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AZ CORP COMMISSION
DOCUMENT CONTROL

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October 28, 2003

Docket Control
Arizona Corporation Commission
1200 West Washington Street
Phoenix, Arizona 85007

Arizona Corporation Commission
DOCKETED

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DOCKETED BY

SUBJECT: **INTERVENER DIRECT TESTIMONY**

REFERENCE: Docket No. W-03512A-03-0279

Commissioners, and Hearing Officer:

I represent myself to the Commission and Hearing Officer as a private citizen of Pine, Gila County, Arizona, and as a customer of the Applicant. I would testify with pertinent factual information and submittals of supporting evidence for consideration by the Applicant, the Commission Hearings and Staff. As additional standing in the community, I currently serve on the Environmental Planning Committee for the Section 208 of the EPA Clean Water Act administered by the Central Arizona Association of Governments (CAAG) for Gila and Pinal Counties in Arizona; formerly served as a Director on the Board of the Pine / Strawberry Water Improvement District (PSWID); and currently serve as the delegated PSWID Agent administering the PSWID "Project PS 2002-01," [a geo-hydrologic investigation performed under contract to the PSWID]. I will address the long term, reliable water supply issues in the community to the ACC based upon recent developments and considerations, including the completion of the geo-hydrologic investigation and study of these issues.

Intervener's Statement of Position:

I submit to this Commission that the Applicant (Pine Water Co.) has not supplied domestic water to the community of Pine in adequate quantities to meet the year-round demand for a number of years, including 2003. This past year was the highest number of days that the community was in a "Stage 5" status during the summer months. The restrictions imposed on the customers' water consumption under Stages 2 through 5 set the quantity of water delivered far below an acceptable level. This is not "conservation" when it is allowed to continue year after year. It is a violation of public trust and is a mis-appropriation by failing to supply.

According to the Public Notice that I received as distributed to the customers of the Applicant,..."(Company) filed...for an increase of approximately 41 percent over adjusted test year revenues....The Company also seeks authority to incur long-term indebtedness in the amount of $178,000.00."

As significant as this increase in rate and indebtedness may seem, and lacking a full disclosure of what this additional revenue and capital may accomplish to provide an adequate delivery of water to meet the demand, it appears, on the surface, that it will not

solve the water shortage problem. Therefore, as an Intervener, I am against the Commission's approval of the Company's requests in this matter, unless the Company will show and demonstrate that they can, with these increased rates and investment, soon be willing and able to service the Community's normal demand for domestic water year round.

In addition to the two request items noted above in the Public Notice, subsequent documents, including the Notice of Publication submitted 28 August, 2003 , added a third item in the title as, "APPLICATION OF PINE WATER COMPANY FOR A DETERMINATION OF THE CURRENT FAIR VALUE OF ITS UTILITY PLANT AND PROPERTY AND..."

Upon reviewing a copy of the Company's Application document furnished by the Company on this date, it appears that the determination of the current Fair value of its utility plant and property only serves to substantiate the requests for the permanent rate increase and the shift of some of the inter-company payable balance into long-term indebtedness and some into equity. It does not appear to apply this determination of value to any new capital investment to improve the supply of water and the ability to deliver same. As an Intervener, I remain against the Company's request.

Intervener Testimony Regarding to Original Two Items of the Application

I refer to my prior Intervener testimony before this Commission on April 8,2003, as contained in Attachment "A" herein, and submit it, in general, as Testimony in this Hearing..

1) Specifically, on Attachment A, page 2, the topic entitled, "**How much water?**" still applies. The Pine / Strawberry Water Improvement District (PSWID) has adopted a daily consumption figure of 375 gallons per day per residential unit as applicable to the District, including the Pine community. The PSWID Board adopted this value on February 8, 2003 in a regular meeting.
2) On Attachment A, page 3, the "**CONCLUSION**" still applies. Particularly, the statements: **"We have the water!"** and **"Put enough capital to work where it does the most good."**
3) On Attachment A, page 2, the statement, "By mid-year 2003, a technical report will have become public from the Pine / Strawberry Water Improvement District (PSWID) that will address the feasibility of withdrawing groundwater from a regional aquifer in the Redwall Limestone." This has now been fulfilled. The final report of this geo-hydrologic investigation is referenced herein as Attachment "B".
4) On Attachment A, page 2, the statement, "This report will identify a number of prospective drilling sites, identify depth to water, and provide preliminary drilling requirements and specifications along with preliminary estimates of costs." The Attachment B report contains this information, except that the "...preliminary drilling requirements and specifications..." is a separate document that has not been released as of this date, but may be forthcoming shortly.

This Intervener requests that the technical information contained in the report document, Attachment B, should be fairly considered by the Company and its parent company, Brooke Utilities, Inc., for improving and upgrading the facilities and assets to service the Community's normal demand for domestic water year round. These points are offered below as significant to the Company's ability to fulfill its CC&N charter from this Commission.:

1) The Attachment B document asserts why the strata currently tapped by Company's wells, and those of the sister company, Strawberry Water Company, are not a reliable nor an adequate supply for the present demand and long-term growth of the Community.
2) The document further asserts and defines the area where the "most favorable conditions" prevail, (aquifer fully confined), for drilling into the regional Redwall Limestone (R-Aquifer). See Fig. 6-10 and Fig. 6-11. Also, interpreting the contour lines depicted on these figures defines a larger area that may be successfully drilled to water at the same static level, but under less favorable conditions (an unconfined aquifer, with less water depth above the impermeable basement rock).
3) The "Summary of estimated costs to drill and pump test well", found in Appendix "C" of the report document, identifies the high cost of drilling and developing a successful well under the local conditions encountered by two previous attempts to penetrate the R-Aquifer from this elevation. The drilling methodologies were carefully evaluated and selected to overcome the demonstrated difficulties that have been encountered in the local area. It is believed that only a high production well, producing 300-500 gallons per minute, will be an economically feasible option under this cost scenario.
4) High pump-rate wells are desirable from both the mechanical and power efficiency standpoints, and also maintain a capacity to meet peak summertime demand. It is preferred to invest in high-production rated wells and pumps and reduce the reliance upon surface storage and water quality processing facilities to balance supply and demand.

Considering these points, it would appear that the level of investment, and perhaps the rate increase, would not provide significant improvement in the water supply and infrastructure to meet the desired demand. Even considering a series of lower cost wells of less depth in the upper strata, with the points stated above as prevailing, a better solution to solving the water shortage problem seems to lie in tapping the R-Aquifer.

More directly to the issue, I submit that it is appropriate that Brooke Utilities and/or its regulated water companies undertake the capital investment to tap this source of water, and that the Commission provide the Rate Base structure modifications for the financial viability of such investment. The Intervener is confident that Company under this arrangement can provide the water supplies for these communities more expeditiously and economically to the beneficial use by the communities than any other options under consideration.

Some will protest that we, the community residents and property owners, cannot afford such water rates. Some will claim we should obtain grants or subsidies to ease the cost impacts of such investments. Only the consumers who must deal with the lack of water and the restrictions on water usage seem compelled to step up and pay the price. Subsidies and grants do not seem to be available when we want them. With the emergency expenditures for the current War on Terror and the disastrous fire conflagrations, as well as the budget plight of the State of Arizona, who is going to throw money our way to develop our water supply? In the end, the price that we consumers pay for our water, if we truly want it, will compensate the costs and provide the return on capital to deliver water to our taps. All other considerations fail, and they fall to the reality of these facts.

The Company and the Commission can greatly enhance the acceptability of the costs and the need for conservation in the community by applying a tiered system of water rates based upon the utilization of waters from both the present well field in the upper strata and the lower strata R-Aquifer. A base level of lesser cost water will continue to be produced from the upper strata, and should be allocated for a base sustenance consumption. Water in ever increasing quantities over time,

pumped from the R-Aquifer, should carry escalated charges for those who wish to pay the price for higher consumption.

The present well field in the upper strata needs to be well managed to reach its optimal maximum production of the lesser cost water. Currently, there are very diverse views regarding the characteristics of the upper strata groundwater. There is a great lack of factual information on hand to evaluate and interpret these differing viewpoints. The published expert opinions are in opposition one to another. The PSWID Project PS 2002-01 invested in the capability to start the long-term collection of water and well data for overcoming this lack of information. The Attachment "E" document provides an overview of the purpose and scope of the "PSWID Wells Database & Resource Management System."

The POSTSCRIPT document, included within the Attachment B document, identifies the PSWID Wells Database System as a useful and forceful tool to gain more insight and operational understanding of the well field pumping from the upper strata. It was the intent of the District, at the time its development was contracted, that this tool would be open to all the water suppliers to the community on a cooperative basis. It requires data input and provides useful information that, over time, will enable a better management of the groundwater resource and provide a simpler, easier to understand picture of the water supply dynamics to the layman. It will also serve as the truth test for the validity of our local groundwater management concepts.

This Intervener recommends to the Company that it press the PSWID to open this cooperative use of this tool, to place present and future data into this system, and to benefit from the knowledge and understanding it may provide.

