WATER RESOURCES OF THE INNER BASIN OF SAN FRANCISCO VOLCANO, COCONINO COUNTY, ARIZONA

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GENERAL

The highest peak of San Francisco Mountain rises to an altitude of 12,633 feet, approximately 6,000 feet above the surrounding plateau. The several high peaks are arranged in a horseshoe pattern which is open to the northeast and forms the periphery of the Inner Basin. The location of the Inner Basin is shown on Figure 1.

One of the earliest sources of municipal water for Flagstaff was from springs located in the Inner Basin which were first used by the City in 1899. From that date to the present the springs have been developed to supply significant amounts of water in the spring and summer of most years. Beginning in 1967, the groundwater supply from the Inner Basin was further developed with a drilling program which, by 1970, resulted in five producing wells. Figure 2 shows quantities consumed and sources of all municipal water for Flagstaff from 1949 through 1973.

HYDROGEOLOGIC FEATURES

The Inner Basin is a collapse and erosional feature in San Francisco Mountain,an extinct volcano of Late Cenozoic age, which lies approximately eight miles north of Flagstaff. The outcrop patterns of geologic units in the Inner Basin are shown in Figure 3.

The oldest rocks exposed in the Inner Basin are a sequence of andesitic pyroclastics, breccias, and lava flow rocks which are assigned to stage 1 of Robinson's (1913) second general period of eruption in the San Francisco Volcanic Field. The stage 1 rocks are believed to be moderately permeable, particularly where they have been fractured by structural movements. The younger volcanic rocks of stages 2, 3, 4, and 5 contain less pyroclastics and breccias and are believed to have a lower permeability. Intrusive igneous rocks are well exposed in the Core Ridge, which is believed to be the principal vent area for the volcano. Other intrusive rocks occur as dikes which crop out in the walls of the Inner Basin. Intrusive igneous rocks and stage 2, 3, 4, and 5 lava flow rocks are believed to be aquitards and provide perching conditions for local perched groundwater reservoirs which occur in the walls of the Inner Basin.

