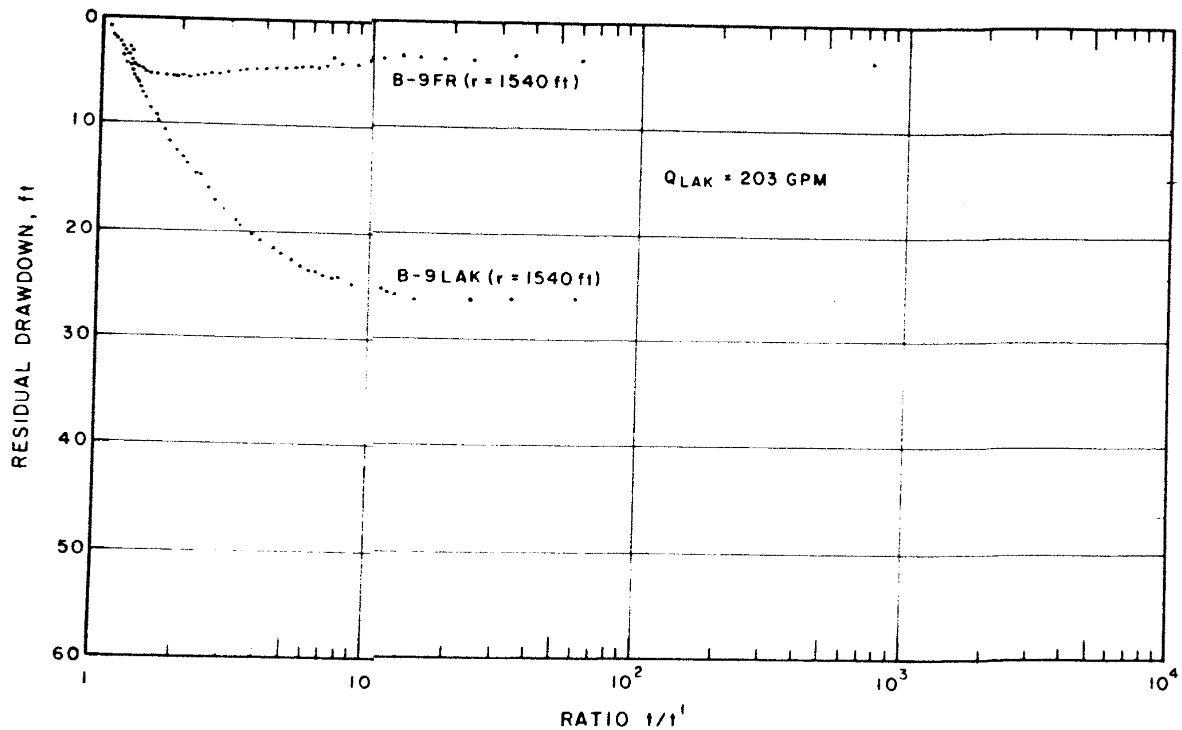


Figure 24 Recovery Graphs for B-9 Observation Well Group, Lakota Aquifer Test

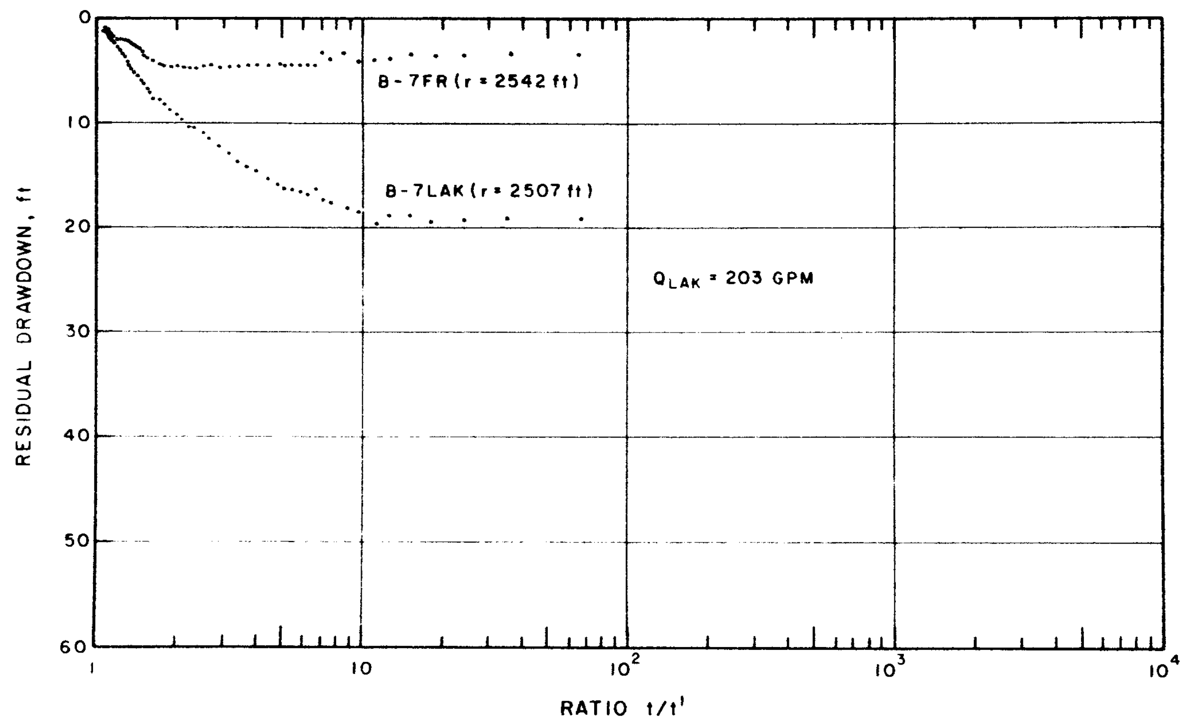


Figure 25: Recovery Graphs for B-7 Observation Well Group, Lakota Aquifer Test