Additional Supporting and Reference Documentation

A recent assessment and professional overview of the "R-AQUIFER IN NORTHERN ARIZONA" may be found in the Attachment "D" document. This is the Final Abstract of a paper presented at the Arizona Hydrological Society 2003 Annual Symposium in Mesa, AZ. In September.

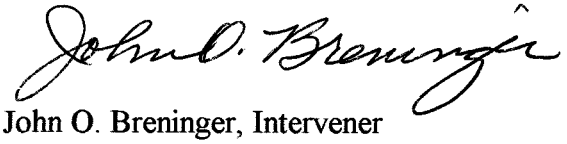
The Table of Contents of the three volume set of the "PSWID SPECIAL REFERENCE DOCUMENT COLLECTION" may be found in the Attachment "C" document. This document collection includes the accumulation of early documents held by the PSWID Agent and furnished to the Morrison-Maierle Chief Geologist for evaluation as described in the Attachment B document. It also contains most of the documents from a comprehensive literature search and interviews performed during the investigation, as well as some other recent documents made available to the PSWID. This Collection comprises the most complete known assemblage of reports and documents of the geo-hydrological investigations applicable to the Pine and Strawberry area. These documents will be deposited in the Isabelle Hunt Memorial Public Library in Pine, AZ, in the near future. They will be held in a special reference section for PSWID documents and will be available for public inspection and reference.

CONCLUSION:

Would the Commission please take a new look at the rate structure for water that it has ruled for this Community, and reconsider the need for a significant increase in capital investment on the part of the water utilities that can be justified by the rate base. **We have the water!** We need the means to put it into the delivery system. The projected study of demand indicates that the costs may be borne by a considerable increase in consumption. A tiered price/rate structure may be required. The Commission should rule to facilitate the residents of this Community to use all the water they want to pay for! I say again: **Put enough capital to work where it does the most good.**

- End of Testimony -

Respectfully submitted,



John O. Breninger, Intervener

ATTACHMENTS:

A. "Presentation of Testimony in Hearing before ARIZONA CORPORATION COMMISSION," RE: Docket Nos. W-03512A-03-0104 and W-03512A-03-0106, April 18, 2003, by John O. Breninger, Intervener, including "Request for Late Filing of Exceptions" dated May 5, 2003
B. "Investigation of Groundwater Availability for the Pine/Strawberry Water Improvement District," Prepared by Michael B. Kaczmarek, RG, Chief Geologist, Morrison-Maierle, Inc., dated July 2003, including PSWID Project PS 2002-01 Report, dated October 1, 2003, entitled "POSTSCRIPT to PSWID Project PS 2002-01 Final Report"
C. Table of Contents, "PSWID Special Reference Documents Collection, Volumes I, II & III," PSWID Project PS 2002-01, dated October 22, 2003
D. Errol L. Montgomery & Edwin H. McGavock, "R-AQUIFER IN NORTHERN ARIZONA", AHS 2003 ANNUAL SYMPOSIUM FINAL ABSTRACT, ERROL L. MONTGOMERY & ASSOCIATES, INC.; 1550 E. Prince Road, Tucson, AZ 85719, emontgomery@elmontgomery.com, (520) 881-4912, fax (520) 881-1609
E. "Purpose and Scope of the PSWID Wells Database System," PSWID Project PS 2002-01 Report dated October 3, 2003, by PSWID Agent John Breninger

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ATTACHMENT "A", Intervener Testimony by J. Breninger, Docket No. W-03512A-03-0279, Oct. 28,2003

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April 18, 2003, Revised April 21, 2003 (Corrected Docket Number)

PRESENTATION of TESTIMONY in HEARING before
ARIZONA CORPORATION COMMISSION
RE: Docket Nos. W-03512A-03-0104 and W-03512A-03-0106

Commissioners, and Hearing Officer:

As a qualified Intervener to this subject Hearing today, I represent myself to the Commission as a private citizen of Pine, Arizona, and as a customer of the Applicants. I testify with pertinent factual information and submittals for the Hearing and Commission/Staff consideration from a collection of technical information, from public documents, and additionally as supported from my standing in the Community due to my service with, but not as a representative from, 1) the Environmental Planning Committee for the Section 208 of the EPA Clean Water Act administered by the Central Arizona Association of Governments (CAAG) for Gila and Pinal Counties in Arizona; and 2) the Pine / Strawberry Water Improvement District Board in Gila County. I will address the long-term water supply issues in the Community for the ACC based upon recent developments and considerations.

I submit to this Commission that the Interim Rate Increase and Curtailment Tariff actions requested and being heard today, and in the related Decisions of the Commission, are continuing a pattern of "band-aiding" the water problems of the Pine and Strawberry Area (Community) in an ineffectual manner. I acknowledge that both of these matters seem prudent and needed in the short term of where we are now, but I further submit that such actions subvert and delay a true improvement in the underlying causes of the problems being addressed. The Commission and the regulated water utility need to address the real underlying problem with an appropriate level and application of capital investment that I will address below. I ask the water utility along with the Commission and Staff to consider this in their recommendations and Decisions to progress toward the real and long-term solution. I repeat: **Put enough capital to work where it does the most good.**

As the largest purveyor of water in Pine, Pine Water Co. and the supporting infrastructures of Strawberry Water Co. and the parent company, Brooke Utilities, seem unable to deliver an adequate and consistent supply of water in Pine during the summertime peak demand. In my opinion, the purveyors that serve the Community at-large have over-utilized the available source of water in the Supai Formation, and this water source has proven to be inadequate in the face of prolonged drought and increasing demand. (See Attachment #1, entitled, "Water at Three Levels"). Both of these statements, (over-utilized and inadequate) have been pronounced since as early as 1987 from the Arizona Dept. of Water Resources (ADWR) for this Community. [If the Commission does not have these pronouncements on file, I would be willing to obtain them for the record.] The opportunity to overcome this deficiency will probably happen by going into a regional aquifer within the deeper Redwall Limestone and lower strata.

Up till the present time, this option of deep wells from a regional aquifer has not been accepted, neither as possible nor practical, and consequently, the Community is still short of water as it continues to expand and grow. So, what is new or different today?

By mid-year 2003, a technical report will have become public from the Pine / Strawberry Water Improvement District (PSWID) that will address the feasibility of withdrawing groundwater from a regional aquifer in the Redwall Limestone. A geo-hydrologist has been contracted by PSWID to perform this work, which is nearing completion. This report will identify a number of prospective drilling sites, identify depth to water, and provide preliminary drilling requirements and specifications along with preliminary estimates of costs. A further task of this contract is to evaluate the current literature and collection of the prior technical reports of the water resources in and relating to this Community. This is a new report regarding our groundwater supply, and I request that it be considered by the Commission and Staff to the benefit of the Community as describing the locally undeveloped source of water.

Although this work was undertaken by the PSWID with District taxes in addressing its charter, "...to represent the interests of the Communities in securing long term and reliable sources of water for the Communities,..." the information it represents will be public and intended for use to benefit the Community. PSWID has yet to develop plans for how this source of water would be developed and put to use. PSWID is not currently chartered to serve as a purveyor of water to the community. The Community is served by a mix of private wells, three private water companies regulated by ACC, and four domestic water improvement districts, which are formed as Special Taxing Districts under Title 48 of the Arizona Revised Statutes. A possible consideration by PSWID would be to develop a well field to provide Supplemental Water to these purveyors on a wholesale basis at the well-head delivery points, but this has yet to be considered and the funding addressed.

More directly to the issue, I submit it is appropriate that Brooke Utilities and/or its regulated water companies undertake the capital investment to tap this source of water and that the ACC provide the Rate Base structure modifications for the financial viability of such investment.

Some will protest that we, the Community residents, cannot afford such water rates. Some will claim we should obtain grants or subsidies to ease the cost impacts of such investments. Only the consumers who deal with the lack of water and the restrictions on water usage seem compelled to step up and pay the price. Subsidies and grants do not seem to appear when we want them. In the end, the price that we consumers pay for our water, if we truly want it, will compensate for the costs and capital required to deliver water to our taps. All other considerations fail, and they fall to the reality of this fact.

So, how much water is required to serve this Community? How much of it will the water companies alone need to supply? Can the Supai Formation be further developed to supply this much water?

How much water? Again, the PSWID has reviewed the present and future considerations of this question, and as a result, has adopted on February 8, 2003, "WATER SUPPLY AND DEMAND FOR THE PINE/STRAWBERRY WATER IMPROVEMENT DISTRICT GILA COUNTY, ARIZONA" (See Attachment #2). This demand was projected to the year 2050 and indicates a water consumption far in excess of the quantities currently provided. (See Attachment #3 for a graphical chart of this demand/supply). This demand was based upon anticipated growth and unrestricted consumption, not such as the Community culture currently exhibits under the continuing levels of conservation, restriction and constrained growth. Evidence of the pressure for increased consumption in Northern Gila County is that the **per capita** consumption of water is on the increase, as reported by the Town of Payson and Brooke Utilities. It appears that the conservation ethic just isn't what it used to be!

How much from the water companies? Most of it, as indicated by the number of connections reported by Brooke Utilities and taken as a percentage of the entire community.

