WATER RESOURCES OF THE WOODY MOUNTAIN WELL FIELD AREA, COCONINO COUNTY, ARIZONA

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GENERAL

The Woody Mountain municipal well field is located on the Coconino Plateau approximately 6 miles southwest of Flagstaff, Arizona, and is within the San Francisco Volcanic Field. The location of the Woody Mountain well field is shown in Figure 1.

Beginning in 1954 the groundwater resources of the Woody Mountain well field area were developed with a drilling program which, by 1968, resulted in six producing wells. Figure 2 shows quantities consumed and sources of all municipal water for Flagstaff from 1949 through 1974.

HYDROGEOLOGICAL FEATURES

The Woody Mountain well field lies east of and adjacent to the Oak Creek Fault on the downthrown side. The uppermost lithified rock units are lava-flow rocks which issued from several volcanic vents which include Woody Mountain volcano. The outcrop patterns of geologic units in the Woody Mountain area are shown on Figure 3.

The sequence, in descending order, of rock units in the Woody Mountain well field is alluvial and colluvial deposits, volcanic rocks, Moenkopi Formation, Kaibab Limestone, Coconino Sandstone, Supai Formation, and Redwall Limestone. Alluvial and colluvial deposits comprise a mixture of rock fragments which range in size from silt to boulders, lie above the water table, are moderately to highly permeable, and enhance rapid infiltration of surface water. Volcanic rocks include cinders and other pyroclastic rocks, and lava-flow rocks. Cinders occur as a thin mantle which covers older rock units, and provide excellent infiltration media. Intense fracturing in lava-flow rocks appears to provide recharge conduits. Thickness of lava-flow rocks penetrated by Woody Mountain wells ranges from 233 to 611 feet. Sandstone and mudstone strata of the Moenkopi Formation lie above the water table for the principal aquifer, but where unfractured provide perching conditions for small perched groundwater reservoirs which occur in lava-flow rocks and in Moenkopi sandstone interbeds. Although the Moenkopi has been removed by erosion at most locations on the Coconino Plateau, thickness of Moenkopi strata where penetrated by Woody Mountain wells ranges from 67 to 142 feet. The Kaibab Limestone lies above the water table and contains numerous joints and faults which have been enlarged by solution and provide recharge conduits. Average thickness of the Kiabab Limestone in the Flagstaff area is approximately 300 feet, however, in the Woody Mountain area the Moenkopi is commonly present, which indicates that post Moenkopi erosion has not attacked the Kaibab, the thickness of the limestone ranges from 355 to 428 feet. The Coconino Sandstone is the principal aquifer in the Woody Mountain well field. Permeability of unfractured Coconino is low; wells drilled into unfractured Coconino have specific capacities of less than one gallon per minute per foot of drawdown (gpm/ft). Fracturing enhances yield from the Coconino; wells drilled into highly fractured portions of the aquifer have specific capacities which may exceed 4 gpm/ft. Thickness of the Coconino Sandstone in the Flagstaff area and in the Woody Mountain well field ranges from 700 to 905 feet. The uppermost 50 to 150 feet of the Supai Formation is a sandstone which is similar in lithology to the Coconino Sandstone and comprises the lowermost part of the Coconino aquifer system. The remainder of the Supai Formation consists of interbedded mudstone and sandstone strata with a few thin beds of limestone, and is believed to be an aquitard. Although Woody Mountain wells bottom prior to completely penetrating the Supai, thicknesses of approximately 1500 feet have been established by measured sections near Sedona, Arizona, and by logs oil test wells in the Flagstaff area (McGavock, 1968). The Redwall Limestone is believed to extend from 3100 to 3400 feet in depth below the land surface in the Woody Mountain well field and is the aquifer for large springs which discharge into the Verde River and into the Grand Canyon. The Redwall Limestone is a potential aquifer in the Flagstaff area.