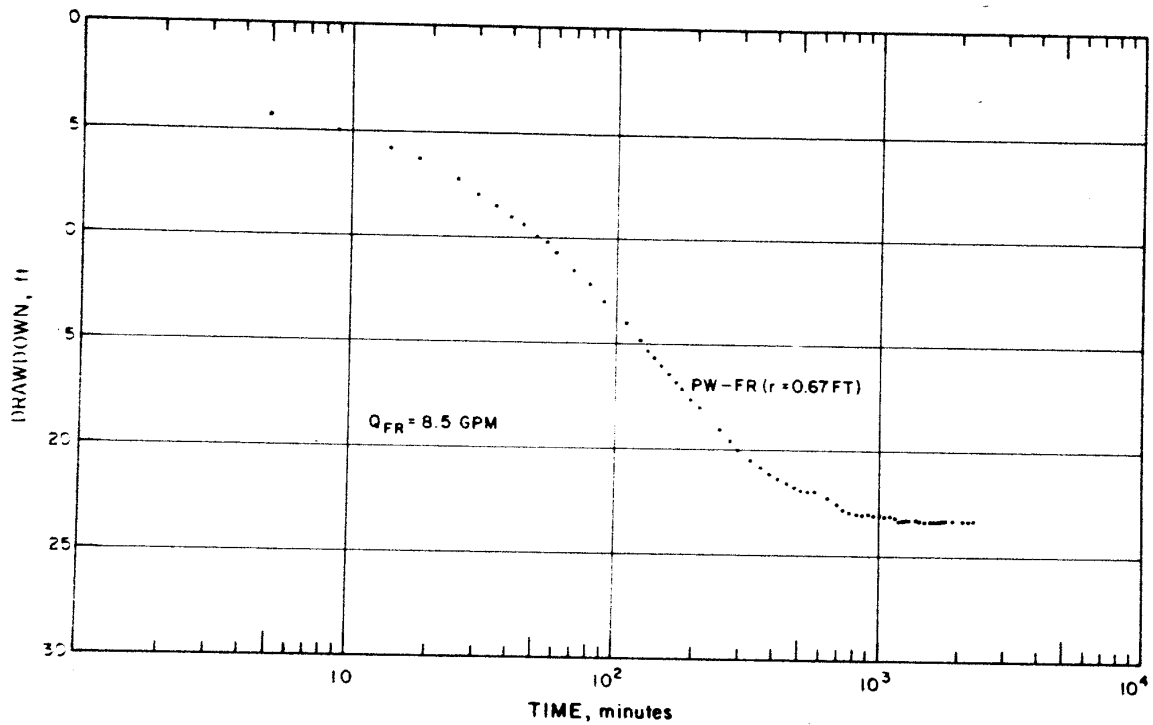


Figure 26: Semilogarithmic Graph of Drawdown for the Pumped Well, Fall River Aquifer Test

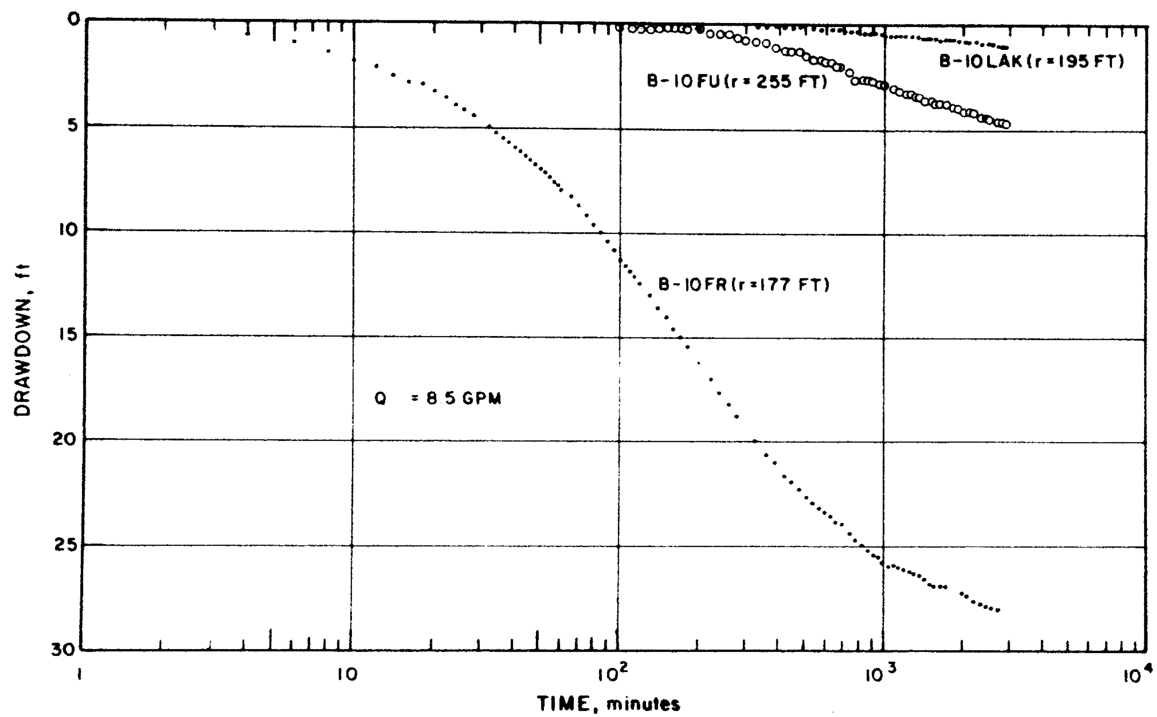


Figure 27: Semilogarithmic Graphs of Drawdown for B-10 Observation Well Group, Fall River Aquifer Test