ATTACHMENT #1, ACC Testimony by John Breninger

WATER AT THREE LEVELS

The Language of Groundwater in Pine and Strawberry

Soil Water
Upper/Lower Supai Water
Redwall Limestone Water

Soil Water – This is water that plants feed on, that makes the ground look moist when you dig holes, or makes things damp when lying on or in the ground. It generally is confined to the upper fifty feet, or less. It is the first dispersal of precipitation on its way to finding a saturated level, or evaporating away into the air, or turning into water vapor held in the soil.

Lack or depletion of soil water near the surface during 2002 is the primary cause of the die-off of Ponderosa Pines in the Pine and Strawberry areas. This water normally is not considered suitable for domestic use.

Upper/Lower Supai Water – This is the water that supplies nearly all of the wells currently in service in the Pine and Strawberry areas. The Upper Supai formation, above the white-banded Fort Apache Formation, is the source of the outflow of Pine Creek and the associated springs in Pine Creek Canyon. This water moves out from under the Mogollon Rim and percolates downward, into and through the Lower Supai Formation, where the wells are able to intercept this flow. This flow does not accumulate into a regional aquifer in this strata, but continues to move through and out of the area as "water on the fly".

A near-relative of this water is that which accumulates in the alluvium of Pine Creek Canyon at the lower levels and forms a local and limited aquifer supplying a number of wells before it, too, continues downward and out of the area into the cavern system of the Redwall Limestone at the lower levels.

This source of water has not proven to be adequate or reliable to supply the demand of the Communities.

Redwall Limestone Water – The legendary source of water, known as the Regional Aquifer, that is denied by some, may yet be found in the Redwall Limestone strata. This water emerges at a number of springs from under the Mogollon Rim, but at a much lower level than the Pine Creek springs. This is the source of the water for Fossil Creek Springs, which have a long, recorded history of a large and very constant flow of water.

Because the Redwall Limestone in the nearby area underlies the Colorado Plateau where it is stable and mostly unbroken or unfaulted, it is probably a fully confined aquifer that receives its recharge from a huge area north of the Rim and east of Pine/Strawberry, perhaps as far as Promontory Point, or even to Showlow and Snowflake.

This is the source of water currently being investigated by the PSWID for a reliable, long-term water supply for the Communities.

Prepared by:
John Breninger, 1/8/02, revised 4/16/03

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WATER SUPPLY AND DEMAND
FOR THE
PINE/STRAWBERRY WATER IMPROVEMENT DISTRICT
GILA COUNTY, ARIZONA

Introduction

The Pine/Strawberry Water Improvement District (PSWID) was formed to develop a long-term source of water to adequately supply current and future property owners in the area. In December 1997, the PSWID Board of Directors adopted a Water Consumption Factor for the area. The Board of Directors has agreed that an updated Supply And Demand Model is required. This document provides that model which includes current water production and expected build out of the area.

Discussion

A Water Supply And Demand study is required to support the role of the PSWID in fulfilling the primary function to provide a reliable, long-term water supply to the communities of Pine and Strawberry. The immediate need is for this study to provide the design guidelines for the water demand profiles applicable from now and into the future. These water demand profiles are a necessary input for hydrologists to adequately define well design requirements for quantity, size and water delivery rates. The water demand profiles are also necessary for development of designated sites, individually, in sequence, as the actual supplemental water demand unfolds to: prove the water, plan the water development, secure funding, drill production wells, develop and operate water delivery points.
Data used to reach a conclusion for this model was obtained from the Water Consumption Factor adopted by the PSWID in 1997; 'Official Policy' of the Planning and Zoning Division of Gila County; Urban Design Studio LLC, consulting firm preparing the Gila County General Plan during years 2002 and 2003; and water production figures of the Pine and Strawberry Water companies. Other sources of information are noted within this document.

Considerations

Urban Design Studio LLC, (UDS), in preparation of the Gila County General Plan, and the Gila County Planning and Zoning Division, determine Pine/Strawberry a seasonal use area. UDS formulates less people per homes in their considerations. For example, total build out, under current zoning, suggests 5390 homes and 5121 people for Pine. Thus, they suggested to PSWID, forecasting water requirements for the number of people would be more appropriate than homes or connections. PSWID does not totally agree with this approach. PSWID believes that this does not allow for heavy water consumption during summer months and holiday weekends. Part time, seasonal usage differentials seem to be disappearing in the area, and water consumption per capita appears to be on the increase as reported by the local water providers' statistics.
Numerous sources of water consumption data were studied in the preparation of the PSWID 'Water Consumption Factor'. Using the census figure of 2.3 persons per household, daily consumption figures ranged from 345 gpd in Camp Verde Az. to 524 gpd in McFarland Ca. PSWID has adopted the target of 375 gpd.

UDS has calculated the following total build out under current zoning:

Strawberry	2559	Homes
	2431	People
Pine	5390	Homes
	5121	People
Total	7949	Homes
	7552	People

In addition, PSWID requires data relative to water consumption by commercial units in the communities to complete this model. The Yellow Pages of QwestDex Commercial, year 2002, was used to gather types and numbers of individual business in Pine and Strawberry. These businesses, depending on estimated water usage, were adjusted to equivalent residential units. For example, medical, dentist, was adjusted to reflect 2 residential units, while agricultural and ranch, was adjusted to reflect 10 residential units. This added 848 residential units to the forecasted 7949 for a total of 8797.

Restaurants	9
Motels, B& B, RV Parks	7
Beauty Shops	2
Retail/Counter Services	13
Combination	2
Laundries, Ice Making	3
Industrial	39
Total	75 X 4 = 300 residential units
Churches & Orgs.	6
Health Care, Medical Dental, Fitness Cent.	4
Other Prof. Services	27
Total	37 X 2 = 74 residential units
Animal Care, Ranch Agriculture	5 X 10 = 50 residential units

Total 424 residential units. Assume amount to double by year 2025 and remain flat through 2050, PSWID added the 848 equivalent units.

Water Demand @ Rated Usage: 8797 Units X 375 gpd = 3,298,875 gpd
(Assume 50% maximum utilization of pumping capacity)

May-Sept. Dec. 20 thru Jan.5 resort area multiplier X 1.8 = 5,937,975 gpd
(Assume 90% maximum utilization of pumping capacity)

Holiday weekend peak demand multiplier X 4.0 = 13,195,500 gpd
(Assume peak demand to be buffered by local storage over
5-day span and 95% maximum utilization of pumping capacity)

Base rate of water supply yield = 6,597,750 gpd @ 100% pumping capacity
Or 4581 gpm continuous well production. Adjusted for 90% operational efficiency = 5091 gpm operational well production.

Water production predicted by month in year 2050:

January	115,460,625
February	92,368,500
March	102,265,125
April	98,966,250
May	220,364,850
June	178,139,250
July	220,364,485
August	184,077,225
September	148,449,375
October	102,265,125
November	98,966,250
December	131,295,225

Total annual water production is predicted as 1,692,982,650 (1.7 billion) gallons or 5,196 acre-feet of water.

Average daily water production as reported by Pine and Strawberry Water Companies over the past four years equals 680,000 gallons per day, or 472 gallons per minute. Estimated water production of the one additional private water company, and the four domestic water improvement districts is 149,625 gallons per day, or 104 gallons per minute.
Total current annual water production is estimated as 302,959,000 gallons.

Summary

Arizona is a desert state where water is continually becoming a scarce commodity. Pine/Strawberry in the past year, with emphasis in Pine, experienced severe water availability conditions. Pine/Strawberry has been known for many years to have a short supply of water, and is dramatically affected by drought conditions. It should be expected that water conservation measures would always be necessary, but not a hardship as they have been in the past. An adequate water supply can and should be developed to meet the expected growth in population by year 2050.

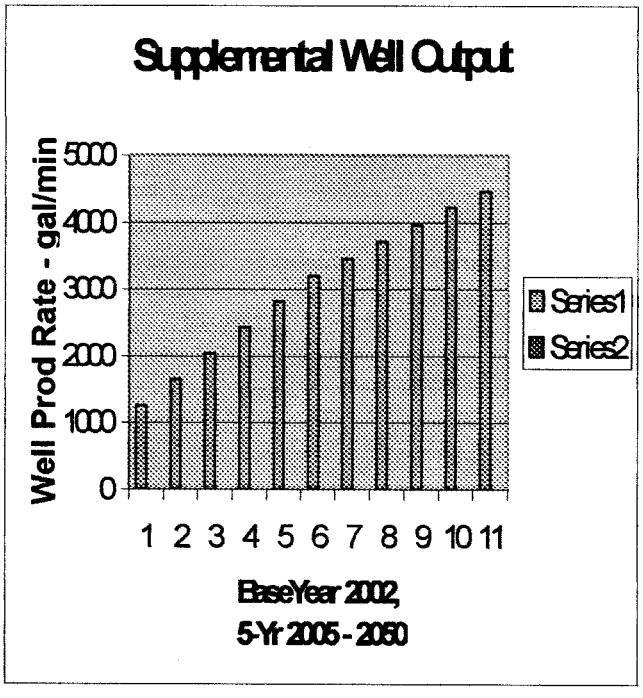
Prepared by Pine/Strawberry Water Improvement District
Committee members:
Gary Hezel
Betty Gooder
John Breninger

Adopted by Pine/Strawberry Water Improvement District Board of Directors
February 8, 2003