The Oak Creek Fault trends north-south, and is downthrown approximately 400 feet on the east side. Antithetic faulting near the Oak Creek Fault inclines strata of the downthrown block downward toward the Oak Creek Fault and creates a structural trough. Transverse faults cut the Oak

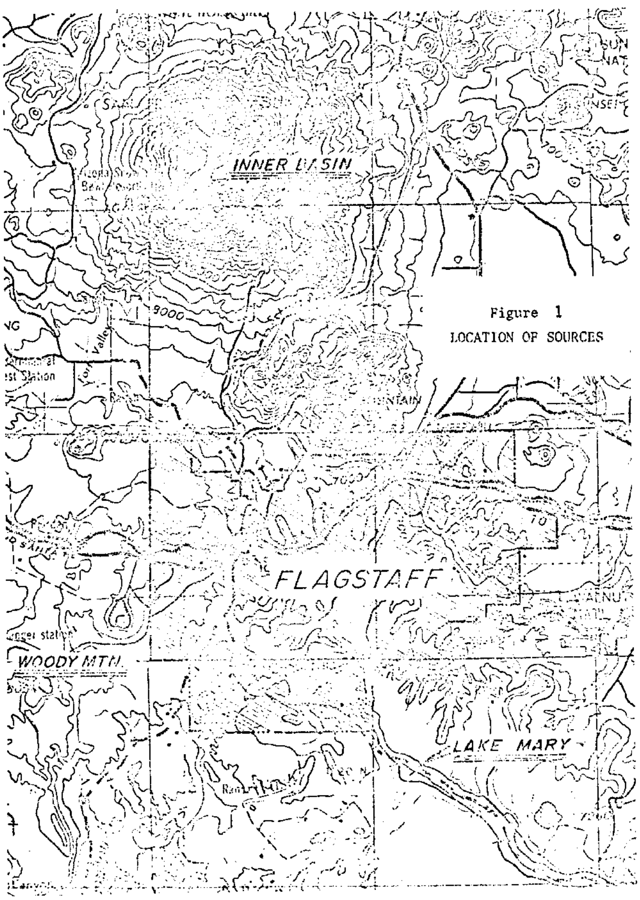


Figure 1
LOCATION OF SOURCES

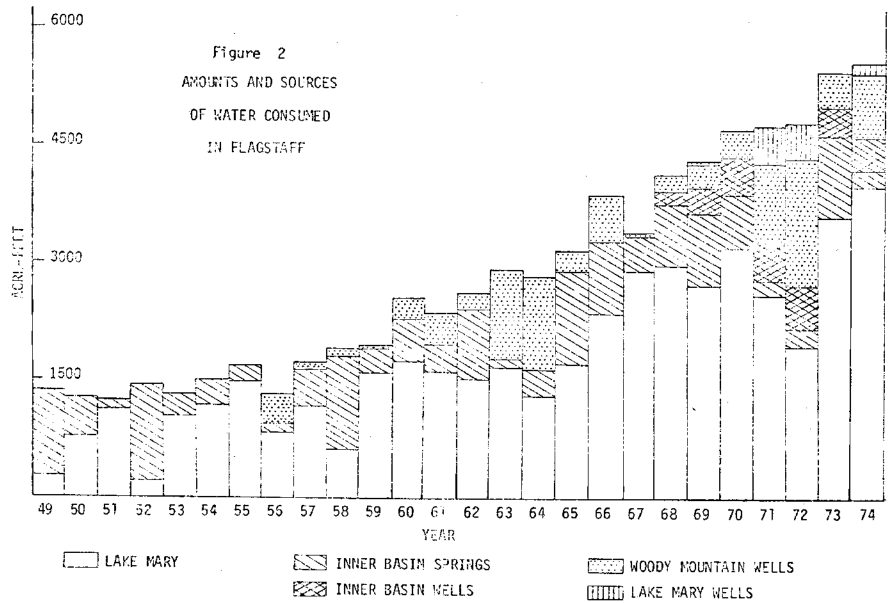
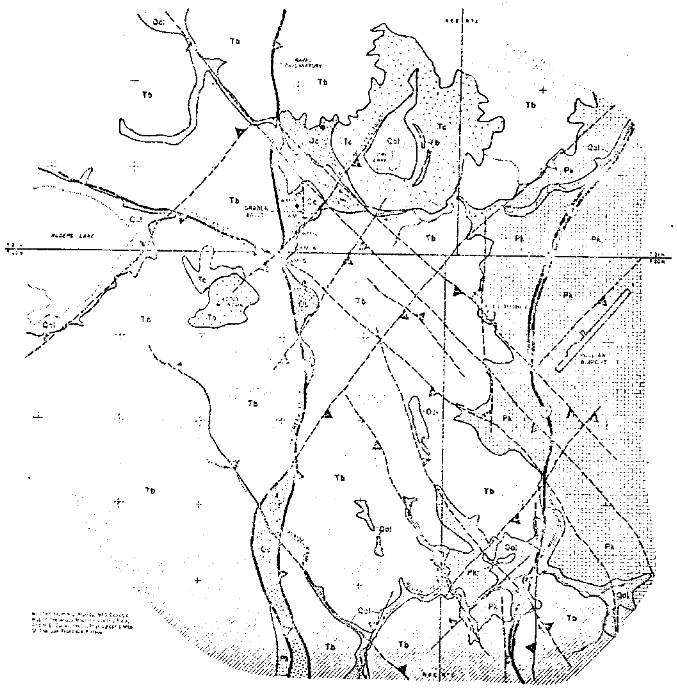