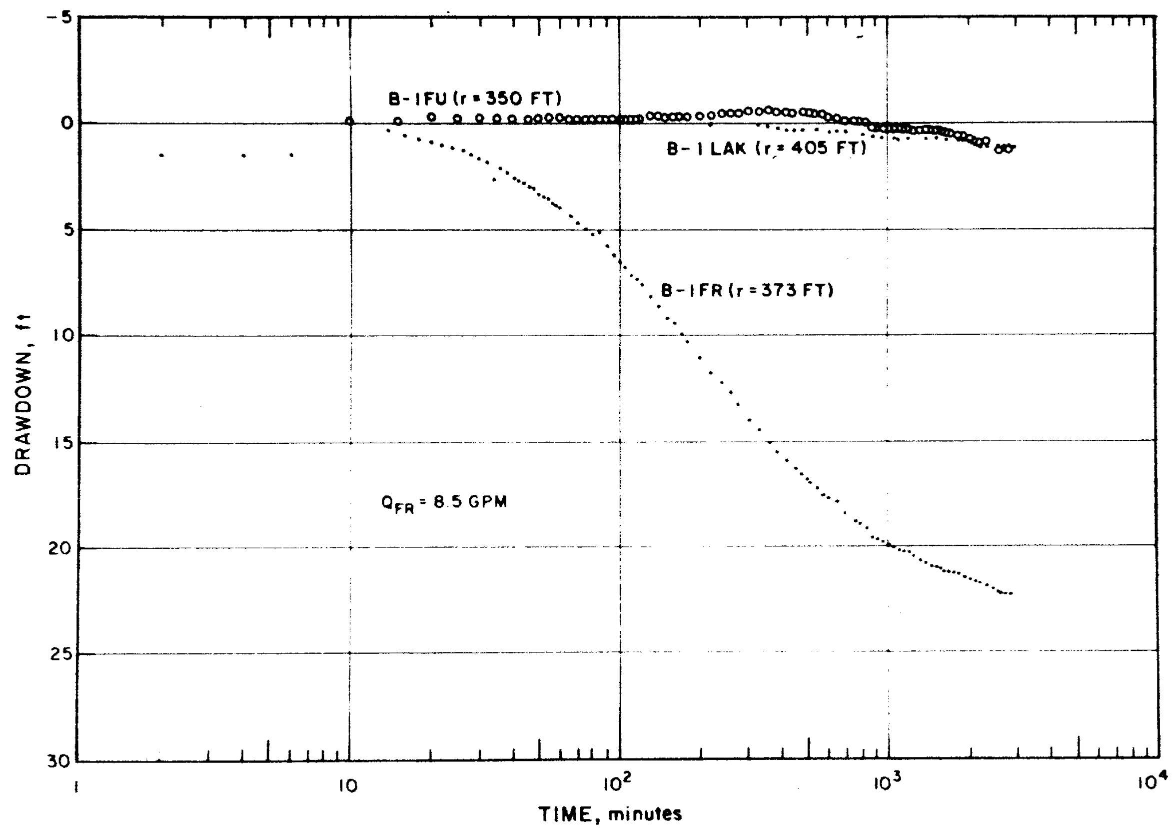


Figure 28 : Semilogarithmic Graphs of Drawdown for B-1 Observation Well Group, Fall River Aquifer Test

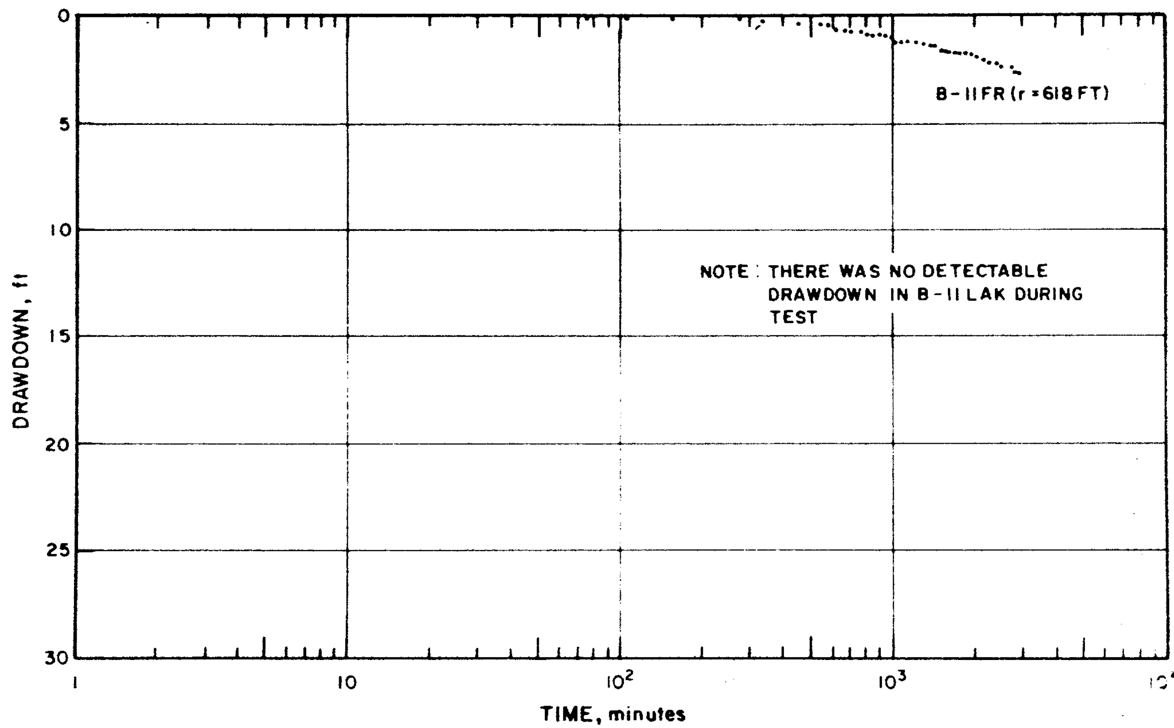


Figure 29: Semilogarithmic Graph of Drawdown for B-11 Observation Well Group, Fall River Aquifer Test