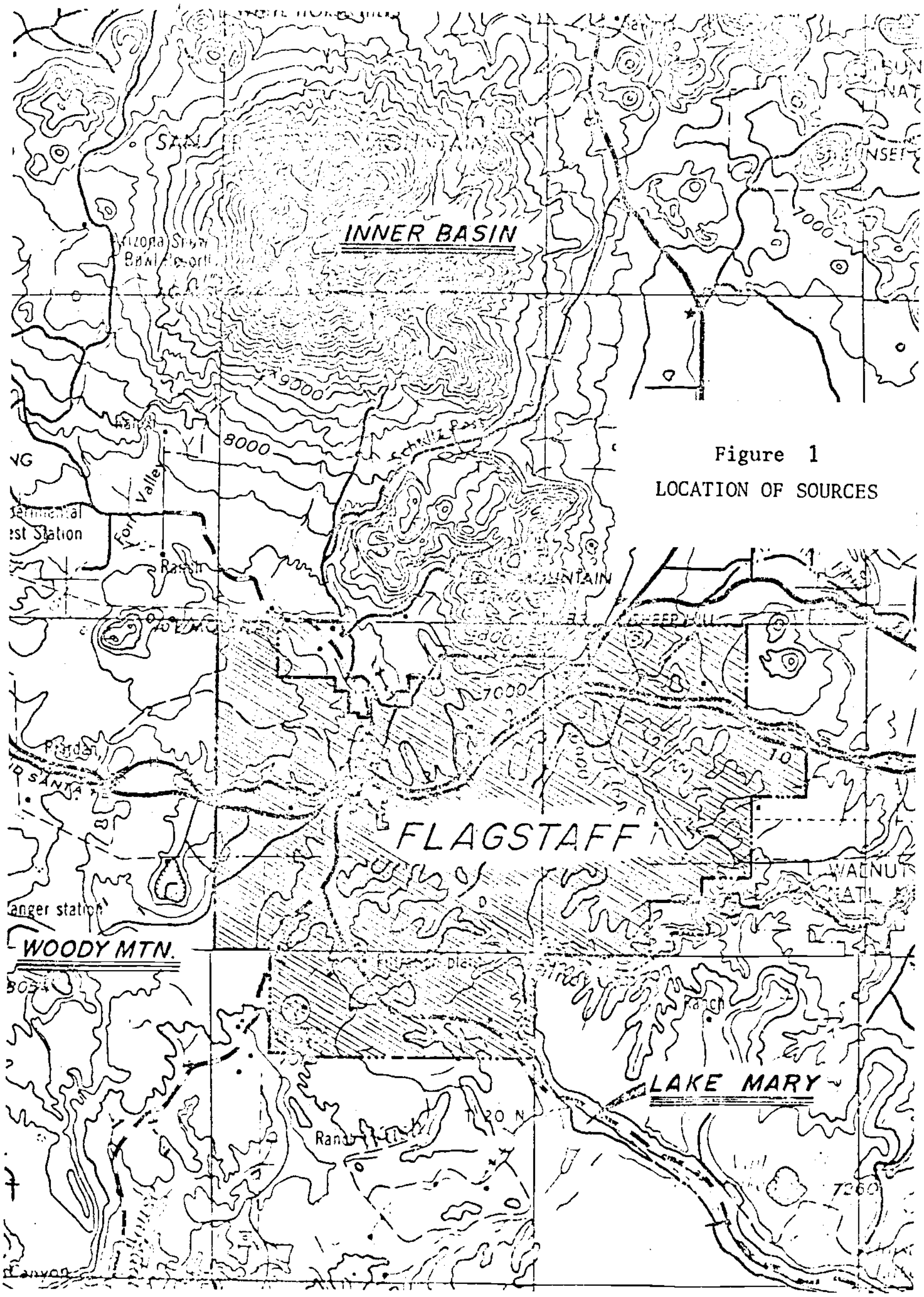


Figure 1
LOCATION OF SOURCES

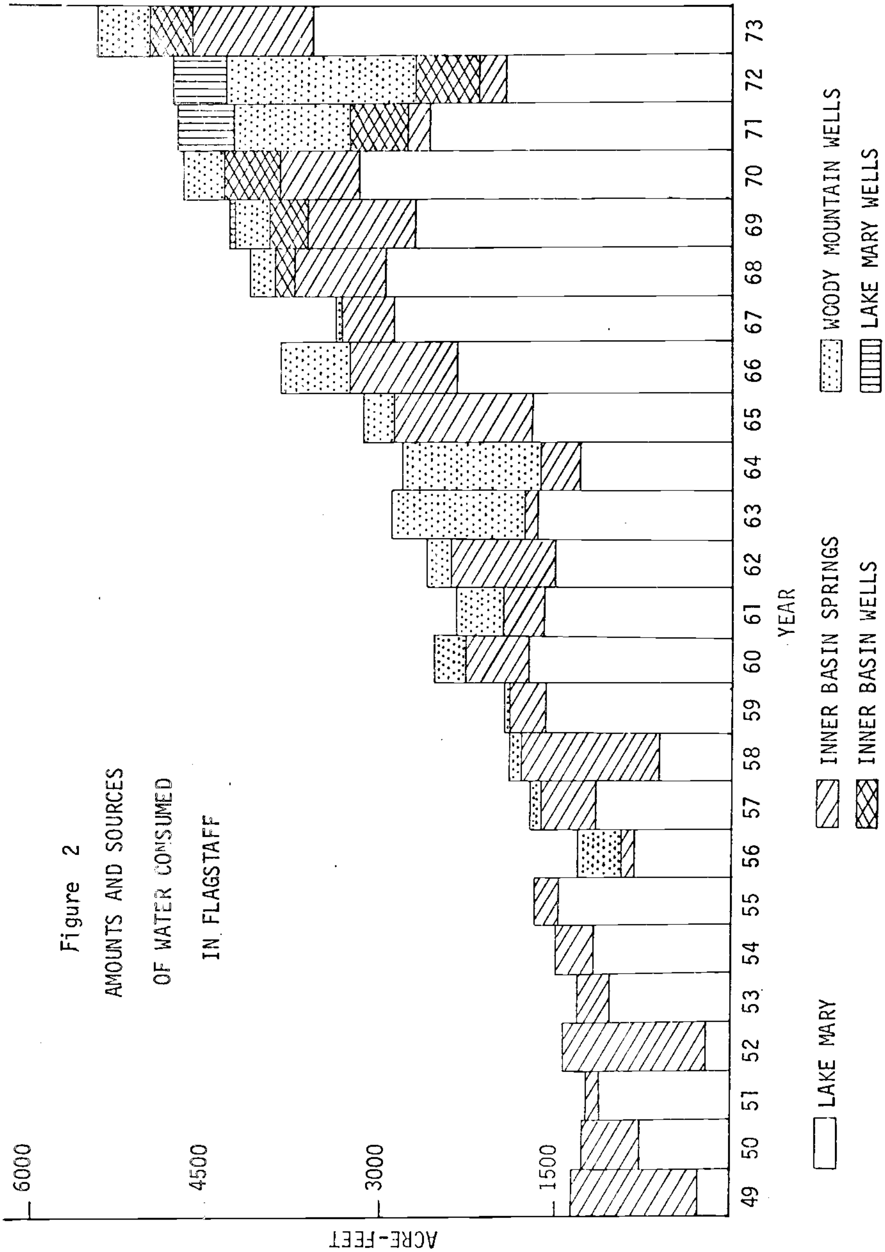
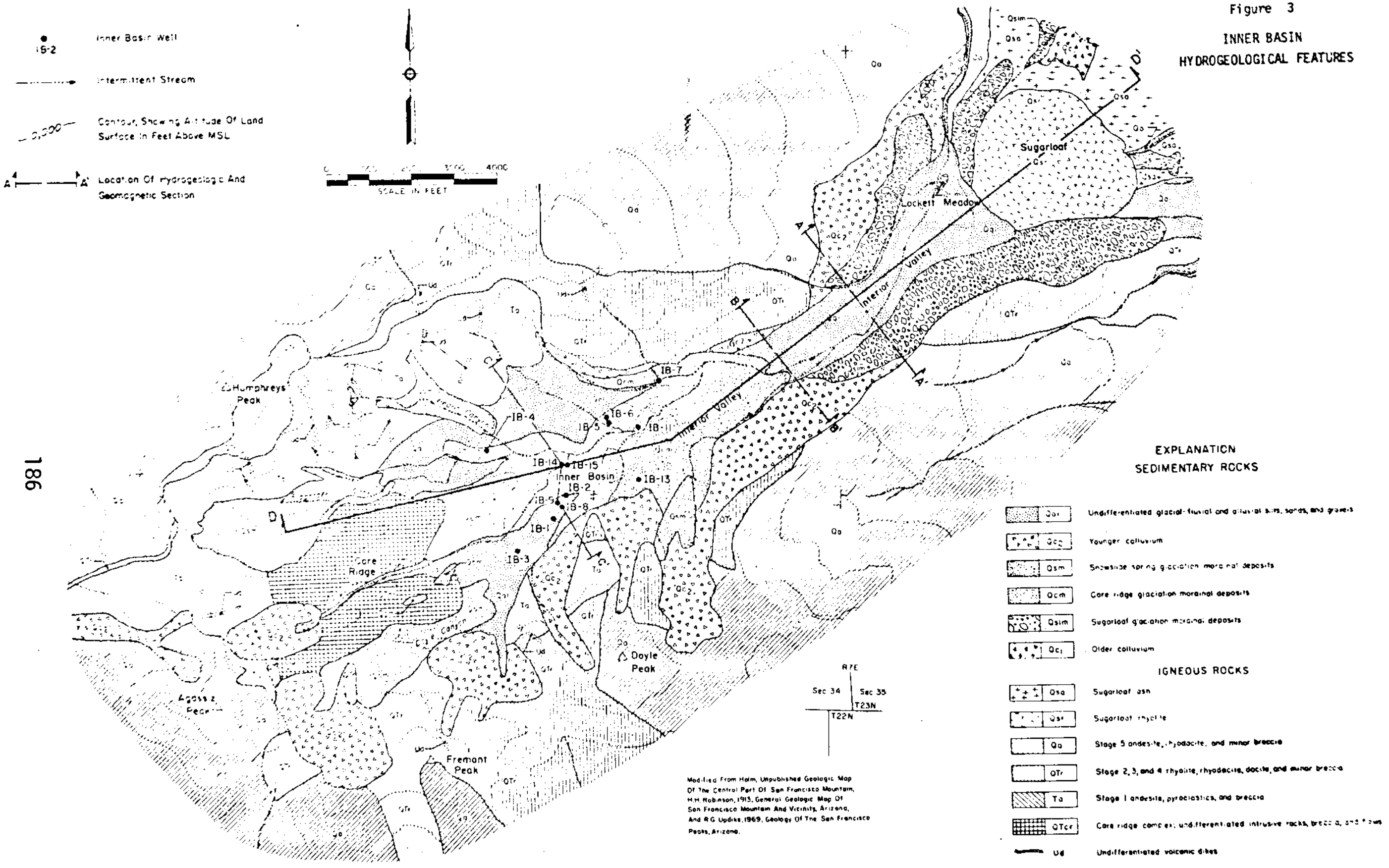