Figure 2
AMOUNTS AND SOURCES
OF WATER CONSUMED
IN FLAGSTAFF



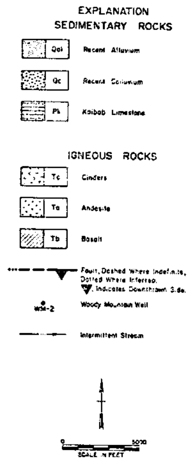


FIGURE 3

HYDROGEOLOGIC FEATURES OF WOODY MOUNTAIN WELL FIELD

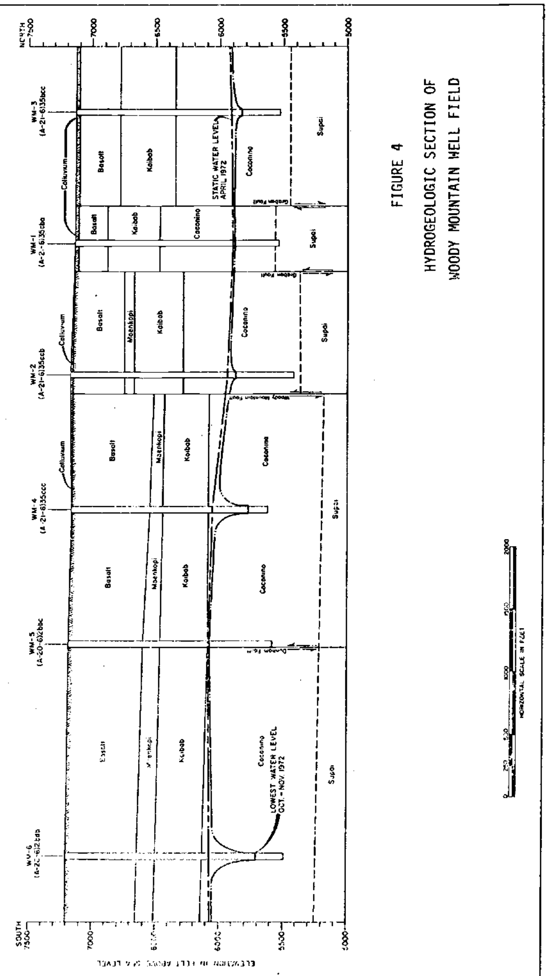


FIGURE 4
HYDROGEOLOGIC SECTION OF
WOODY MOUNTAIN WELL FIELD

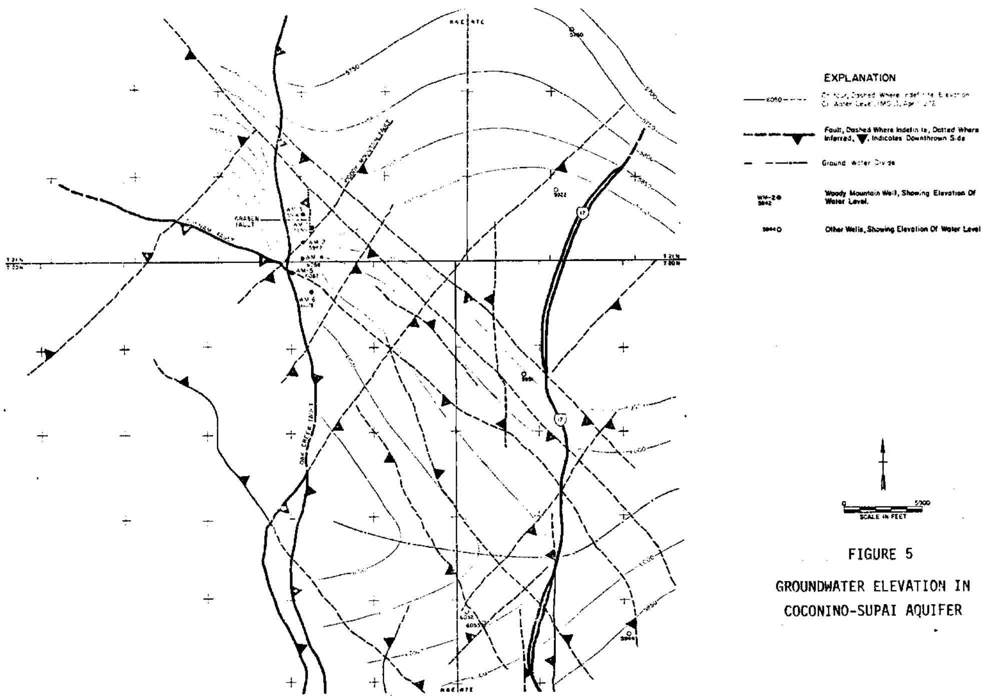


FIGURE 5

GROUNDWATER ELEVATION IN COCONINO-SUPAI AQUIFER

TABLE 1

SUMMARY OF DATA FROM LONG-TERM PUMP TEST (1972-73)

WOODY MOUNTAIN WELL FIELD

Well No.	Date Turned On	Static Water Level Feet (c)	Well Discharge gpm	Water Level Decline, in Feet, After Pumping Started: One Hour	One Day	End of Test 208 Days	Water Temp F°	Specific Conductance Micro-mhos	Water Level Recovery, in Feet, After Pumping Stopped: One Hour	One Day	90 Days	150 Days
WM-1	Not pumped	1237.3 / 5899.4	0	< 0.1	< 0.1	13	-	-	< 0.1	< 0.3	8	10
WM-2	May 3, 1972	1225.2 / 5942.0	295.4 (306.7-May 4) (276.0-Jul 19)	15	24	65	53	250	18	28	55	59
WM-3	May 20, 1972(a)	1215.2 / 5914.3	402.6 (413.9-May 22) (390.7-Oct 27)	26	39	81	54	230	42	52	73	76
WM-4	Apr 25, 1972	1165.0 / 6058.0	435.5 (462.5-Apr 30) (372.1-Oct 22)	131	164	283	52	240	176	216	272	279
WM-5	Not pumped	1100.7 / 6087.2	0	< 0.1	< 0.1	12	-	-	< 0.1	< 0.3	6	9
WM-6	Apr 10, 1972(b)	1126.4 / 6075.7	560 (569.5-July 1) (541.8-Apr 17)	250	290	340	54	230	325	336	350	357

Nov. 4, 1972 Pumping operations were terminated in all wells.
Water level recovery measurements began and were continued through April 1973.

(a) Completion of turn-on sequence of four wells.

(b) Pumping operations began with turn-on of WM-6.

(c) Water level in feet below land surface / Elevation of water level in feet above sea level