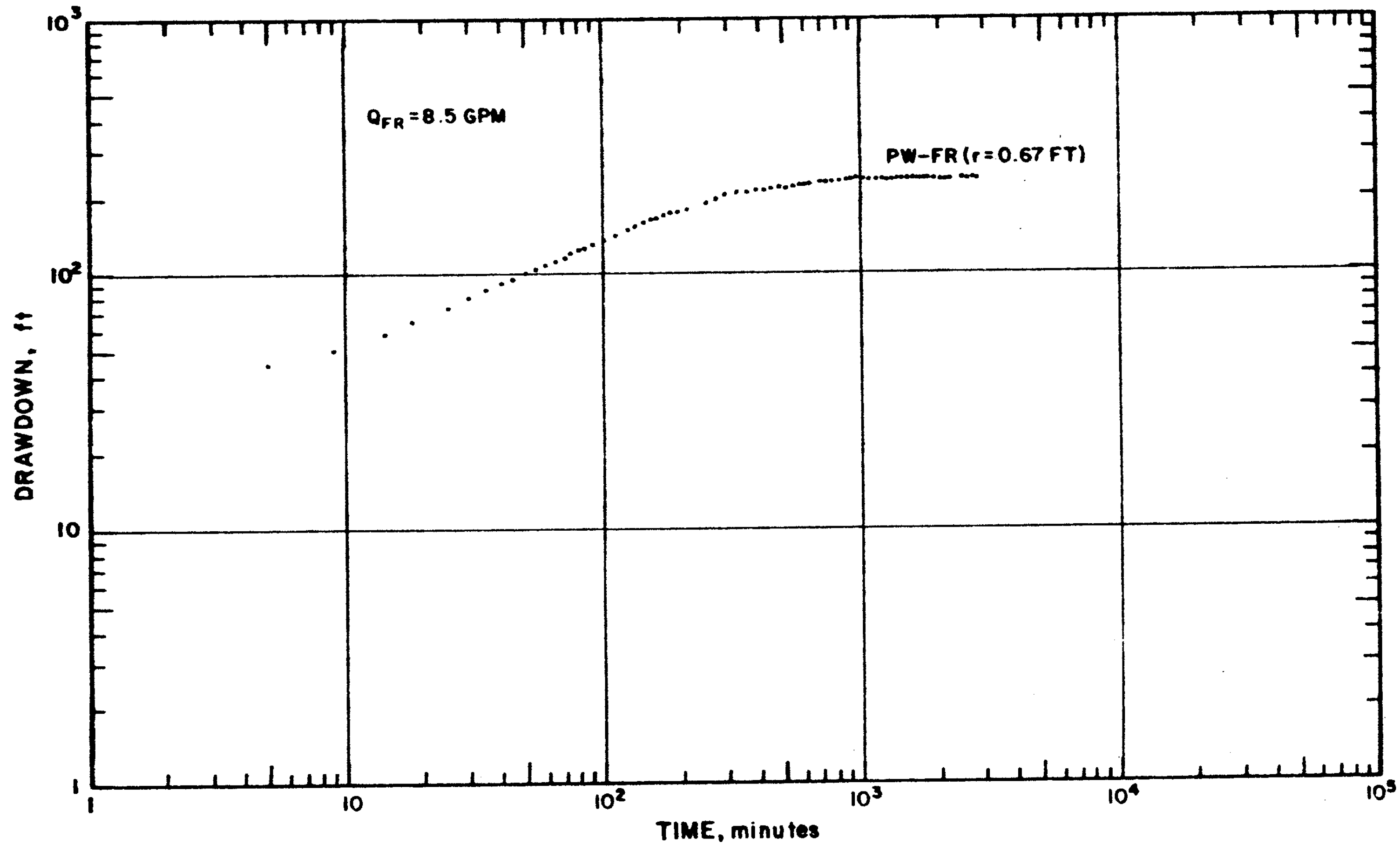


Figure 30: Logarithmic Graph of Drawdown for Pumped Well, Fall River Aquifer Test

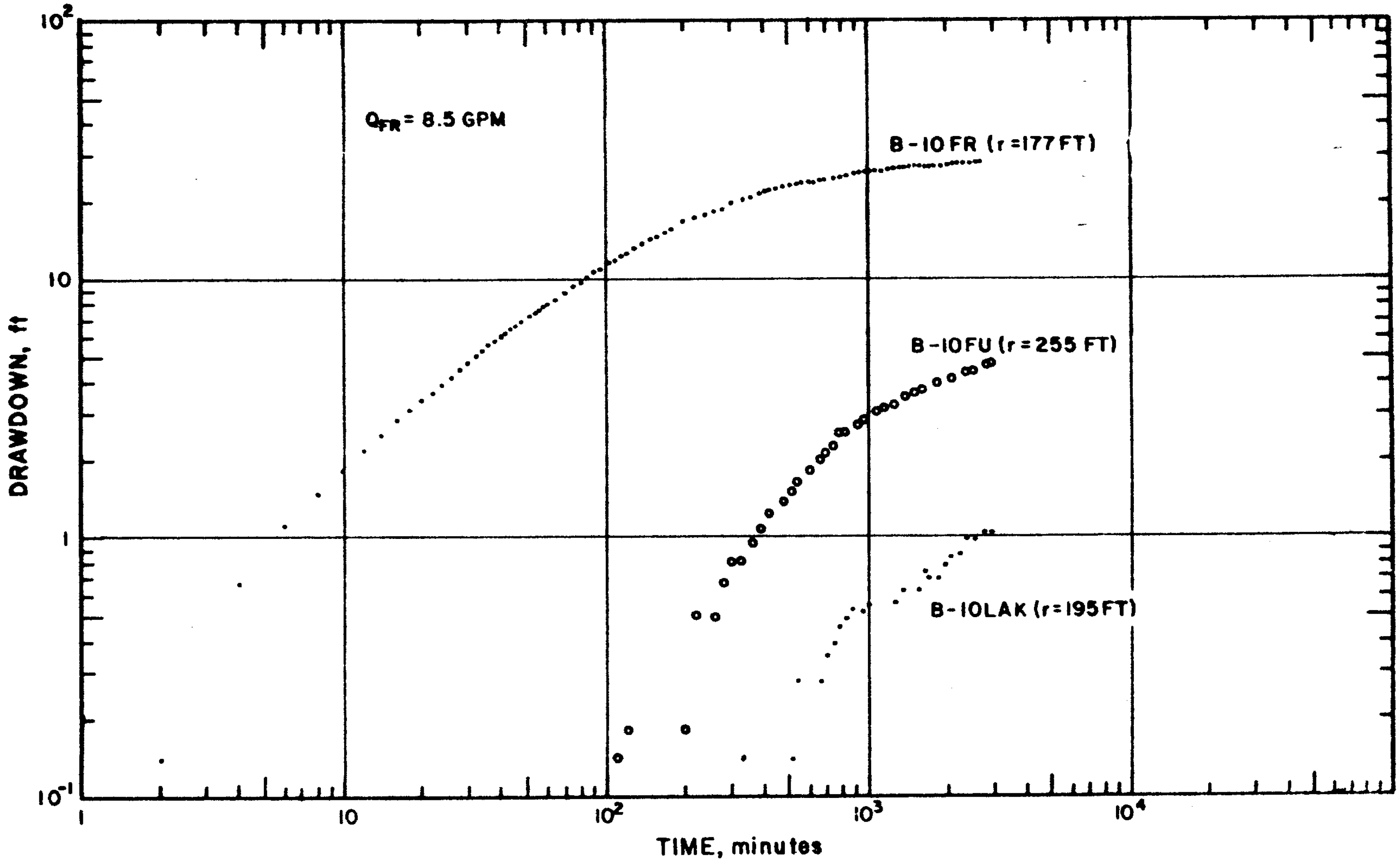


Figure 31: Logarithmic Graphs of Drawdown for B-10 Observation Well Group, Fall River Aquifer Test