Figure 2
AMOUNTS AND SOURCES
OF WATER CONSUMED
IN FLAGSTAFF

Figure 3

INNER BASIN
HYDROGEOLOGICAL FEATURES



Modified From Holm, Unpublished Geologic Map Of The Central Part Of San Francisco Mountain, H.H. Robinson, 1913, General Geologic Map Of San Francisco Mountain And Vicinity, Arizona, And R.G. Updike, 1969, Geology Of The San Francisco Peaks, Arizona.

Unconsolidated rocks in the Inner Basin comprise colluvial deposits which mantle the inner and outer slopes of San Francisco Mountain, and glacial morainal and alluvial deposits which crop out on the floor and are interbedded in the subsurface of the basin. The unconsolidated rocks range in size from clay or silt to boulders, and are poorly sorted. The colluvial rocks have a high porosity and permeability and are efficient infiltration media. Morainal deposits are poorly permeable and where they occur above the water table they provide perching conditions for local perched groundwater reservoirs. Where morainal deposits occur below the water table they retard water movement and cause artesian conditions where they overlie permeable alluvial rocks. Alluvial deposits are moderately permeable and comprise the principal aquifer which extends to depths greater than 500 feet in the Inner Basin. Figures 4 and 5 are hydrogeologic sections of the Inner Basin and show subsurface hydrogeologic relations.

Holm (1974) suggests that the Inner Basin and Interior Valley may be the modern expression of a graben which formed during late stages of volcanic activity in the San Francisco Volcano. The locations of faults which are inferred to bound the graben are uncertain as those faults are covered by colluvial, glacial, and alluvial rocks. Stage 1 rocks which underlie the alluvial aquifer in the Inner Basin and Interior Valley are believed to be intensely fractured in the graben and may be a potential aquifer for future Inner Basin wells.

INNER BASIN SPRINGS

Between 1899 and 1961 seven large springs and several small springs were developed to produce from perched groundwater reservoirs for the Flagstaff systems. The springs were developed as infiltration galleries or combinations of infiltration galleries and inlet boxes.

Discharge from Inner Basin springs is large during the March-July period which is the period during and shortly after the snowmelt season. Discharge is small during the November-February period when the perched reservoirs are largely depleted. Flow from Inner Basin springs during 1973 is given in Figure 6.

INNER BASIN WELL FIELD

Between 1966 and 1971 thirteen cased wells numbered IB-1, IB-2, IB-3, IB-4, IB-5, IB-6, IB-7, IB-8, IB-9, IB-11, IB-13, IB-14, and IB-15 were constructed in the Inner Basin. Eight were exploration holes. Five wells (IB-2, IB-6, IB-9, IB-11, IB-14) range in depth from 248 to 502 feet and were constructed to produce water for the Flagstaff system. Of these five, one (IB-11) is a flowing artesian well, two (IB-9 and IB-14) are equipped with pumps and engines, and two (IB-2 and IB-6)