Creek Fault and provide additional fractures in the Coconino aquifer. The most prominent transverse fault is the northwesterly trending Dunnam fault. Other transverse faults are the northeasterly trending Woody Mountain fault and the north-south trending Graben fault. Figure 4 is a hydrogeological section of the Woody Mountain well field and shows subsurface hydrogeological relations.

Groundwater contours of static water level conditions in the Woody Mountain area are shown on Figure 5 and indicate that the well field is recharged from the southwest and discharges to the northeast. A groundwater divide occurs south of the well field.

WOODY MOUNTAIN WELL FIELD

Between 1954 and 1968 six cased wells numbered WM-1, WM-2, WM-3, WM-4, WM-5, and WM-6 were constructed near Woody Mountain. The wells range in depth from 1,515 to 1,712 feet and presently (1975) have a combined potential discharge of 3.3 million gallons per day (mgpd). WM-1 and WM-3 penetrate the Supai Formation. WM-2, WM-4, WM-5, and WM-6 bottom in the Coconino Sandstone. All Woody Mountain wells are equipped with submersible electric pumps.

LONG-TERM PUMP TEST

A long-term test of the Woody Mountain well field was begun on April 10, 1972 after pre-test water levels had been monitored and recorded. Wells were individually turned on at eight to seventeen day intervals. By May 20, 1972 four wells (WM-2, WM-3, WM-4, and WM-6) were operating. WM-1 and WM-5 were not pumped and served as observation wells. The pumping phase was completed on November 4, 1972. During the pumping phase, measurements were made of pump discharge, water level, temperature, and conductance. Water levels were measured during the recovery phase which continued into 1973. Data were obtained for other factors which include power failures, precipitation, and barometric pressure. A summary of water level drawndown and recovery data is listed in Table 1.