ATTACHMENT "A", Intervener Testimony by J. Breninger, Docket No. W-03512A-03-0279, Oct. 28,2003
ATTACHMENT #3, Supplemental vs Total Water Requirements – Pine/Strawberry Area

Supplemental Water Reqmts
(Ref: 1-11-02 Preliminary Draft)
Well Production, gpm

(Originated 12-30-02)	Yr 2002	Yr 2005	Yr 2010	Yr 2015	Yr 2020	Yr 2025	Yr 2030	Yr 2035	Yr 2040	Yr 2045	Yr 2050 (Revised)
375gpd usage	1831	2221	2610	3000	3389	3779	4031	4283	4536	4788	5040
Current Production	576	576	576	576	576	576	576	576	576	576	576
Reqd Supl 375gpd	1255	1645	2034	2424	2813	3203	3455	3707	3960	4212	4464



- END - ATTACHMENTS

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May 5, 2003

Arizona Corporation Commission
Attn: Docket Control
1200 West Washington Street
Phoenix, Arizona 85007-2927

Subject: Request for Late Filing of Exceptions

RE: Docket Nos. W-03512A-03-0104 and W-03512A-03-0106
Recommendation of the Administrative Law Judge to the Commissioners (Commission's Working Session and Open Meeting tentatively to be held on May 13, 2003 and May 14, 2003
Pursuant to Hearing of April 18, 2003. Phoenix, Arizona, Dwight Nodes, presiding Administrative Law Judge

I hereby request the Commission (Docket Control) to receive and allow my late filing of exception to the proposed Opinion and Order recommended by the Administrative Law Judge as referenced above in the Matter of the Pine Water Company, Inc. (Curtailment Tariff/Rates). I regret not meeting the assigned deadline for filing, and beg forbearance as I was away and unable to respond in a timely manner.

I believe that a statement concluded from my testimony as a qualified interverner (in propria persona) did not accurately reflect my testimony. I have discussed this with Judge Dwight Nodes on this date, and I believe I have his concurrence to this correction.

The exception I submit corrects, for the record, a statement made in the document Section II. Discussion, D. Other Issues, page 10, Line 5, to wit:
"...Supai Formation..."
should be: "...Redwall Limestone Formation..."

I reference, by explanation, excerpts from the page 1, of my testimony document, "PRESENTATION of TESTIMONY in HEARING before ARIZONA CORPORATION COMMISSION, RE: Docket Nos. W-03512A-03-0104 and W-03512A-03-0106"
"As the largest purveyor of water in Pine, Pine Water Co. and the supporting infrastructures of Strawberry Water Co. and the parent company, Brooke Utilities, seem unable to deliver an adequate and consistent supply of water in Pine during the summertime peak demand. In my opinion, the purveyors that serve the Community at-large have over-utilized the available source of water in the Supai Formation, and this

water source has proven to be inadequate in the face of prolonged drought and in creasing demand. (See Attachment #1, entitled, "Water at Three Levels")." ... "By mid-year 2003, a technical report will have become public from the Pine / Strawberry Water Improvement District (PSWID) that will address the feasibility of withdrawing groundwater from a regional aquifer in the Redwall Limestone."

I trust this is adequate clarification of the correcton I have requested.

Respectfully submitted,

John O. Breninger, Intervener

Encl. (10) copies

FILE: ACCIntervene03.doc

ATTACHMENT "B"
Intervener Direct Testimony,
by J. Breninger
Docket No. W-03512A-03-0279

August 2003

Investigation of Groundwater Availability for the Pine/Strawberry Water Improvement District

Prepared for:
Pine/Strawberry Water Improvement District
P.O.Box 134
Pine, AZ 85544

MORRISON MAIERLE, INC.
An Employee Owned Company

Investigation of Groundwater Availability for the Pine/Strawberry Water Improvement District

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JULY 2003

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EXECUTIVE SUMMARY

The communities of Pine and Strawberry have historically experienced severe water shortages in the summer months. The on-going shortages currently jeopardize the future growth of the community on undeveloped private properties and limit addition of new customers to water companies for existing subdivisions that have not reached full build-out. Recent investigations conducted by the Pine/Strawberry Water Improvement District (PSWID) reveal that the water supply shortages caused by seasonal decreases in well yields are the result of limitations inherent in the hydraulic properties of the fractured rock aquifers that supply water to wells in the PSWID area. The limitations of groundwater flow through the fractured rocks to pumped wells cause predictable decreases in well yields as pumping times increase. Although drought or below average precipitation conditions exacerbate the seasonal groundwater shortages, they are not the fundamental cause of the shortages, a conclusion supported by the fact that water shortages have historically occurred at the end of as many as 12 consecutive years of above average precipitation trends. The investigations show the currently utilized groundwater sources, in the Schnebly Hill and Supai strata, are inadequate to support existing demands let alone future growth.

Investigation of the PSWID area for alternative sources of groundwater supplies has identified a deep aquifer in the Redwall Limestone and associated strata as the most favorable groundwater resource from which to develop additional sustainable water supplies for the area. An exploration well referred to as the Strawberry Borehole was drilled through the Redwall and associated strata in year 2000, under the sponsorship of the Northern Gila County Water Plan Alliance and the supervision of the PSWID, and verified that groundwater with good chemical quality for use as public water supply is available in the units. The investigations identify the northwestern part of the PSWID area as the most favorable location for development of a well field in the Redwall Limestone and associated strata.

A site for a test/production well is recommended in the southwest quarter of Section 20, T12N, and R8E. A 12-inch nominal diameter test well, suitable for later use as a production well, is recommended. The estimated depth to the top of the Redwall Limestone is 1,560 feet and the total depth of the well potentially may reach 2,110 feet. The anticipated depth to the static water level in the well is 1,505 feet. The 12-inch diameter configuration of the well will allow installation of deep-set pumps and motors capable of pumping rates ranging from 150 gpm to more than 1000 gpm, depending on the yield of the aquifer and the needs of the communities supplied by the well.

PREFACE

PURPOSE: In 2002, the Pine/Strawberry Water Improvement District (PSWID) undertook an investigation, (PSWID Project P/S 2002-01), to identify potential new sources of groundwater and to document the present groundwater conditions in and around the District area. This Preface identifies the objectives of the subject PSWID Project and highlights the work performed since November 4, 2002 by the Consultant, Morrison-Maierle, Inc., of Helena, Montana. The Preface statements are intended for public information from PSWID and an introduction of the Consultant's Chief Geologist, Mr. Michael B. Kaczmarek, the presenter of the preliminary findings and report to the Board and the public at a PSWID Special Meeting on July 19, 2003.

INTRODUCTION: This Preface is intended to summarize in concise, laymen's language what the Project is for and what the PSWID Board and the Communities are receiving in the work performed on this Contract. These statements in no way supersede the findings, technical report, or the presentation of Mr. Kaczmarek or Morrison-Maierle Inc.

HISTORICAL PERSPECTIVE: The Pine & Strawberry area of Gila County is a Community of historical significance in Arizona. The Community's domestic water needs are largely obtained from ground water and served by a mix of private wells, regulated water utilities, and domestic water improvement districts. The Pine/Strawberry Water Improvement District (PSWID) boundaries encompass the general extent of the area, excluding the service areas of the domestic water improvement districts noted above, but the District itself does not provide domestic water service to the Community. The map showing the approved boundaries of the District is shown in Figure 1-1 and others of this report. The Arizona Department of Water Resources has deemed this area to have an "inadequate water supply."

This District was formed in 1996, and, "The purpose of the Board is to represent the interests of the Communities in securing long term and reliable sources of water for the Communities,..." (Reference PSWID Bylaws). This Project is a significant step towards fulfilling this purpose.

The firm of Morrison-Maierle, Inc. was selected to perform the professional Geohydrological/Engineering Services desired by the PSWID Board to assist in the development and evaluation of data being collected in the Northern Gila County area and to develop a District Water Resource and Action Plan directed at groundwater development and the well siting of deep production wells in the Pine / Strawberry area of Gila County, Arizona.

Desired Outcomes: (Reference: RFQ&P / PROJECT NUMBER: P/S 2002-01)
[Information comments per this Preface shown in Bold Italic font]

The following criteria and expectations were utilized to guide and direct the efforts of the Engineering firm or firms working on this project:

The PSWID Board desired the development of a District Water Resource and Action Plan for the Study Area and contracted for the professional services to perform this Scope of Work. The plan included, at a minimum, the following components:

1. Existing Groundwater Resources and Methods of Delivery shall be documented and evaluated for current and future planning purposes.

   [Refer to M-M Report, Section 5.1, pages 47-45]

   COMMENT 1A: [Summary – The surface flow of Pine Creek only marginally supported the needs of a 140 person population base in 1967 – with very little potential for development of a higher utilization.]

   [Refer to M-M Report, Section 5.2–5.5, pages 48–73, Pine general area and Portals subdivisions]

   COMMENT 1B: [The Kaczmarek review of the historic pump data, interpretations and conclusions based on radial flow analyses explains that these results are not consistent with the inadequate production of water from the associated well fields. Even the conflicting interpretive reports from ADWR on the amount of the water supply were not only overly optimistic, they also applied values to broad areas that were appropriate only to fractures of limited distribution and extent. Pine and Strawberry do not have nearly the amount of groundwater available in the strata pumped by the existing well fields that were generally represented.]