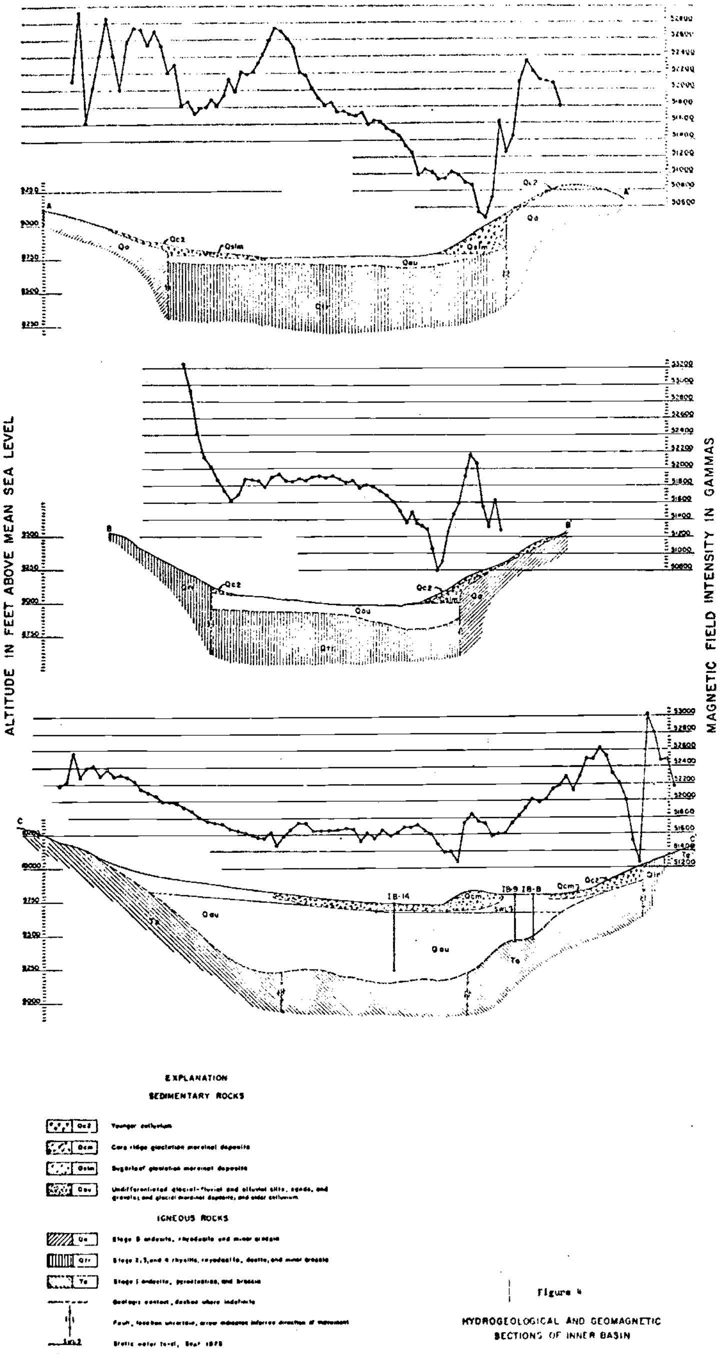


Figure 4

HYDROGEOLOGICAL AND GEOMAGNETIC SECTIONS OF INNER BASIN

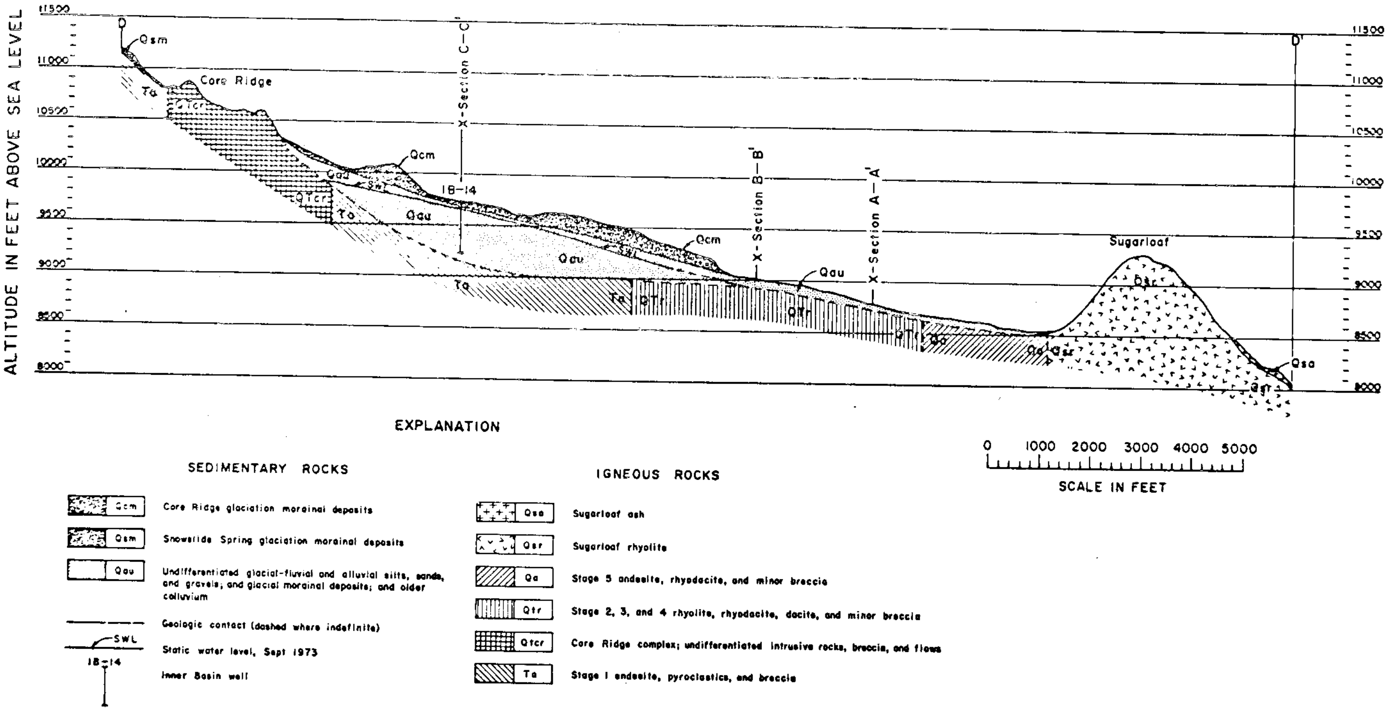


Figure 5

HYDROGEOLOGIC SECTION D-D'
INNER BASIN AND INTERIOR VALLEY

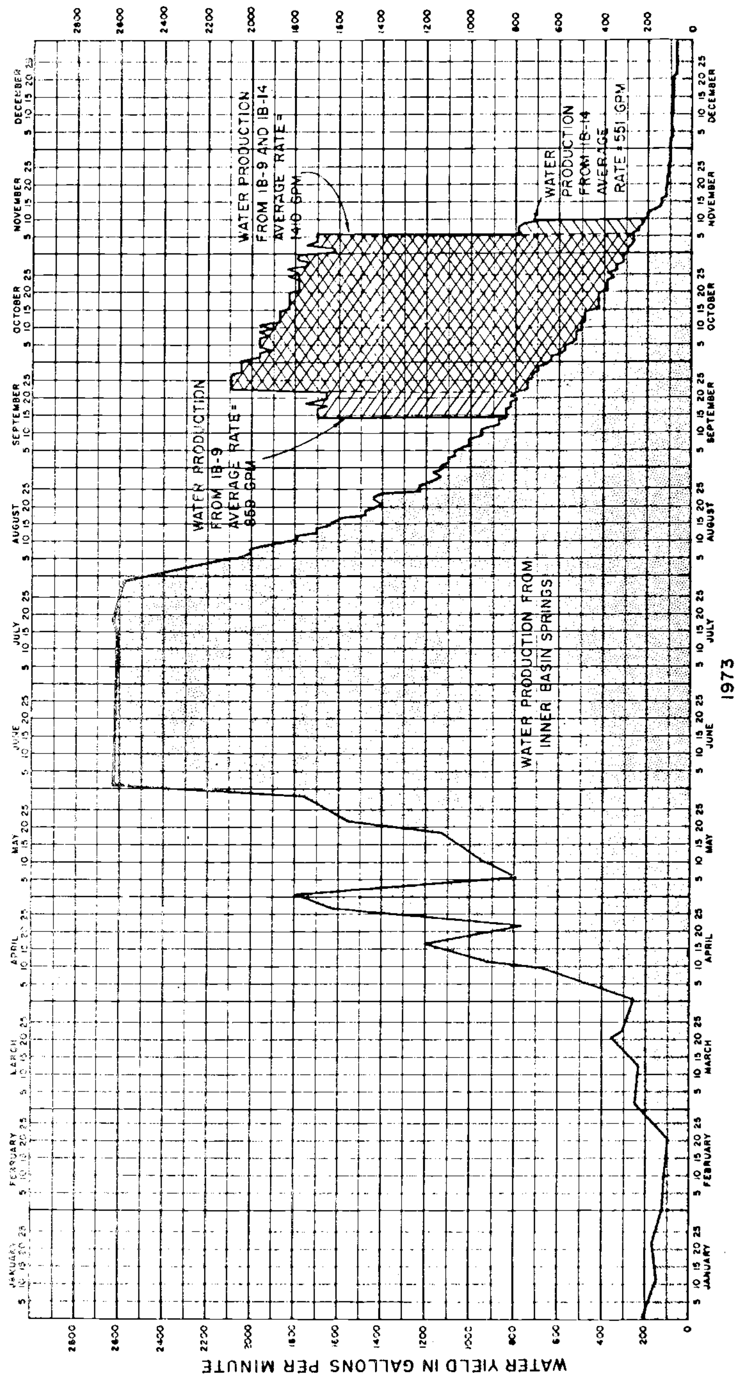


Figure 6

HYDROGRAPH OF PRODUCTION FROM INNER BASIN SPRINGS AND WELLS are not presently (1974) equipped. The locations of Inner Basin wells are shown on Figure 3.

Inner Basin wells have been used in all summers of the past eight years when municipal water demand was high and when flow from Inner Basin springs was low. The season in which water can be produced from Inner Basin wells is limited due to difficult access. Roads to the Inner Basin are usually closed by snow in October or November and remain closed until mid May or early June. Discharge from Inner Basin wells during 1973 is shown in Figure 6.

LONG-TERM PUMP TEST

A long-term test of the Inner Basin well field was begun on September 15, 1973 after pre-test water levels and flow from springs had been monitored and recorded. The test began with pumpage of IB-9 at a rate of 859 gpm (gallons per minute). After water level response was monitored in the other wells, IB-14 was placed into production at a rate of 551 gpm on September 22. Except for artesian flow from IB-11 which ranged from 230 gpm early in the test to 20 gpm at the end of the recovery phase, the remaining wells were used solely as observation wells to monitor water level response to the pumpage of IB-9 and IB-14. During the pumping phase of the test, measurements were made of discharge from wells, discharge from springs, water level decline, water temperature, and conductance.

The recovery phase for IB-9 began on November 6, 1973 when the diesel engine, power supply for that well, failed. Water level recovery measurements for IB-14 began on November 10. Recovery measurements continued through November 18, 1973, when roads to the Inner Basin were closed by snowfall. A summary of water level drawdown 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 coefficients of transmissibility and storage of the aquifer, and interference effects. During both the drawdown and recovery periods water level data showed the influence of boundaries and of leakage from the perched reservoir into the principal aquifer and from the principal aquifer into the underlying volcanic rocks.

Inspection of water level data from IB-4 did not indicate a discernible response to pumpage from wells. Data from IB-4 were used solely to determine rates of leakage from the principal aquifer.