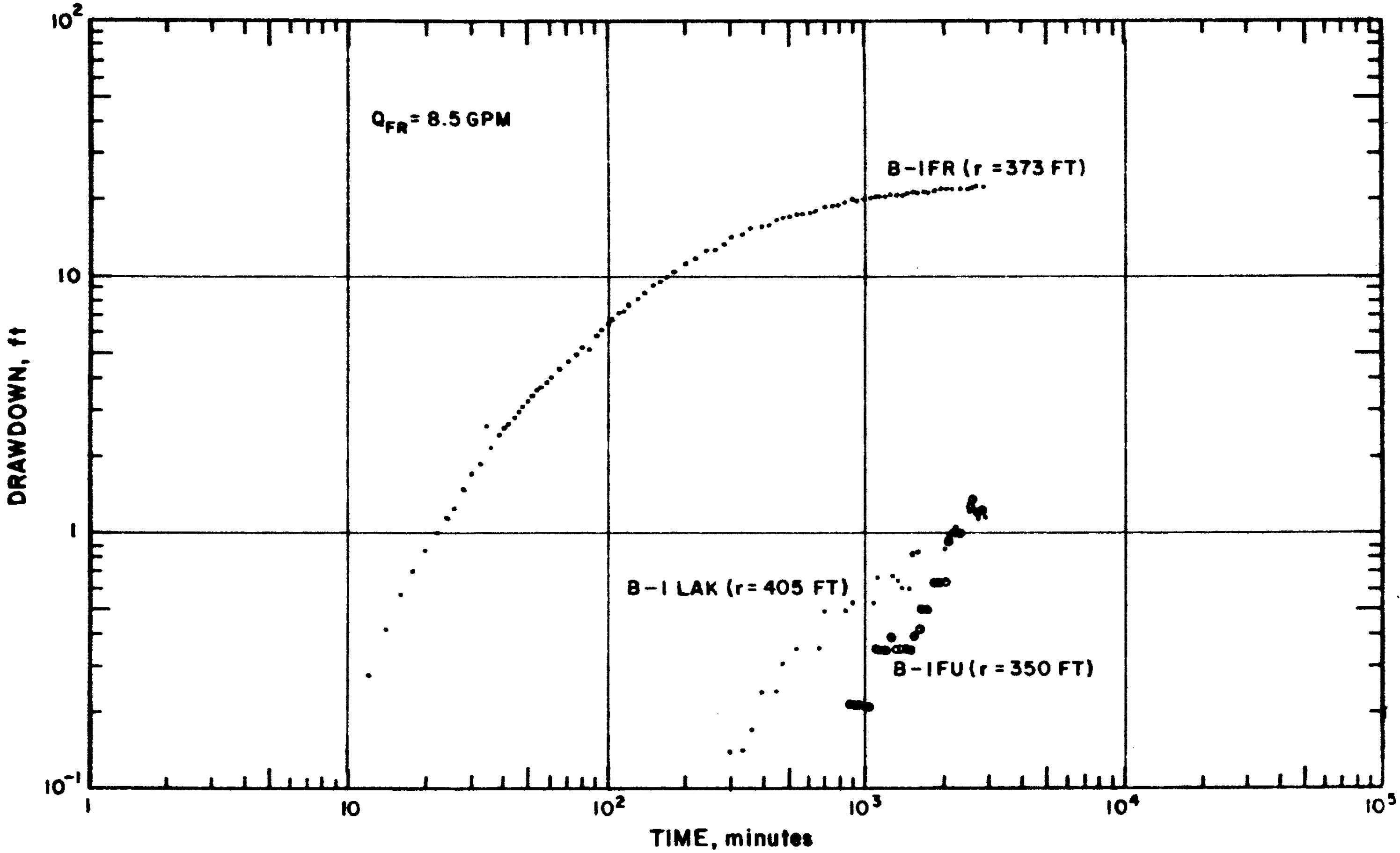


Figure 32: Logarithmic Graphs of Drawdown for B-1 Observation Well Group, Fall River Aquifer Test