   [Refer to M-M Report, Section 5.6, PAGES 73–85, Selected Strawberry and Pine wells pump tests]

   COMMENT 1C: (Ref. Page 75) "Similar to other historic analyses of pumping tests and groundwater flow in this area, ... inappropriately applies radial flow analysis to linear flow conditions. ... Therefore the estimates of groundwater availability presented in the report are likely in error".
   [The referenced report, published in 2002, continues to portray that there is more water in this area than the area's wells production performance indicates.]

2. Evaluate and establish a baseline reference of prior information and data, including that presently held by PSWID, for new exploration and

development of water resources. The list of documents held by PSWID may be found in the [RFQ&P] Appendix, "Preliminary List of Studies for Pine - Strawberry Area."

[Refer to M-M Report, Section 5.7, pages 85 – 87, Discussion of Radial vs. Linear Flow implications]

COMMENT: (Reference page 96) "...the adequacy of the groundwater resource...has been demonstrably inadequate to support...the demands for water supply in the Pine area and marginal in the Strawberry area. ...Accordingly, it is necessary to seek alternative sources of water for the PSWID communities."

3. Establish an inventory of wells into a database suitable for future collection and integration of groundwater data. Provide operational guidelines to gather and utilize well data and to produce reports from the database.

   [Refer to M-M Report, Section 1.2, pages 4 – 5, GIS Effort]

   COMMENT: [The Wells Database was developed for PSWID on this Contract and provides an initial download of 1604 well registrations data from ADWD; the programming to permit the management of the data and generating reports; and a geographical information systems (GIS) software package. This database system is the basic set of tools that may serve PSWID well into the future of developing and managing sources of water for the Communities.]

4. Two to Five locations for drilling future production wells shall be identified, evaluated and ranked in order of suggested development. Engineering Methodology, Site Conditions, Anticipated Depth to Groundwater, Legal Requirements, Environmental Issues, Development Costs and other factors shall be identified in the District Water Resource and Action Plan and taken into consideration when ranking order is established.

   [Refer to M-M Report, Executive Summary, page v, and Section 6.4, pages 113 - 137]

   COMMENT 4A: [Most favourable area for drilling to Redwall Limestone – Fig. 6-10, page 114]

   COMMENT 4B: [Initial recommended test/production well site – Fig.6-11, page 116]

   COMMENT 4C: [Well Design Considerations – Section 6.4.2, page 117 ff.]

5. Provide budgetary estimate of costs, drilling specifications and preliminary well design requirements for wells at each of the sites recommended.

   [Refer to M-M Report, Executive Summary, page v, and Section 6.4.2, pages 117 - 120]

   COMMENT: [See Appendix C of M-M Report]

6. A topographical map, identifying the two to five drilling locations, shall be developed and included in the recommendations in the District Water Resource and Action Plan.

   [Refer to M-M Report, Section 6.4, Fig. 6-10 & 6.11, pages 114 & 116]

   COMMENT: [The topographic maps contained in the M-M technical report, are also in an electronic format and will become part of the data files in the PSWID Wells Database and GIS system.]

7. Other Observations and Recommendations, as may be appropriate, to provide a thorough and complete Planning Document for continued use by the PSWID Board, are invited.

   [Refer to M-M Report, Section 6.4.3, 6.4.4, 6.4.5 and Section 7]

   COMMENT: [The technical observations and discussion are grouped under three headings:]

   6.4.3 Structural Considerations
   6.4.4 Hydrogeologic Considerations
   6.4.5 Source of Recharge

   [These observations may form the basis for future planning and development of a long term, reliable source of groundwater supply for the Pine / Strawberry Community. Further exploration to prove the supply of water and evaluate the deep regional aquifer characteristics is part of that future development.]

   [ADDITIONAL COMMENT: See "Local Observations, Section 7, pages 137 – 144]

Project Preface
Respectfully prepared and submitted July 2003

John Breninger, Chairman
PSWID Deep Well Exploration Committee

1. INTRODUCTION

This report provides the results of an investigation commissioned by the Pine/Strawberry Water Improvement District (PSWID) for the purposes of documenting present conditions and identifying potential new sources of groundwater in the Pine and Strawberry area of Gila County, Arizona, according to a scope of work initially described in RFQ&P Project Number P/S 2002-01, dated July 24, 2002 and modified by subsequent contract negotiations.

1.1. General Background

Domestic water for the Pine/Strawberry area is provided by a combination of private wells; regulated utility companies; and Domestic Water Improvement Districts (DWID). Information provided in the PSWID document, "PS 2002 PERCEPTIONS of WATER SUPPLY in the PINE-STRAWBERRY AREA", dated August 17, 2002, indicates there are approximately 150 privately owned wells in use to provide domestic and irrigation water. Regulated utilities listed in the foregoing document include the Pine Water Company, Inc. (formerly E&R Water co.); the Strawberry Water Company, Inc., both owned by Brooke Utilities Inc.; and the Hunt Water Company in Strawberry. Domestic Water Improvement Districts include the Pine Creek Canyon DWID, the Pine Water Users DWID, the Solitude Trails DWID, and the Strawberry Hollow DWID. Figure 1-1 shows the exterior boundaries of the PSWID, the exterior boundaries of the Pine and Strawberry community areas, and four areas that are excluded from the PSWID although they are within its exterior boundaries. The three public water companies serve those parts of the PSWID that are not included in the Domestic Water Improvement Districts. The Fuller Ranch area in Strawberry is an additional exclusion, but is included in the service area of the regulated water utility.

The water supply in Strawberry is somewhat more reliable than that in Pine; however, the groundwater source in both communities is subject to limitations. Since the latter half of the 1980's, Pine has experienced recurrent water supply shortages. In 1989, Pine experienced a water supply shortage characterized by the Arizona Department of Water Resources (ADWR) as a shortage of 37,000 gallons per day (gpd) (ADWR, 1989; p. 1); however, this was based on a demand limited to five gallons per person per day. Demand for water prior to the emergency and curtailment of water use was estimated to be about 360,000 gpd (250 gpm) on weekends and 120,000 gpd (83 gpm) on week days (ADWR, 1989; p. 8) compared to well field production of 43,000 gpd (30 gpm), resulting in a shortage of 317,000 gpd (220 gpm) on weekends and 77,000 gpd (53 gpm) on week days. The 1989 shortage was partially offset by trucking water from Strawberry to Pine.

Figure 1-1: Boundary of the PSWID with exclusions.

Exterior Boundary of Pine/Strawberry Water Improvement District (PSWID)

Boundary of Pine or Strawberry Community Area

Water System Excluded from PSWID

Strawberry Community Area Boundary

PSWID

Pine Community Area Boundary

Portals IV (Excluded)

Pine Water Users (Excluded)

Fuller Ranch (Excluded)

Strawberry Hollow (Excluded)

Solitude Trails (Excluded)

In April 1996, an information packet prepared by ADWR to address water supply concerns in the Pine/Strawberry area stated:

> "***Since 1973, the state has analyzed the water adequacy for every new subdivision in the Payson/Pine/Strawberry area to determine if there is enough water available to meet the proposed use for 100 years. Throughout this time, almost all subdivisions in the area have received a Statement of Inadequate Water Supply from the state. The primary reason for the inadequate supply has been the drought sensitive nature of the area.***
>
> ***During the past 2 decades, subdivisions totaling about 5,100 lots have applied for water adequacy statements, 98% of which have not demonstrated adequacy.***"

In an Environmental Assessment for a proposed water line between Strawberry and Pine, to allow excess capacity from wells in Strawberry to be used to offset shortages in Pine, the U.S. Forest Service stated:

> "***Previously, Pine residents that are customers of E&R Water Company have been under water use restrictions imposed by the water company – as allowed by the Arizona Corporation Commission (ACC), including a 40% reduction in indoor use, no outdoor use, and limited livestock watering. During the summer of 1997, Brooke Utilities hauled 4.5 million gallons of water from Strawberry to Pine to ease the water shortage. Five additional wells have since been drilled in Pine but only two have achieved a water standard necessary for economic development and there is uncertainty over a long-term reliable source of water in Pine.***" (Payson Ranger District, 1999)

Since 1999, an 8-inch water transmission line has been constructed by the Brooke Utilities Company to convey water from wells in Strawberry to offset shortages in Pine. However, the transmission line cannot is not the solution to water shortages at Pine, where enforced curtailment of domestic water use continues, but simply provides an alternative to trucking water to Pine.

It was in the face of the historic water supply shortages in the Pine/Strawberry area that concerned citizens formed the PSWID. The historic seasonal failure of many wells in the area during summer demands, coupled with the poor success rate associated with drilling new wells, indicated the existing groundwater source developed by wells down to about 500 feet was already over utilized and not adequate to meet future increases in demand for water. Accordingly, the PSWID, working in cooperation with other entities, participated in drilling of a

deep exploration well in Strawberry to investigate the potential for developing groundwater from deeper strata, particularly the Redwall Limestone and associated Martin Formation. The deep exploration well, referred to as the "Strawberry Borehole" was successful in verifying availability of groundwater from the Redwall/Martin strata and provided samples of the groundwater which, when analyzed, indicated the chemical quality of the water was quite good and suited for use in public water supplies.