Water level data from IB-11 were inspected for use in computing aquifer parameters and boundary effects. Because the portion of water level decline due to artesian discharge could not be separated from that decline due to pumpage from wells, water level data from IB-11 were not used.

Table 1

SUMMARY OF DATA FROM PUMP TEST OF INNER BASIN WELL FIELD (1973)

Well No.	Date Turned On	Static Water Level (feet) (a)	Well Dis-charge (gpm)	Water Level Decline After Pumping Started			Water Temp (°F)	Specific Conduc-tance (Micro-mhos)	Water Level Recovery After Pumping Stopped (b)		
				One Hour (feet)	One Day (feet)	End of Test 52 Days (feet)			Six Hours (feet)	One Day (feet)	End of Test (feet)
IB-1	Not pumped	$\frac{148.8}{9685.1}$	0	<0.1	1.0	51	---	---	-1.0	-1.0	-1
IB-2	Not pumped	$\frac{124.1}{9649.8}$	0	1.0	6.0	92	---	---	3.0	7.0	24
IB-4	Not pumped	$\frac{94.2}{9848.8}$	0	<0.1	0.1	5	---	---	<0.1	<0.1	-1
IB-6	Not pumped	$\frac{139.9}{9498.1}$	0	<0.1	0.1	11	---	---	-0.2	-0.5	-2
IB-8	Not pumped	$\frac{141.8}{9649.7}$	0	2.0	7.0	93	---	---	3.0	7.0	24
IB-9	Sept. 15, 1973	$\frac{143.2}{9649.7}$	859	9.0	13.0	102	39	69	14.0	18.0	34
IB-11	Not pumped (c)	Flowing	130 (d)	---	---	---	38	78	---	---	---
IB-14	Sept. 22, 1973	$\frac{70.9}{9659.1}$	551	8.0	12.0	152	38	75	49.0	52.0	64

(a) $\frac{\text{Water level in feet below land surface}}{\text{Altitude of water level in feet above sea level}}$

(b) Negative sign (-) indicates continued drawdown during recovery phase of test

(c) Uncontrolled - discharge by artesian flow

(d) Estimated average artesian discharge during pumping phase of test

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 2,900 to 328,000 gpd/ft (gallons per day per foot). The early drawdown and recovery data indicated transmissibility values which are larger than those indicated by later data. The largest values are attributed to the influence of high permeability paths provided by interbeds of alluvial deposits between wells. The smallest values are attributed to the influence of boundaries.

The most reliable transmissibility values are believed to be those determined using the latest drawdown and recovery data collected prior to the time when the influence of boundaries became significant.

COEFFICIENT OF STORAGE

Coefficient of storage of the principal aquifer in the Inner Basin 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 0.2 to 22 percent using data from IB-1, IB-2, IB-6, IB-8, and IB-14.

Early drawdown and recovery data, which indicated large transmissibility values, usually indicated the smallest coefficient of storage values. Late data, which were influenced by boundaries, also indicated small coefficient of storage values. Drawdown data which were judged most reliable for computing transmissibility were also believed to be most reliable for use in computing coefficient of storage.

DISCUSSION AND SUMMARY

The areal distribution of aquifer parameters indicates that average values of coefficient of transmissibility and storage are greatest in the southwestern part of the aquifer in the vicinity of wells IB-1, IB-2, IB-8, and IB-9 and are less in the central part in the vicinity of IB-6 and IB-14. Average transmissibility and coefficient of storage in the northwestern part of the aquifer are not known; however, no water level decline in IB-4 in response to pumpage of IB-9 and IB-14 indicates that the transmissibility of the aquifer near IB-4 is small. These areal variations of aquifer parameters are interpreted to indicate that the abundance of interbeds of glacial morainal deposits is less in the southeastern part and is greater in the central and northwestern part of the aquifer.

Average coefficients of transmissibility and storage of the principal aquifer are estimated to be 14,000 gpd/ft and 0.08 respectively.

INFLUENCE OF BOUNDARIES

The response of water levels to pumpage from wells in the Inner Basin aquifer is influenced by aquifer boundaries where the alluvial rocks abut less permeable volcanic rocks. Projected locations of the Inner Basin aquifer boundaries are shown on Figure 7.

In the analysis of drawdown for the principal aquifer, image wells for IB-9 and IB-14 were located across the southeast, southwest, and northwest boundaries. Analysis using the theory of images indicated:

1) The influence of the southeast boundary was an increased rate of drawdown in the southeastern part of the aquifer and increased rates of drawdown in wells IB-1, IB-2, IB-8, IB-9, and IB-14.

2) The duration of the Inner Basin aquifer test was not sufficient for the southwest aquifer boundary to influence rates of drawdown. With longer periods of pumping this boundary would cause rates of drawdown in the southwestern part of the aquifer to increase.

3) The northwest boundary caused an increased rate of drawdown in the northwestern margin of the aquifer but did not influence water levels in wells. With longer periods of pumping the influence of this boundary would cause increased rates of drawdown in IB-4, IB-6, and IB-14.

OCCURRENCE AND FLOW PATTERN

The average quantity of water which enters the Inner Basin aquifer each year as recharge is equal to the average amount of water which leaves the Inner Basin as discharge from springs and wells, from evapotranspiration and sublimation, and from leakage.

INFLOW

The amount of water available for recharge to the Inner Basin aquifer system is equal to the average annual precipitation in the watershed area. The area of the Inner Basin watershed is 2,420 acres and is shown on Figure 7. Average annual precipitation for the Inner Basin watershed is estimated to be 36.4 inches, based on the 1957-1973 average; half of this precipitation occurs as winter snowfall. Potential recharge is approximately 7,350 acre-feet per year. Recharge is believed to occur chiefly from infiltration from snowmelt.