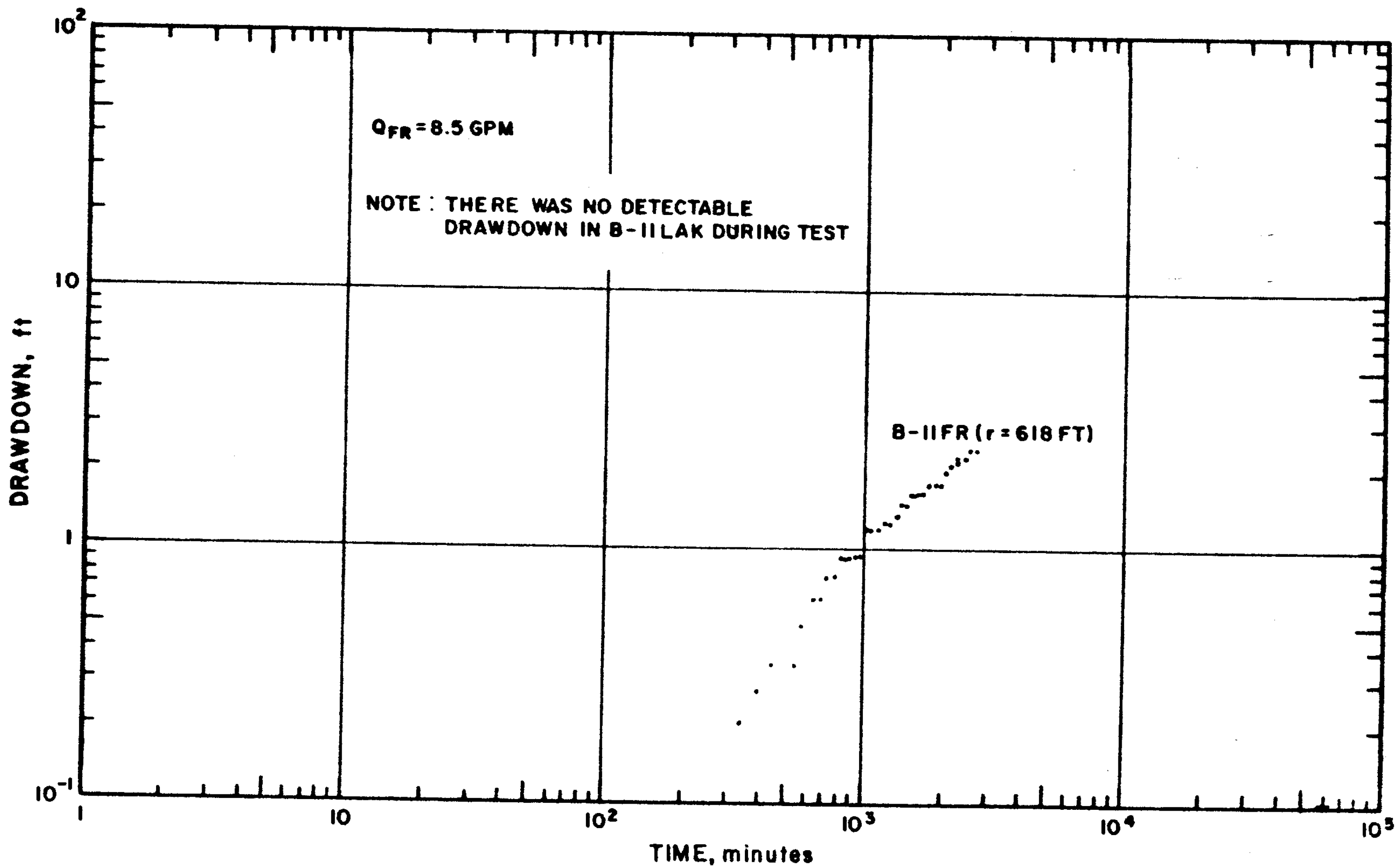


Figure 33: Logarithmic Graphs of Drawdown for B-11 Observation Well Group, Fall River Aquifer Test

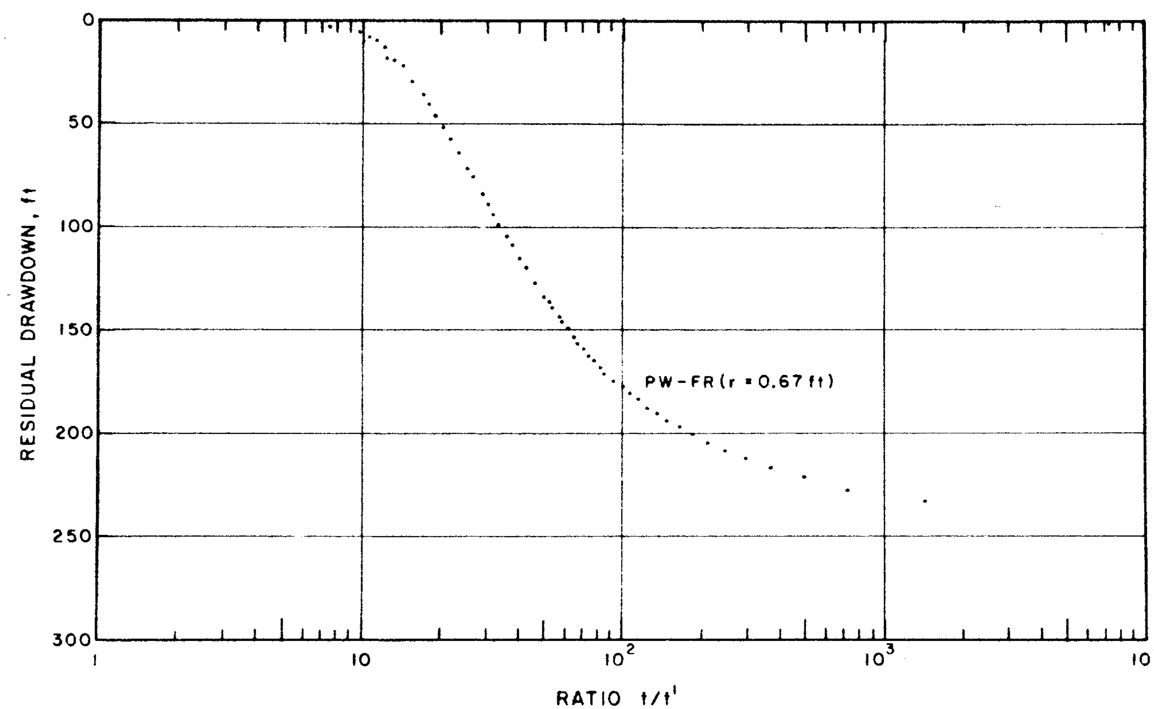


Figure 34: Recovery Graph for Pumped Well, Fall River Aquifer Test

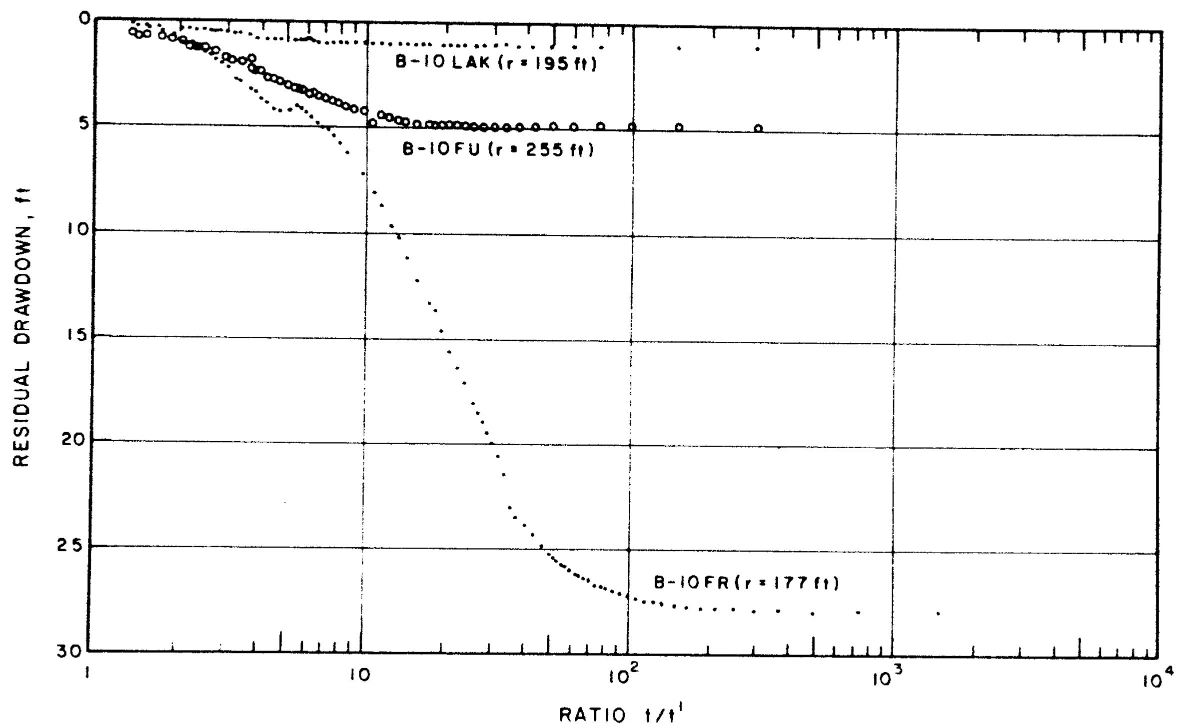


Figure 35: Recovery Graphs for B-10 Observation Well Group, Fall River Aquifer Test