Subsequently, the PSWID funded the 2002-2003 investigations reported herein for the purpose of developing additional information about potential alternatives to the historically developed groundwater source, with particular emphasis on how to conduct additional investigation of the deep aquifer in the Redwall/Martin strata, including identification of favorable sites for a test/production well or well field and provision of a design for a test/production well.

The 2002-2003 PSWID investigations included a general review of the existing source of groundwater, historically regarded as strata of the Supai Group. The review provided some new information about the local geology that can change the historic perceptions about the sources of groundwater. The new information included recognition of Schnebly Hill strata in the upper part of a sequence formerly regarded as consisting entirely of Supai strata. Other new information included reevaluation of existing pumping test data from PSWID area wells with contemporary aquifer test interpretation techniques. Reexamination of the test data discovered that groundwater flow to wells completed in the Schnebly Hill and Supai strata is controlled by fractures that impose limitations on long-term well yields.

Geologic outcrops were surveyed with precision Global Positioning Satellite (GPS) methods so that an accurate map of the local geologic structure could be constructed. The geologic structure maps produced were used to reassess the distribution of Schnebly Hill, Supai, and Naco strata in the PSWID as well as to evaluate the most favorable location at which to drill a test/production well within the PSWID boundaries. A favorable location was found for construction of a well field into the Redwall Martin strata at depths ranging from 1,950 to 3,100 feet, assuming penetration of 550 feet of Redwall Martin strata.

1.2. GIS Effort

Separately from the geologic and hydrologic investigations, steps were taken to equip the PSWID with computer hardware and software for the District's use in on-going evaluation of groundwater conditions and support of the planning effort. It was intended that the system provided would be suitable for use far into the future. The effort to provide this system was subcontracted to the consulting firm of GeoSystems Analysis, Inc. (GSA) in Tucson, Arizona.

GeoSystems Analysis, Inc. (GSA) has developed a system that will assist the Pine / Strawberry Water Improvement District (PSWID) with long-term monitoring of its groundwater resources. This system integrates two components: a Geographical Information System (GIS), and a groundwater and well Data Management System (DMS) database. The GIS operates in Arcview 8.3, a software package designed by the Environmental Systems Research Institute that permits a user to compile and present multiple data layers from several sources. The DMS is created in MS Access®, and consists of internal data storage tables and an interface that permits the user to select and retrieve existing data, and to enter and manage newly-acquired data.

To initiate both systems, an area of interest to the PSWID was defined, and data were collected in appropriate formats. For the GIS platform, data were compiled from the Arizona Land Resource Information System and the Arizona Regional Imagery Archive. These data included digital raster graphics, digital orthophoto quarter quadrangles, digital elevation models, and Arcview shapefiles. The history of the data compiled for the GIS platform, including how it was developed and how it had been manipulated over time, was collected with the data and incorporated into the system. The GIS platform will allow a user to overlay and compare dissimilar types of information, compile data from several sources into a single presentation, analyze relationships and trends in the data, and design and present interactive maps.

Data incorporated into the DMS is derived from three sources: the Arizona Department of Water Resources (ADWR) Well Registry Distribution Database, the USGS Groundwater Site Inventory (GWSI), and a sample data set of additional well information provided by the PSWID. The data consist of approximately 1,605 wells currently registered with the ADWR, additional construction and water level information for about 100 wells from the GWSI, and synthetic test data for nine wells from PSWID. The user interface, designed by GSA, allows stored data to be retrieved according to criteria, such as dates and locations, selected by the operator. A built-in report produces basic well data, lists water levels, and a constructs a well hydrograph in printable form for any chosen well. Data input forms allow approved system administrators to enter new water level, pumping, and water quality data, and to edit or update existing data. The DMS is designed to be expandable to meet the future needs of the PSWID.

1.3. Summary of Findings

The 2002-2003 PSWID investigations determined that the principal source of groundwater currently in use in the PSWID area (Figure 1-1) is sandstone units in the Schnebly Hill Formation, underlying the Strawberry community area, and fractured sandstone, siltstone and limestone in the upper part of the Supai Group, underlying the Pine area. Analysis of pumping test data from wells in the two communities revealed that the hydraulic performance of the Schnebly Hill

and Supai Group strata is controlled by flow in fractured rock; however, the Schnebly Hill strata also store and transmit groundwater in the porous rock containing the fractures whereas the only storage and flow of groundwater in the Supai Group strata is through fractures with no contribution from the rock containing the fractures.

Accordingly, wells in the Strawberry area have been more reliable than wells in the Pine area because abstraction of groundwater from fractures penetrated by wells in the Strawberry area is supported by release of groundwater from porous rocks in the Schnebly Hill strata. The fractures delivering water to pumped wells completed in the Supai Group strata in the Pine area do not receive groundwater from storage in the surrounding rock and the release of groundwater storage to support pumping at Pine is solely from the fractures.

The response of the Schnebly Hill and Supai aquifers to pumping tests at Strawberry and Pine indicates the hydraulic characteristics of the fracture systems conveying groundwater to the pumped wells impose inherent limitations on groundwater yield. The hydraulic characteristics of the fracture systems dictate that maximum well yields initially available from the fractures during short-term pumping tests will inevitably decrease in response to longer duration pumping. The limitations causing decreasing well yield with increasing pumping duration are mitigated to some extent by release of groundwater to the pumped fractures from the surrounding porous rocks in the Schnebly Hill Formation, giving wells in this formation somewhat more reliability than wells in the Supai Group; however, wells in both aquifers ultimately exhibit decreasing yield in response to increased pumping during periods of increased seasonal demand for water.

The decrease in well yields is experienced on a seasonal basis in response to increased community demand for water during the summer months. The decrease in well yields is a function of increased pumping duration to meet demands for water during the summer months and results from the hydraulic limitations of the fractured rock, not from a seasonal lack of recharge to the aquifers. The onset of water shortages in 1989, when seasonal demand exceeded the production capacities of the well fields, occurred at the end of 12 years of above average precipitation trends in the region. Therefore, it is obvious the water shortages were not the result of drought. The shortages occurred despite above average precipitation conditions and, presumably, above average recharge conditions.

Therefore, it cannot be anticipated that climatic conditions will change for the better and resolve the chronic water shortage problem, even temporarily. However, it can be anticipated that the currently on-going period of below average precipitation conditions will make the water shortage problem worse. This is an important distinction because the ADWR (1996) has stated the groundwater supplies are inadequate due to sensitivity to drought. Long-term

precipitation records showing shortages occurred at the end of 12 years of above average precipitation demonstrate that the shortages were not the result of drought and therefore were caused by an inadequate groundwater resource.

Long-term precipitation records indicate the current below average precipitation trends began at the end of 1992. The same long-term records include periods of below average precipitation trends for as much as 25 consecutive years with only a few included years of above average conditions. Accordingly, the current period of below average precipitation, now in its eleventh year, may be only the beginning of a much longer period of below average conditions.

A factor contributing to the water shortages occurring since at least 1989 has been overestimation of the available water resource by consultants responsible for calculation of the groundwater resource available to the communities, as required under the Adequate Water Supply Program administered by the Arizona Department of Water Resources (ADWR). This factor has been recognized by the ADWR and summarized in a 1996 ADWR Information Packet or the Payson/Pine/Strawberry Area as follows:

> "***The Adequate Water Supply Program began in 1973 because of state law makers' concerns over land in Arizona being sold without available long-term water supplies. To address this concern, the Adequate Water Supply Program was designed to ensure disclosure of the water supply situation of a property offered for sale. When DWR was created in 1980, it assumed administration of the program.***
>
> ***Under the law, a developer proposing to offer four or more lots of subdivided or unsubdivided land for sale of lease must demonstrate to DWR if an adequate water supply will be available to satisfy the needs of the proposed development for at least 100 years. Importantly, if the developer does not demonstrate that an adequate water supply exists, the property may still be developed. However, a statement disclosing the lack of an adequate water supply must be included in the public report and all promotional materials and contracts for the development.***
>
> ***Since 1973, the state has analyzed the water adequacy for every new subdivision in the Payson/Pine/Strawberry area to determine if there is enough water available to meet the proposed use for 100 years. Throughout this time, almost all subdivisions in the area have received a Statement of Inadequate Water Supply from the state. The primary reason for the inadequate supply has been the drought sensitive nature of the area.***" (ADWR, 1996) Emphasis Added

Although the calculations of the 100-year supply for various subdivisions in Pine and Strawberry by various consultants have repeatedly shown the available groundwater resource exceeded anticipated demands, the ADWR has recognized that the aquifers consist of fractured rock with limited storage capacity. Therefore, the ADWR issued Statements of Inadequate Water Supply for "almost all subdivisions in the area" because they correctly perceived that such aquifers are sensitive to drought.