ANALYSIS

After the pumping and recovery phases of the test were completed, water level drawdown and water production data were analyzed to determine specific capacities, coefficients of transmissibility and storage of the aquifer, and interference effects. Specific capacities of the pumped wells ranged from 1.53 gpm/ft for WM-6 to 4.95 gpm/ft for WM-3.

COEFFICIENT OF TRANSMISSIBILITY

Drawdown and recovery data were used to compute transmissibility using the methods of Theis (1935) and Jacob (1950). The graphic plots of drawdown and recovery data indicated a series of line segments, each of which was used to compute transmissibility. The computed values ranged from 4,600 to 33,500 gallons per day per foot (gpd/ft). The largest transmissibility values were computed using early data from pumped wells and using data from observation wells. The smaller values were computed using late data from pumped wells. The smaller values are attributed to the influence of turbulent water flow which occurs in fractures adjacent to the well bore.

The most reliable transmissibility values are believed to be those determined using the observation well data and using early drawdown and recovery data which was collected prior to the time when the influence of turbulent flow became large. The average areal coefficient of transmissibility for the Coconino aquifer at Woody Mountain is estimated to be 30,000 gpd/ft.

COEFFICIENT OF STORAGE

The coefficient of storage of the Coconino aquifer at the Woody Mountain well field was computed from drawdown and recovery data using both the Theis and Jacob methods of analysis. Only data from observation wells were used in computations for coefficient of storage. The computed values ranged from 7 to 9 percent using data from WM-1 and from 8 to 9 percent using data from WM-5. It is believed that recharge during the pump test influenced water levels in the aquifer and that the coefficient of storage computed may be larger than the true value. The coefficient of storage for the Coconino aquifer at Woody Mountain is estimated to be 5 percent.

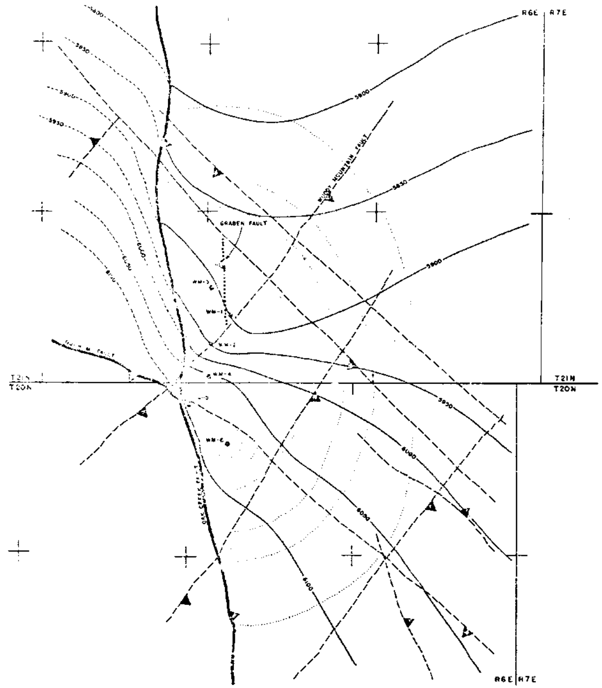


FIGURE 6

GROUNDWATER ELEVATION AND COMPUTED DRAWDOWN IN COCONINO-SUPAI AQUIFER

INFLUENCE OF INTERFERENCE

Interference in the Woody Mountain well field was measured directly in the observation wells and was found to be 13.1 feet in WM-1 and 12.5 feet in WM-5 at the end of the pumping phase of the test. Computations were made using coefficients of transmissibility of 30,000 gpd/ft and storage of 5 percent. The theoretical interference at WM-1 was computed to be 13.5 feet, and at WM-5 was computed to be 14.0 feet.

The similarity of measured and computed interference confirms the computed magnitude of the aquifer coefficients and also allows computation of interference effects of each Woody Mountain well at other wells. The results of theoretical computations, assuming all Woody Mountain wells were pumped are given in the following table.

PUMPING WELL	PUMPING RATE (GPM)	INTERFERENCE (IN FEET) AFTER 200 DAYS OF PUMPING					
		WM-1	WM-2	WM-3	WM-4	WM-5	WM-6
WM-1	280	--	3.8	3.8	2.4	1.5	0.9
WM-2	300	4.1	--	2.9	4.0	2.5	1.5
WM-3	400	5.3	3.9	--	2.3	1.5	0.6
WM-4	450	3.8	6.0	2.7	--	6.0	3.6
WM-5	400	2.1	3.3	1.5	5.3	--	3.9
WM-6	560	1.7	2.7	0.9	4.4	5.4	--
TOTAL	2390	17.0	19.7	11.8	18.4	16.9	10.5

Interference becomes greater with increased time of pumping, with higher rates of pumping, and with closeness of the interfering wells. Analysis of data for the Woody Mountain well field indicates that interference would be negligible between wells spaced at distances greater than 6,000 feet for pumping periods as long as two hundred days.