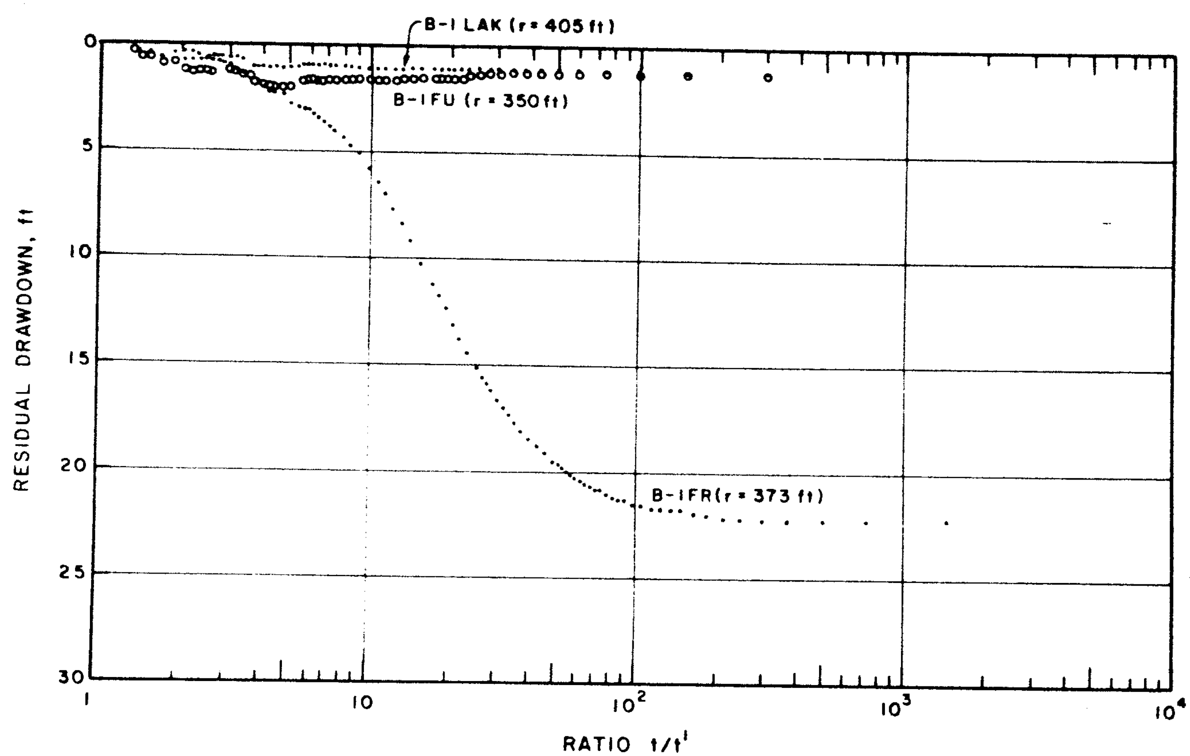


Figure 36: Recovery Graphs for B-1 Observation Well Group, Fall River Aquifer Test

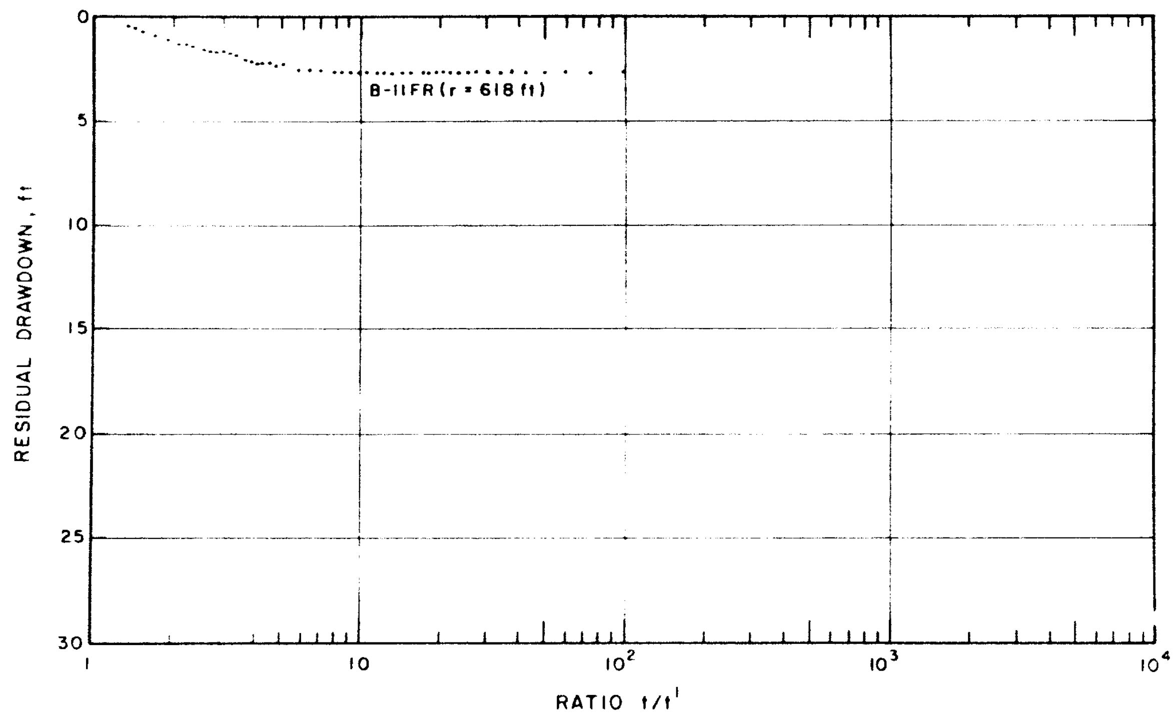


Figure 37 Recovery Graph for B-11 Observation Well Group, Fall River Aquifer Test