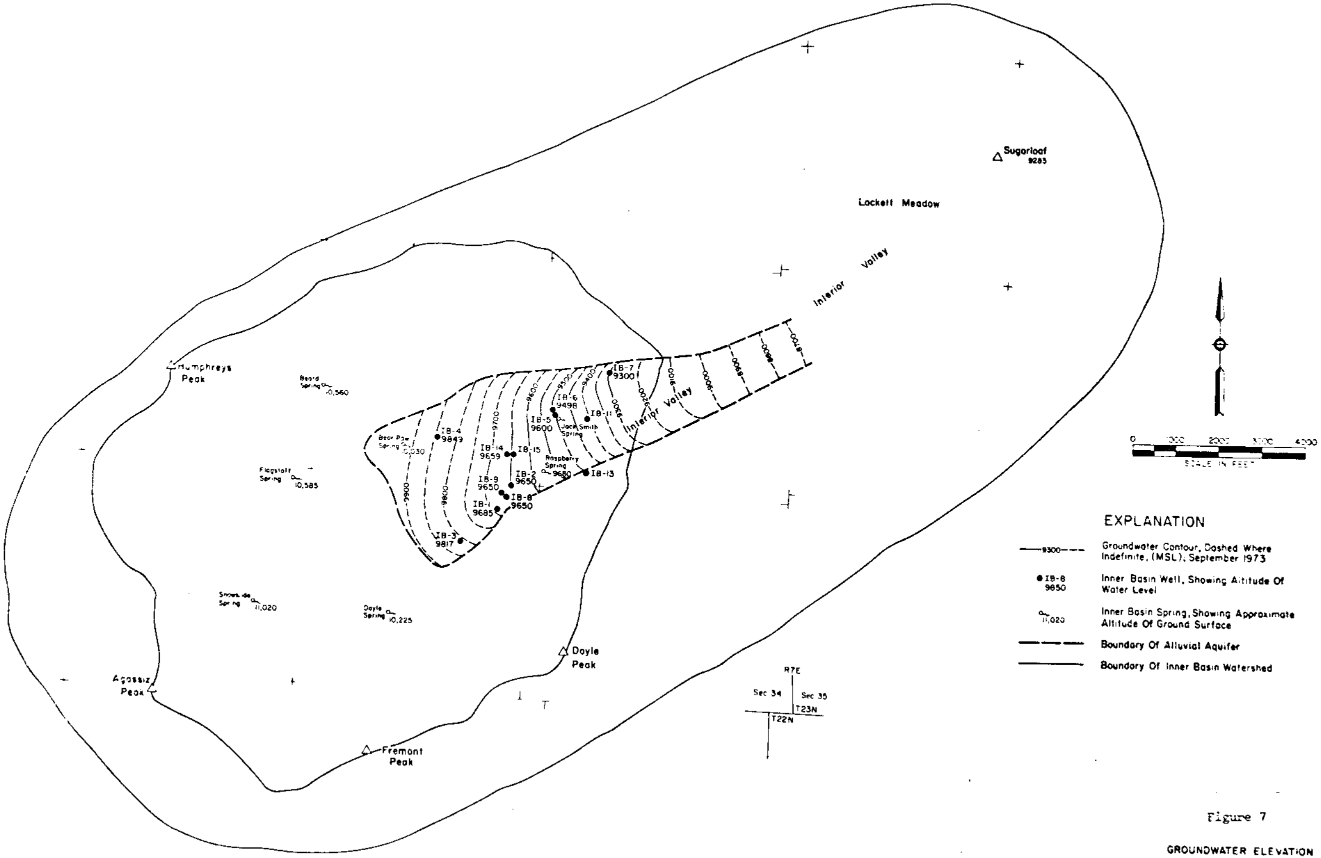


Figure 7

GROUNDWATER ELEVATION IN ALLUVIAL AQUIFER

CIRCULATION AND STORAGE

Groundwater contours of the static water level conditions in the principal aquifer are shown on Figure 7. The general pattern of groundwater flow is from recharge areas at the margins of the aquifer toward natural discharge areas below and northeast of the well field.

Groundwater storage in the principal aquifer is restricted because the areal extent and the depth of the aquifer are limited,because the aquifer media are poorly sorted, and because the interbedded morainal deposits yield only meager amounts of water. The average quantity of recoverable water in the principal aquifer was estimated using computed specific yield and estimated aquifer volume to be 8,000 acre-feet. Additional quantities of recoverable water may occur in fractured stage 1 volcanic rocks below the Inner Basin and Interior Valley.

DISCHARGE

Outflow from the Inner Basin comprises evaporation, transpiration, sublimation from the winter snowpack,discharge from springs and wells, and leakage from the principal aquifer to the underlying volcanics. Discharge from evaporation has not been estimated but is believed to be large. Outflow via transpiration and sublimation is estimated from analysis of data in an unpublished report by the U. S. Bureau of Reclamation to be 3,200 acre-feet per year. Average discharge from springs from 1951 through 1973 was 445 acre-feet per year. Average discharge from wells from 1969 through 1973 was 440 acre-feet per year. Leakage from the principal aquifer into the underlying fractured volcanic rocks was estimated from average rate of water level decline in wells which are not influenced by pumpage of other Inner Basin wells, and from estimates of aquifer volume and specific yield and is approximately 1,150 acre-feet. Estimated inflow and outflow are summarized below:

Average Annual Inflow from Precipitation = 7,350 acre-feet

Average Annual Outflow

From Wells = 440 acre-feet

From Springs = 445 acre-feet

From Transpiration and Sublimation = 3,200 acre-feet

Leakage from Principal Aquifer = 1,150 acre-feet

Evaporation = Unknown

Average Annual Outflow (incomplete) = 5,235 acre-feet

The difference between the inflow and outflow values given above is 2,115 acre-feet and is approximately equal to evaporation.

