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The Relationship of the Annual Snowpack to the Water Yield from the Inner Basin of the San Francisco Peaks, Arizona

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ABSTRACT

During the period 1970-1991 the glaciofluvial deposits in the Inner Basin of the San Francisco Peaks, Arizona, have produced as much as 28% and as little as 2% of the annual water supply of the city of Flagstaff. This water is produced from wells and developed springs. Regression analysis indicates that water production shows a good correlation with maximum snow water equivalent, especially the production of the springs (r = 0.92). However, scheduled snow surveys may miss the maximum snow water equivalent measurement. The installation of a Snotel telemetry site would produce a daily record, thus insuring this maximum measurement. The Snotel data should contribute to the development of better water production forecasts.

INTRODUCTION

Water for the city of Flagstaff, Arizona, comes from three major sources - (1) surface water impounded by upper and lower Lake Mary, (2) ground water pumped from Lake Mary and Woody Mountain well fields, and (3) springs and wells located in the Inner Basin of San Francisco Mountain. This study concentrates on the Inner Basin water resource.

San Francisco Mountain stands as a massive isolated landform known locally as the San Francisco Peaks or simply "The Peaks." It is an important feature both from the aesthetic and the hydrologic viewpoint. It is, in fact, an "oasis" where precipitation and snowpack accumulation are much greater than anywhere else in the region. It is for this reason that the Inner Basin water resource is so significant.

Geologic History

The geology of the San Franciso Peaks is summarized by Chronic, 1983, and Breed, 1989. The San Francisco Peaks are the remains of a composite volcano located just north of the city of Flagstaff. This volcano is approximately 1.8 million years old and was active until 200,000 years ago. Eruptions produced lava flows and pyroclastics composed primarily of andesite, dacite, rhyolite, and basalt. It is estimated that the mountain once reached an elevation of 15,600 feet (4755 meters). The configuration of the mountain indicates that an eruption may have blown off the top and one side thus creating an interior valley opening to the northeast. The mountain was subjected to three known periods of glaciation, the last of which occured 10,000 to 12,000 years ago. The interior valley or Inner Basin is filled with colluvium and glaciofluvial deposits in the form of moraines and outwash. These deposits generally range from 100 feet (30 meters) to 500 feet (150 meters) in thickness (Harshbarger, 1974).

Present Day Features

San Francisco Mountain today is comprised of a rim surrounding three sides of the caldera, the Inner Basin. Most of the rim is steep sided and is in excess of 11,000 feet (3353 meters) elevation. The highest peaks along the rim are Mt. Humphreys, the highest point in Arizona at 12,633 feet (3850 meters), and Mt. Agassiz, 12,356 feet (3766 meters). The mountain rises about 6000 feet (1830 meters) above the city of Flagstaff (Harshbarger, 1974). The floor of the Inner Basin slopes downward to the northeast and generally ranges between 8500 feet (2590 meters) and 10,400 feet (3170 meters) elevation (Harshbarger, 1974; Chronic, 1983; Breed, 1989).

Precipitation

The elevation and relief of the San Francisco Peaks creates orographic lifting of air masses which produces significant precipitation, half of which falls as snow (Bureau of Reclamation, 1972). The magnitude of the orographic effect is reflected in the differences in average annual precipitation for stations near the base of the mountain versus stations within the Inner Basin. Flagstaff and Fort Valley receive an average annual precipitation in the range of 22 to 23 inches (559 to 584 millimeters). Two standard gages located in the Inner Basin show an average annual precipitation ranging from about 37 inches (940 millimeters) at the Snowslide Canyon site to 43 inches (1092 millimeters) at the Bearpaw site. These Inner Basin gages have recorded as little as 23 inches (584 millimeters) and as much as 68 inches (1727 millimeters) in a year over the 30 year period 1961 - 1990. About 15% of the annual precipitation falls during the October - November period and about 40% falls from December through March. The summer thunderstorm season, July - September, accounts for about 31% of the annual moisture (Table 1).

Water Resources

The city of Flagstaff acquired water rights on the San Francisco Peaks as early as the 1890's (Martin, 1969; Harshbarger, 1974). Water was transported from springs in the Inner Basin by an 8 inch (203 millimeter) pipe line. In 1926-27, a 14 inch (356 millimeter) replacement pipe was installed. From 1900 to 1941 this was the sole source of municipal water for Flagstaff. Lake Mary was constructed south of Flagstaff and became a source of water for the city starting in 1949. The Woody Mountain well field was developed and has produced water since 1956. Wells were then drilled in the Inner Basin in the 1960's and early 1970's (Akers, 1964; Bureau of Reclamation, 1968; Harshbarger, 1974). The first production figures for these wells were reported in 1966. As wells were drilled production increased until

Table 1. Average annual precipitation in the San Francisco Peaks area and percent of annual precipitation for selected periods of the year.