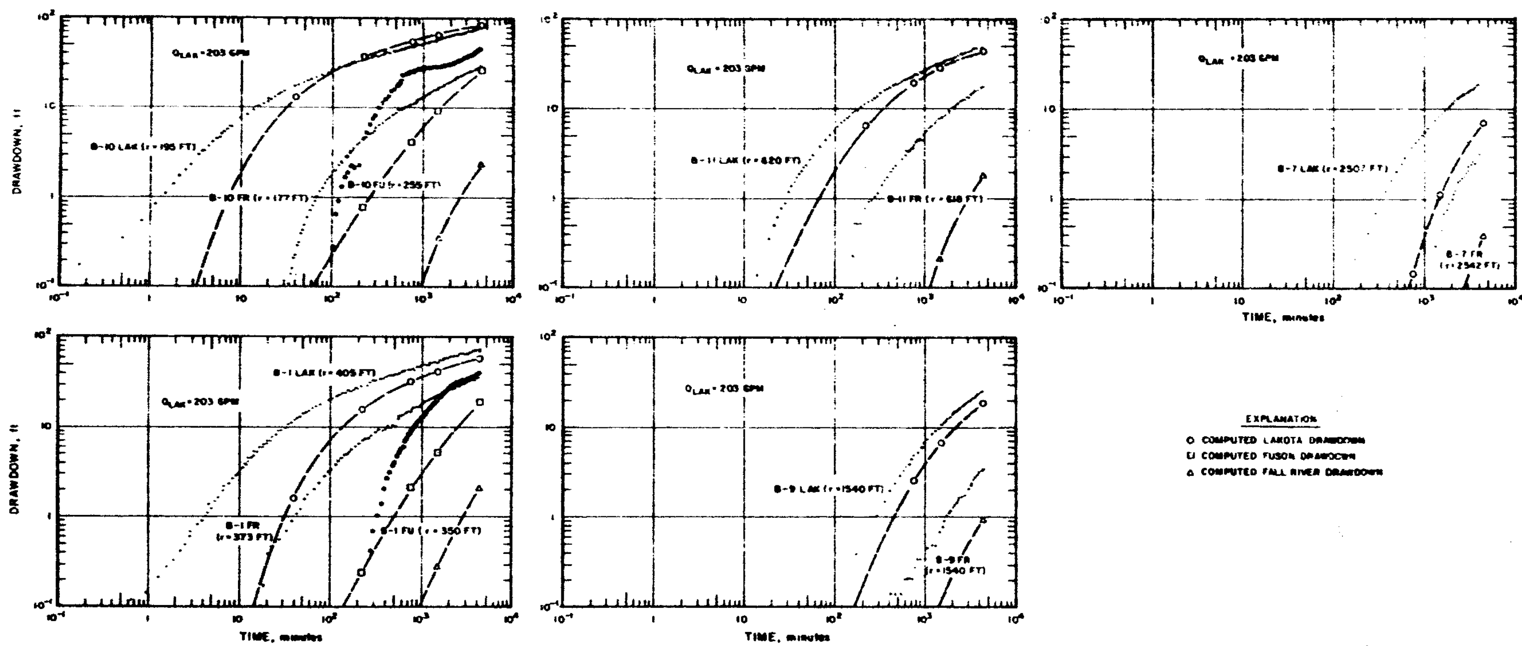


Figure 38 : Results of Initial Lakota Aquifer Test Simulation

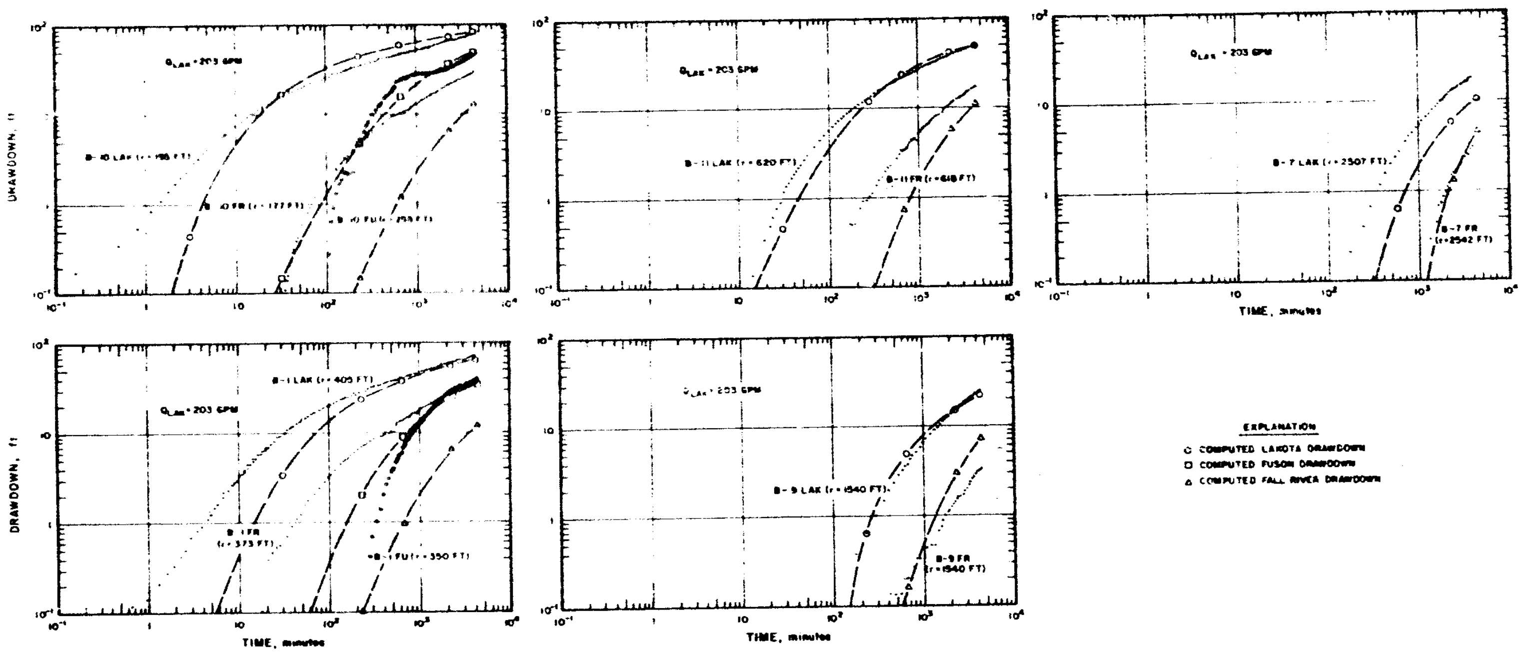


Figure 39 : Results of Final Lakota Aquifer Test Simulation

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