WATER LEVEL CONTOURS

Figure 8 shows the composite effect of the pumping wells and of boundaries on water levels in the principal aquifer at the conclusion of the pumping phase of the test. The positions of the drawdown lines were computed using estimated average aquifer parameters of 14,000 gpd/ft and 0.08 for coefficients of transmissibility and storage.

INFLUENCE OF PUMPAGE FROM WELLS ON DISCHARGE FROM SPRINGS

Analysis of the aquifer systems in the Inner Basin indicates that springs issue from perched reservoirs which occur in the walls of the Inner Basin, beyond the margins of the principal aquifer, or issue from perched reservoirs which lie above the water table in the principal aquifer; hence, rates of leakage are not increased by a lowering of water levels in the principal aquifer. This conclusion is supported by records of discharge from springs in years prior to development of wells and in years when Inner Basin wells were pumped. Inspection of Figure 6 indicates that the decline in rate of discharge from springs was not accelerated through the period in which the Inner Basin wells were pumped.

CONCLUSIONS

The salient conclusions from the Inner Basin water resources study are:

1) The average coefficients of transmissibility and of storage of the principal aquifer are approximately 14,000 gpd/ft and 0.08 respectively.

2) The influence of aquifer boundaries increased rates of drawdown of water levels in the Inner Basin well field.

3) Inner Basin springs issue from perched reservoirs. Pumpage of Inner Basin wells does not influence discharge from Inner Basin springs.

4) The quantity of recharge water to the Inner Basin aquifer system is greater than the average yield from springs and wells. The average quantity of water in storage in the principal aquifer is 8,000 acre-feet.

5) A large amount of water is lost from the Inner Basin aquifer system via leakage into underlying fractured volcanic rocks. A part of the water lost via leakage could be intercepted by pumpage from a well constructed in the Interior Valley.

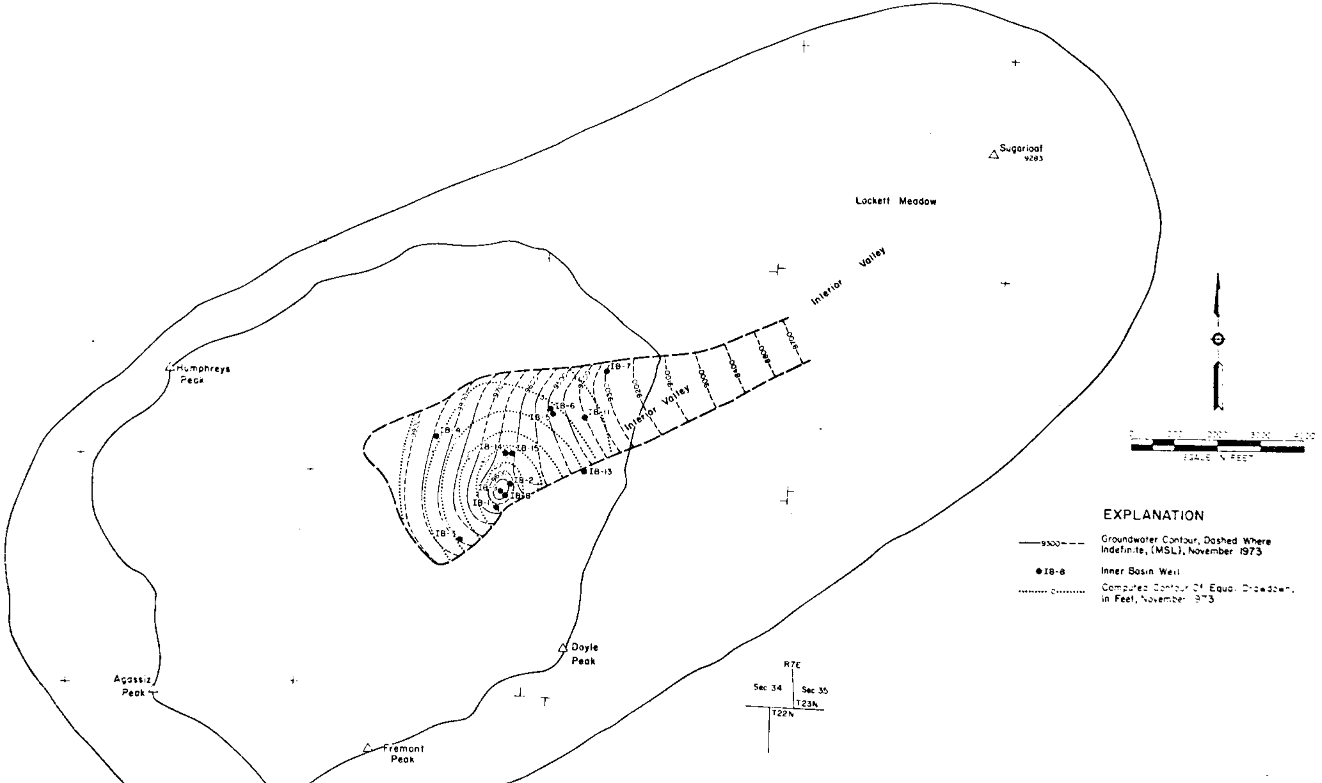


Figure 8

GROUNDWATER ALTITUDE AND COMPUTED DRAWDOWN CONTOURS, ALLUVIAL AQUIFER

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