Stations	Ave. Annual* Prec. in.	mm	Percent of Annual Precipitation Oct-Nov	Dec-Mar	Apr-Jun	Jul-Sep
Flagstaff	22.87	581	16%	40%	11%	33%
Fort Valley	22.15	563	13%	38%	12%	37%
Bearpaw	43.03	1093	16%	43%	12%	29%
Snowslide Canyon	36.87	936	15%	40%	12%	33%

*Based on the 30 year period 1961-1990.

a generally stable level of production was reached in 1970. Three production wells and seven developed springs (Jack Smith, Snowslide, Doyle, Raspberry, Flagstaff, Beard, and Bearpaw) now produce water that is piped to Flagstaff.

Average annual Inner Basin water production from 1970 to 1991 was about 331.8 million gallons (125.6 hectare-meters), usually produced between April and December. During this 22 year period the Inner Basin annual production ranged from a high of 580 million gallons (220 hectare-meters) in 1980 to a low of 56.4 million gallons (21 hectare-meters) in 1991. The 1980 production provided 28% of the total water used by the city of Flagstaff while the 1991 production provided only 2% of the total. On the average, the Inner Basin produced 16% of the water used annually by the city.

Other wells have been drilled on the flanks of the mountain but they have only encountered seasonal water in lava and cinders. A well was drilled to 1200 feet (366 meters) in Hart Prairie near the Snow Bowl ski area on the western flank but the ski area still hauls its water from Flagstaff. Although seasonal streams may flow during periods of heavy rain or snowmelt, no perennial streams flow due to the permeability of the mountain (Martin, 1969; Cline, 1989). Snowmelt and rain infiltrate rapidly. Many springs flow but the resulting streams only run a short distance before going underground. The groundwater resource is correlated to the current year's precipitation, especially the snowpack (Martin, 1969). The success of the Inner Basin wells is tied to the glacial deposits.

Snowpack

Four snow courses are measured on the mountain. Snow Bowl #1 snow course was established on the ski area in 1961 at an elevation of 9960 feet (3056 meters), followed by Snow Bowl #2 in 1964 at an elevation of 11,340 feet (3456 meters). Three more snow courses were established in 1968 in the Inner Basin. These were Snowslide Canyon at 9750 feet (2972 meters), Bearpaw at 10,100 feet (3078), and Doyle Saddle at 10,250 feet (3124 meters). Doyle Saddle was discontinued in 1973. Snowslide Canyon and Bearpaw are in close proximity to the Inner Basin wells and springs.

Twenty-five years of record for Snowslide Canyon shows an average snow water equivalent (SWE) of 12.8 inches (325 millimeters) on March 1 and 15.5 inches (394 millimeters) on April 1. Average SWE for Bearpaw is 17.9 inches (455 millimeters) on March 1 and 21.9 inches (556 millimeters) on April 1. Even though the April 1 average is the larger, in some years the March 1 SWE exceeds that of April 1. It is probable that the actual maximum SWE occurs on some date other than March 1 or April 1.

Analysis

An analysis of the relationship between the SWE on the Inner Basin snow courses and the water production from the springs and wells was made for the 22 year period 1970 - 1991. Water production figures were provided by the city of Flagstaff. The total production, springs contribution, and pumped well volumes for each year were plotted (Figure 1). Absolute production is limited by the capacity of the pipeline. A flow of 2.5 million gallons per day (0.94 hectare-meters) can be maintained in spring and early summer and a flow of 1.05 million gallons per day (0.40 hectare-meters) is usually attainable during drier years and in late season. Production is also limited by the amount of water actually available and the management decisions of how often to run the well pumps. The flow from the springs, being primarily gravity flow, is cheaper to produce than well discharges which require fuel to run the pumps. When the flow of the springs is large, the well production tends to taper off as a cost reduction measure. When the flow is low, more well pumping is done to maintain volume production. When water reserves becomes depleted from both sources, total production decreases.

The relationship between the snowpack and water production was examined by plotting the SWE on the Snowslide Canyon and Bearpaw snow courses for March 1 and April 1 and comparing these graphs to the total Inner Basin production. The relationship was encouraging as illustrated in Figure 2 which used the March 1 Bearpaw data. Since total water production included the pumped well volumes and these volumes were subject to human control, another comparison was made between the snow course data and only the flow of the springs. This would show a more natural response to the water contribution of the snowpack. A very strong relationship existed between Bearpaw March 1 SWE and the flow of the springs over the 22 year period (Figure 3). It appeared that the snowpack was not only highly correlated to the production of the springs but that the response was immediate on an annual basis with very little carryover. This carryover aspect will be the subject of further investigation.