Examination of the 100-year water supply calculations in further detail reveals two limitations in that work. One limitation is that the calculations of groundwater flow through the aquifers were based on the concept that representative values of aquifer "transmissivity" could be used to calculate the groundwater flow. However, review of the test data used to support the calculations reveals that the values of aquifer transmissivity obtained were applicable only to the very limited widths of the fracture systems providing flow to the pumped test wells, not to the entire width of the areas used for calculation of the water resource. Thus, the consultants used values of transmissivity applicable to narrow fracture systems to estimate groundwater flow across broad areas.

The second limitation in the use of the pumping test data from the various subdivisions was the failure to recognize the type of aquifer flow indicated by the response to the tests and the significance of that type of aquifer flow to long-term reliability of well yields. The consultants treated the aquifer response to pumping as if it were radial flow in a homogeneous, porous aquifer material of infinite extent. The equations they used to evaluate long-term response of the wells to pumping were based on the radial flow analytical model of aquifer flow, a model that is not applicable to the aquifers in the PSWID area.

Application by this investigation of more recently developed analytical methods reveals that the aquifer flow to pumped wells is not radial and is not through a homogenous, porous aquifer. The contemporary analytical methods used during this investigation show the flow through the aquifer to pumped wells is along fractures that are highly bounded by relatively impervious rocks that constrain the groundwater flow to essentially linear flow paths. Hydraulic losses along the linear flow paths, and the limited open area of fractures within the aquifer to transmit groundwater flow, exert considerably more constraints on flow to pumped wells than predicted by the radial flow models used by the consultants for their projections. An inherent characteristic of linear flow systems is that the maximum well yields initially available will decline as pumping duration increases. The previous consultants did not recognize the linear flow or its effects on well yields. However, linear flow in fractured rock is the most significant factor contributing to the water supply shortages in the communities of Strawberry and Pine, regardless of drought or fluctuations in recharge to the aquifers.

In fairness to the consultants who performed the previous calculations of 100-year supplies, the radial flow methods they used have been a commonly accepted standard of practice by consultants and regulators for many years. However, as the growth of society places more burdens on our natural resources, consultants and regulators recognize the need to apply more exacting methods for evaluating resources such as groundwater, and more appropriate methods developed from past research are slowly being adopted. The analytical methods used by this investigation for recognizing and evaluating linear flow were developed by the early 1980's, but have taken nearly two decades to be recognized and assimilated into mainstream practice by engineers and hyrogeologists in this country.

The limitations revealed by the results of this investigation, regarding the aquifers currently used by existing private and public water company wells in the area, indicate the aquifer systems in the Schnebly Hill and Supai strata are not an adequate resource to support existing or future water demands in the PSWID area. The ADWR came to this same conclusion for slightly different reasons, and issued Statements of Inadequate Water Supply for most of the area.

The seasonal diminution of well yields in response to increased pumping has resulted in historic and continuing water shortages in both Pine and Strawberry since at least 1989. Development of private land in the communities has not reached full build-out and demand for domestic water supply is anticipated to increase in the future, as more homes and businesses are developed in the area. The on-going water shortages have limited the ability to add more homes to the existing service areas of water companies supplying the communities and future development of private property will continue to be adversely affected by the lack of adequate water supply for the communities. Therefore, there is an immediate need to identify and develop additional sources of water to support both the existing communities and future growth. Since surface water sources are not physically and legally available for immediate development, groundwater resources offer the best potential to develop additional water supplies in a timely manner.

The investigations commissioned by the PSWID, and reported herein, indicate the groundwater resources in the Schnebly Hill and Supai strata, historically used for water supplies in Pine and Strawberry, are inadequate to meet current water demand, let alone to support continued growth and future increases in demand for water. Although the latter conclusion is implicit in the history of on-going water shortages, there has always been some debate as to whether the shortages were caused by an inadequate resource or caused by improper management, operation and maintenance of the public water supply wells. The present investigation has determined that the physical properties of the aquifers are the cause of the shortages, that the seasonal decreases in well yields are a function of the aquifer hydraulics and are predictable, and that the differences in

well yields and reliability of wells between the two communities are caused by the presence of different aquifer systems under the respective communities.

Recognizing the inadequacy of the water resources in the Schnebly Hill and Supai strata to satisfy the demand for water supplies in the PSWID area, this investigation evaluated alternative groundwater sources. The Coconino Sandstone, north of the Mogollon Rim, is recognized as a productive regional aquifer; however, the part of the aquifer available to the PSWID is the recharge area for the aquifer, offering little groundwater storage, and is therefore sensitive to drought and fluctuations in recharge conditions. Although initially attractive well yields might be obtained from the Coconino above the rim, there is no indication that long-term continuous pumping rates can be sustained by the resource, due to the foregoing factors. Therefore, the Coconino Sandstone does not appear to be a favorable source of long-term sustainable water supplies for the PSWID, at least within any reasonable distance from the communities.

The alternative identified by the investigation is a deep aquifer contained in primarily limestone strata in the Redwall Limestone and Martin Formation. These strata are referred to collectively as the "Limestone Aquifer". In order to evaluate the potential to develop groundwater from the Limestone Aquifer, a precision survey of elevations on the geologic structure of the PSWID area was completed with precision GPS surveying methods. Geologic structure maps developed from the survey data were used to examine the relationship of the Redwall/Martin structure to the groundwater elevation measured in the Strawberry Borehole that penetrates the Redwall/Martin strata in Strawberry. A map showing the depth from the land surface to the top of the Redwall Limestone was developed from the survey data and digital elevation models of the local terrain, obtained from State of Arizona databases. The data were evaluated to identify the most favorable location for a test/production well within the private land boundaries of the PSWID.

An associated result of evaluation of the geologic structure in the PSWID area was identification of the Schnebly Hill Formation in the PSWID area, a fact not previously recognized, and considerable revision of the definition of the different layers in the local Supai strata. The foregoing efforts, combined with construction of a structural elevation map from the precision GPS survey control points, supported computer generation of a revised geologic map of the strata underlying the PSWID area. Identification of the extent, thickness and distribution of the revised definitions of the various geologic strata contributed greatly to understanding the performance of existing wells in the area.

The analysis of the data for the Limestone Aquifer indicates the most favorable area for completion of water wells into the Limestone Aquifer is the north half of the south half of Section 20, T12N, R8E, at the northwestern end of the Strawberry Valley. Projections of the potentiometric surface of the groundwater and the geologic structure indicate there is a reasonable expectation that the

entire thickness of the Redwall Limestone in the latter area is fully saturated with the groundwater elevation above the top of the Redwall Limestone. The area is associated with a structural trend that suggests aquifer permeability may be enhanced by fractures and solution openings in the limestone beneath the site.

A test/production well site is recommended near the northwestern corner of the PSWID. The land surface elevation at the site, estimated from the 7.5-minute topographic map of the area, is about 5,870 feet. The depth to the top of the Redwall Limestone at the test/production well location is estimated to be 1,560 feet. It is anticipated that as much as 550 feet of Redwall and Martin strata may be penetrated by a test/production well, providing a total estimated well depth of 2,110 feet. The estimated depth to the static water level at the recommended test/production well site is 1,505 feet. A 12-inch diameter well is recommended.

The investigation reported herein incorporates considerable new information into the status of knowledge about groundwater distribution and availability in the PSWID area. More importantly, the investigation presents new concepts and new ways of perceiving the groundwater systems in the vicinity of the PSWID. The new information and concepts provided by this investigation indicate there is a need for considerable additional investigation to refine the quantification of groundwater resources in the area as well as to quantify existing and future demand for water. It is anticipated that this report will provide a new framework for effective accomplishment of future investigations of the groundwater resources in the PSWID area.

2. GEOLOGIC CONCEPTS

The storage, flow, and distribution of groundwater in the subsurface of the earth are controlled by the nature of the subsurface strata, their porosity, permeability, geometry, and discontinuities. Accordingly, the availability and reliability of groundwater resources in the PSWID are strongly influenced by the geologic characteristics of the area. The purpose of this chapter is to describe the sequence, composition and structure of the geologic strata in the subsurface of the PSWID area and show how those factors relate to the availability of groundwater for development by water wells. This chapter also addresses some of the anecdotal information circulating in the public venue.

The majority of the wells in the PSWID area are completed in a sequence of geologic strata historically referred to collectively as the Supai Group. Weisman (1984) provided the most detailed description of these strata in the PSWID in a Master's Thesis project. Other regional investigators provided descriptions of parts of the Supai sequence based on exposures in nearby Fossil Creek and Calf Pen Canyons and Weisman and Weir (1990) applied the usage of Weisman (1984) to a geologic map of the Fossil Springs Roadless Area.

In 1990, Professor Ronald Blakey with the Department of Geology, Northern Arizona University, published research that identified strata in the upper part of the traditional Supai beds as a new geologic formation referred to as the Schnebly Hill Formation. The research by Blakey (1990) identified the Schnebly Hill Formation in a measured section of outcrops in Fossil Creek Canyon and at locations as far to the east of the PSWID as the Fort Apache Reservation. Recognition of the Schnebly Hill strata as geologically separate and different from the underlying Supai strata was a major contribution by Blakey (1990) to the knowledge of geology in north central Arizona, and by extension, in the PSWID area.