WATER LEVEL CONTOURS

The drawdown of water levels in the Woody Mountain well field after 208 days of pumpage is shown on Figure 6. Although the change in position of water level contours indicating maximum drawdown (Figure 6), as compared to the static water levels (Figure 5), is small, the pumping levels in the wells were significantly lower than predicted by theoretical computations. The difference between computed and measured pumping levels is believed to result chiefly from dewatering and from turbulent flow associated with fractures in the aquifer. The performance of the portion of the aquifer in which turbulent flow occurs cannot be assessed using presently available data.

Figure 6 shows the composite effect of the pumping wells on water levels in the Coconino aquifer at the conclusion of the pumping phase of the long term test. The positions of the drawdown lines were computed, and were verified by comparison with actual drawdown in the observation wells. Only the less steep portions of the cones of depression around the pumped wells were used to construct the composite cone.

It may be noted that the composite cone of depression shown on Figure 6 did not reach the groundwater divide which lies south of the Woody Mountain field. The total pumpage was also not sufficient to change the northeasterly pattern of groundwater flow away from the well field. These relations indicate that recharge to the Woody Mountain well field area is in excess of withdrawals.

INFLUENCE OF FAULTS AND FRACTURES

The influence of stratigraphic off-set on the Oak Creek Fault was anticipated to be evident in the analysis of the pumping test of the aquifer; however, no significant effects on water levels have been attributed to this off-set. Some increases in drawdown rate, which have been attributed to decrease in saturated thickness and hence to increased turbulent flow losses, may possibly be due to stratigraphic off-set.

Particular attention was directed to determining the effect of stratigraphic off-set along the Oak Creek Fault, or alternatively, to determining the effect of recharge into the well field from groundwater located in the highly permeable zone immediately adjacent to the Oak Creek Fault. Neither effect was evident in the water level data plots. An effect due to a partial negative boundary caused by stratigraphic off-set is, in theory, indicated by an abrupt steepening of the drawdown data on a Jacob plot. The point in time which the data plot steepens may be related mathematically to the distance from the well to the negative boundary. Distances to boundaries indicated by the Jacob plots did not correspond to distances to mapped faults, including the Oak Creek Fault. Conclusions reached are:

1. The steepening segments of water level data on the Jacob plots are probably due to turbulent flow in the parts of the aquifer near the pumping wells rather than to negative boundaries caused by stratigraphic off-set.

2. The effect of off-set on the Oak Creek Fault may be balanced by the recharge effect of groundwater located in the highly permeable zone adjacent to the Fault.

EXPANSION OF WOODY MOUNTAIN WELL FIELD

The locations of additional Woody Mountain wells are based on geologic data and prediction of intensely fractured areas where the Coconino aquifer is downthrown by the Oak Creek Fault and supplemental faults. These criteria indicate that potential well locations could be selected north or south of the existing Woody Mountain well field.

The selection of future well sites is also dependent upon hydrologic data to indicate locations where the water table is at an elevation which would permit utilization of maximum saturated thickness. Inspection of Figure 5 indicates that the water table is at a maximum elevation south of the existing Woody Mountain well field. Using both geologic and hydrologic data, the optimum locations for future wells are south of WM-6 at the locations shown on Figure 6.

CONCLUSIONS

The salient conclusions from the Woody Mountain water resources study are:

1. The average coefficients of transmissibility and of storage of the principal aquifer are approximately 30,000 gpd/ft and 0.05 respectively.

2. Drawdown in Woody Mountain wells in greater than predicted using theoretical calculations due to turbulent flow near the well bore in the fractured Coconino aquifer.

3. Computed interference between pumped wells in the Woody Mountain well field ranges from 10.5 feet to 19.7 feet after all wells are pumped continuously for 200 days. Interference would be negligible between wells spaced at distances greater than 6,000 feet for pumping periods as long as two hundred days.

4. The negative boundary effect of off-set on the Oak Creek Fault may be balanced by the recharge effect of groundwater located in the highly permeable fractured zone adjacent to the fault.

5. The quantity of recharge water to the Woody Mountain well field is greater than withdrawals from wells.

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