After the graphs were reviewed, the March 1 and April 1 SWE for Snowslide Canyon and Bearpaw were compared to the total Inner Basin water production and the springs production using linear regression analysis (Table 2). A further linear regression was run using the maximum SWE regardless of whether the measurement was on March 1 or April 1 (Table 2). The analysis of the total production produced correlation coefficients that ranged from 0.69 using Snowslide Canyon April 1 data to 0.79 using Bearpaw March 1 data. The analysis of the springs production produced correlation coefficients that

Figure 1. Total water production from the Inner Basin of the San Francisco Peaks, Arizona, 1970 to 1991.

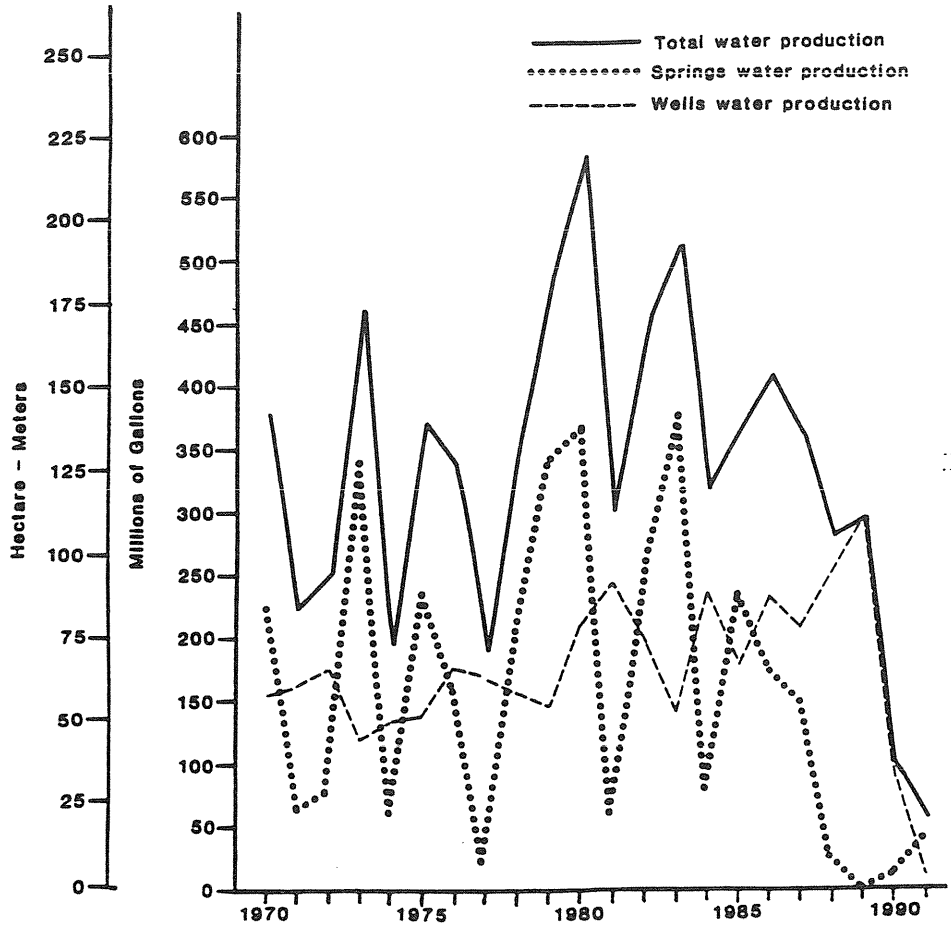

Figure 2. Total water production from the Inner Basin of the San Francisco Peaks, Arizona, compared to the March 1 snow water equivalent on the Bearpaw snow course, 1970 to 1991.

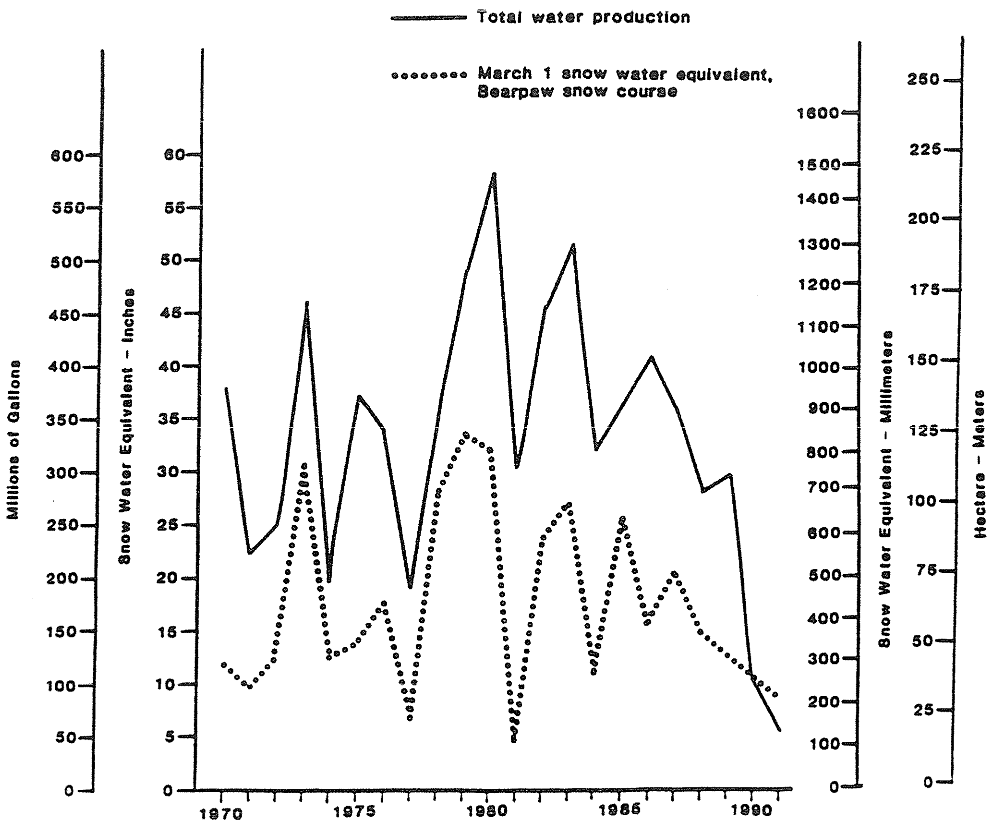

Figure 3. Water production from developed springs in the Inner Basin of the San Francisco Peaks, Arizona, compared to the March 1 snow water equivalent on the Bearpaw snow course, 1970 to 1991.

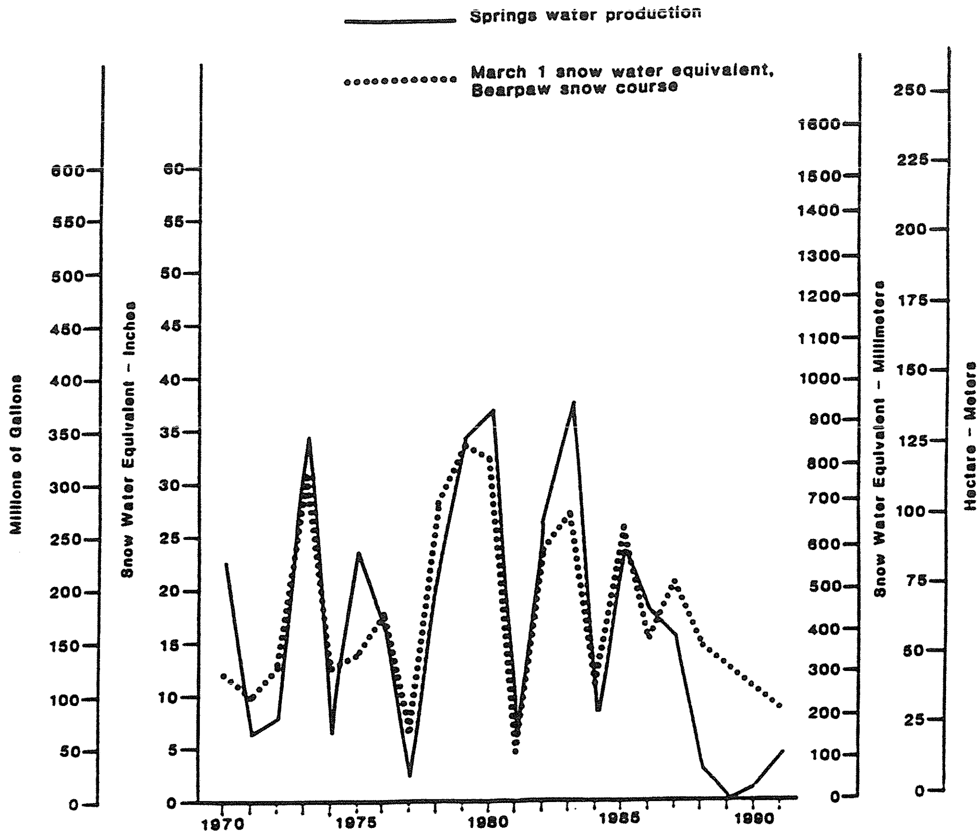

Table 2. Correlation coefficients from linear regression comparing Bearpaw and Snowslide Canyon snow water equivalent (SWE) to the Inner Basin water production.

	Total Production	Springs Production
Bearpaw		
March 1 SWE	0.79	0.86
April 1 SWE	0.76	0.91
Maximum SWE	0.77	0.92
Snowslide Canyon		
March 1 SWE	0.72	0.79
April 1 SWE	0.69	0.86
Maximum SWE	0.71	0.87

ranged from 0.79 using Snowslide Canyon March 1 data to 0.92 using Bearpaw maximum SWE data.

The best equations produced by linear regression:

$$Y = 129.46 + 11.63(X)$$
$$r = 0.79$$

Y = Total Inner Basin water production
X = Bearpaw March 1 SWE

$$Y = -64.40 + 10.16(X)$$
$$r = 0.92$$

Y = Inner Basin springs production
X = Bearpaw maximum SWE

The maximum SWE produced the highest correlation to the water production of the springs and should be valuable in further assessment of the total Inner Basin water production.

The maximum SWE seems to be the best parameter for predicting the annual water production of the Inner Basin. Since manual snow surveys are conducted near February 1, March 1, and April 1, there is a high probability that the actual maximum SWE is not being recorded. A Snotel telemetry site would produce a daily record of the SWE, thus assuring the measurement of the maximum SWE. The daily record could also be used for more detailed monitoring of the snowpack accumulation and ablation.

Standard sensors would also provide precipitation and air temperature data. This would provide an opportunity to evaluate water losses due to evaporation and sublimation which do affect the water production. For example, March 1991 was very stormy and the Bearpaw snowpack on April 1 was measured to be 73 inches deep (1854 millimeters) with 21.1 inches (536 millimeters) SWE. The April 1 average SWE is 21.9 inches (556 millimeters), so a large volume of water production would be expected. April and May were very dry, cool, and windy. On May 20 the snow was only 18 inches deep (457 millimeters) but spring and well production was small. The snow water did not recharge the aquifer and loss due to sublimation is suspected.

Well depth sensors could be added to the Snotel site, thus monitoring aquifer recharge rates. There appears to be an opportunity to enhance the knowledge of the hydrology of the Inner Basin and to use the data to develop models for forecasting and managing water production.

CONCLUSION

The relationships and correlations indicate that snowpack data can be used as a significant factor in predicting the Inner Basin water production on a year to year basis. The highest correlation coefficient from regression analysis was 0.92 when comparing Bearpaw snow course maximum snow water equivalent to the production of the Inner Basin springs. However, manual snow surveys limit the snow water equivalent measurements to a few standard dates. The best chance of improving the assessment of potential water production is to be able to measure the maximum snow water equivalent no matter when it occurs. This could be accomplished by the installation of a Snotel telemetry site. Daily measurements of snow water equivalent, precipitation, and air temperature would also provide data for other environmental studies such as sublimation. Such a site could also monitor well levels. A model of the Inner Basin water production could then be developed for utilities operations.

Literature Cited

Aitchison, Stewart W. The San Francisco Peaks - A biological sky-island. The San Francisco Peaks; Plateau magazine of the Museum of Northern Arizona. Vol.56 No.3 1989.

Akers, J.P., M.E. Cooley, P.E. Dennis. Synopsis of groundwater conditions on the San Francisco Plateau near Flagstaff, Coconino County, Arizona. U.S. Geological Survey. 1969.

Breed, William J. The San Francisco Peaks - A geologist's perspective.

The San Francisco Peaks; Plateau magazine of the Museum of Northern Arizona. Vol.56, No.3 1989.

________ Memorandum report on potential groundwater recharge of the Inner Basin of the San Francisco Mountain. Bureau of Reclamation. 1972.

Chronic, Halka. Roadside geology of Arizona. Montana Press Publishing Co. 1983.

Cline, Platt. The mountain. The San Francisco Peaks; Plateau magazine of the Museum of Northern Arizona. Vol.56 No.3 1989.

Harshbarger & Associates; John Corollo Engineers. Inner Basin aquifer report - City of Flagstaff. 1974.

Martin, E.C. The relation of precipitation to flow from Little Leroux Spring on the San Francisco Peaks, Arizona. US Forest Service research note RM-129. 1969.