This report extrapolates the measured sections of the Schnebly Hill and Supai Group from Blakey (1990), including their subdivisions, from Fossil Creek into the PSWID. When the distribution of the redefined Schnebly Hill and Supai strata is compared to water well locations and water well pumping test data in the PSWID area, it is readily apparent that not only are the Schnebly Hill strata geologically separate from the underlying Supai beds, but they also provide a different type of hydraulic and hydrologic performance to water wells than do the Supai beds. Recognition of the differences in geology and hydrology between the Schnebly Hill and Supai Group provides the basis to explain many of the differences observed between wells completed in Strawberry versus those completed in Pine. Pumping test data from wells in the two communities demonstrate that the hydraulic response of the Schnebly Hill Formation, which underlies Strawberry, is much more favorable to reliability of wells under long-term sustained pumping durations than the hydraulic response of the Supai, which underlies Pine.

2.1. Stratigraphy

In order to understand the significance of geologic conditions in influencing groundwater availability, it is necessary to understand some basic geologic concepts. The geologic materials of interest to this study are sedimentary materials that were deposited as horizontal strata by the advance and retreat of oceans across the Colorado Plateau area. The individual layers of sediment are regionally extensive and are defined by geologists as "formations" based on their composition (lithology) and age. Formations may be subdivided into "members" or may be grouped together collectively as "groups" of strata with a common depositional environment and age. The science of classifying the strata as to group and formation, etc., is referred to as "stratigraphy" and groups, formations, and members are called "stratigraphic units".

Stratigraphic nomenclature can be quite confusing to everyone, including geologists. This is because early in the process of naming formations, the regional continuity of many of the layers was not recognized and the same layer was given different names at different locations. As geologic mapping and research progressed, it was recognized that many of the different formations with different names were actually laterally equivalent to one another.

The problem of recognizing lateral equivalency of different formations across a region like the Colorado Plateau was further complicated by a factor geologists call "facies". Facies are simply the aspect, appearance and characteristics of a rock unit, usually closely related to or reflecting the conditions of its origin. The problem is that a single layer of strata, geologically equivalent and continuous over a large region, may consist of different facies at different locations. This happens because different types of depositional environments existed contemporaneously across the area where the layer or formation was deposited and different types of materials were deposited contemporaneously at the different locations. Therefore, in the early days of geologic mapping and dating of geologic formations, the equivalency of one type of strata to a different type of strata at a different location was not initially recognized. Accordingly, a regionally extensive formation consisting of sedimentary rocks of the same geologic age may have different formation names at different geographic locations.

For example, the Coconino Sandstone (a formation) in the PSWID area is laterally equivalent to the De Chelly Sandstone of northern Arizona, the De Chelly Sandstone Member of the Cutler Formation in other areas, and the Glorieta Sandstone of New Mexico; yet all were given different formation names at different times and places by different investigators. This report adopts the stratigraphic nomenclature of the Colorado Plateau used in Bills et al. (2000), with appropriate modifications to match conditions at Pine and Strawberry, and makes mention of laterally equivalent stratigraphic names only where appropriate for clarity.

2.2. Porosity and Permeability

Porosity and permeability are important concepts in groundwater flow. Porosity is the voids, pores, or interstices between the mineral grains in a rock mass. The pores may consist of inherent porosity provided by primary interstices between the mineral grains, such as in a sandstone, or may consist of secondary openings caused by fractures. Porosity may or may not be interconnected. Therefore, a rock may be porous but not permeable, if the pores are not well connected. In a permeable rock, the pores are interconnected such that vapor or fluid may flow or be transmitted through the rock mass.

2.2.1. Hydraulic Conductivity

Permeability is the capacity of a porous material for transmitting fluid, usually defined as the relative ease of fluid flow under a known pressure difference. In the science of groundwater, permeability is referred to as "hydraulic conductivity" or the quantity of water that will flow through a unit area under a unit head during one unit of time. Hydraulic conductivity is slightly different than permeability in that permeability is a property of only the porous media whereas hydraulic conductivity is a property of both the porous media and water. Typically in the

United States, hydraulic conductivity is referred to as gallons per day per square foot or cubic feet per day per square foot that reduces to feet per day.

2.2.2. Transmissivity

A related concept is transmissivity. Transmissivity is a macroscopic property of an aquifer, namely the property of transmitting water through its entire thickness. Transmissivity is defined as the rate of flow of water at the prevailing temperature through a vertical strip of aquifer one unit wide, extending the full, saturated thickness of the aquifer, under a unit hydraulic gradient. In other words, transmissivity can be defined as the saturated thickness times the hydraulic conductivity. In the United States, transmissivity is typically referred to in gallons per day per foot or square feet per day.

Hydraulic conductivity as distinguished from porosity is a very important concept. Fine-grained materials such as very fine-grained sandstone and/or siltstone may offer high intrinsic porosity, where the grain-to-grain pores are not filled with secondary cement. Although the volume of water stored in such rocks may be volumetrically large, the pore-to-pore interconnections are relatively small such that they offer significant resistance to groundwater flow. The resistance is quantified in the concept of hydraulic conductivity. The hydraulic conductivity and transmissivity are very low in such rocks, and the flow of groundwater through the fine-grained materials is very slow, thus resulting in low yields to wells.

2.3. Structure

Another important geologic concept is that of geologic structure. The initially flat sedimentary rock layers deposited on the Colorado Plateau are now deformed. The deformation consists of folds and discontinuities. Upward folds are termed "anticlines" by geologists and downward folds are termed "synclines". Folds as such are not a significant factor in the geology of the PSWID area; however, the regional tilt of the Colorado Plateau strata is a very significant factor in the search for additional groundwater resources in the PSWID.

Fractures provide discontinuities in the rock that may be extremely significant to the flow of groundwater to wells. Fractures that offset the strata are referred to as "faults" and are present where tectonic forces have sheared the strata. Fractures that do not offset the strata are referred to as "joints" and may have been caused by tension around folds or other forces causing extension of the rock mass. Therefore, joints are often associated with folds and aligned in some geometric relationship with the axis of the folds. In the Colorado Plateau strata at and north of the PSWID, most of the significant fractures are associated with fault zones. Folds and faults are an important aspect of identifying areas where fractures in the rock may have enhanced hydraulic conductivity for groundwater

flow by providing secondary openings in otherwise inherently low permeability materials.

Bills et al. (2000) describe the potential effects of faults on groundwater flow as follows:

> "***In general, fractures formed under compressional stress tend to remain fairly tight and closed, which results in little if any increase in ground-water flow. Fractures formed under tensional stress tend to be more open, which results in increases in ground-water flow in places. In some cases, the blocks on either side of a fault can grind the sedimentary rock into a fine powder that fills the fault zone and substantially reduces ground-water flow. Information on displacement of faults also is necessary to determine the continuity of water-bearing zones and confining layers.***" (Bills et al., 2000; p.28)

Experience with water wells on the south face of the Mogollon Rim has shown that groundwater production is provided from fractures in most of the strata. In many locations, the inherent hydraulic conductivities of the different strata are too low to support significant flow to water wells; however, wells obtain usable production from groundwater flow in fractures. Even porous units like the Coconino Sandstone provide enhanced production where wells penetrate fractures. Thus, an understanding of the fractures is necessary to an understanding of the factors affecting the availability of groundwater to wells and controlling the reliability of the flow to the wells when they are pumped.

The PSWID and surrounding area is traversed by a number of small tensional faults. Although most productive wells in the area are not located on the faults, local water well drillers report that most of the wells penetrate and produce groundwater from fractures or some type of voids in the local strata within the PSWID. This suggests the wells penetrate open joints, possibly associated with the normal faults, and that the joints may be present for considerable distances on each side of faults. However, other explanations are possible.

One local driller with considerable experience in the PSWID area observes that wells drilled between the toe of the Mogollon Rim and the top of the Diamond Rim typically do not penetrate many open joints in the rock whereas wells drilled between the top of the Mogollon Rim and the toe of the Mogollon Rim typically penetrate quite a few open fractures and "broken" zones (Chris Miller, 2003). This experience is peculiar to the PSWID area, probably because that is where most of the wells have been drilled. As previously stated, most of the wells penetrating open joints or "broken" zones in the subsurface of the PSWID are not closely associated with recognized faults, a fact that suggests the open joints are not necessarily related directly to the identified faults.

The foregoing observations may indicate the presence of moderately deep open joints along the south face of the Mogollon Rim due to a tendency for the strata on the relatively steep slope below the rim to extend or tilt downhill under the force of gravity. Tension exerted on the truncated strata on the south-facing slope below the Mogollon Rim by gravity may explain the apparently widespread presence of open joints penetrated by wells in the PSWID with no apparent close association with known faults.

2.4. Solution and Cementation

Other forms of enhanced secondary permeability providing large values of hydraulic conductivity include enlargement of primary porosity or enlargement of fractures by solution in carbonate rocks such as limestone and dolomite. Solution enlargement of pores and/or fractures by dissolution of mineral matrix can greatly increase the hydraulic conductivity of carbonate strata by offering interconnected conduits for groundwater flow. The other side of this coin is precipitation of carbonate and/or silica cement in pores and/or fractures in rock. Secondary cement fills pores and voids, including fractures, and reduces or eliminates porosity and associated permeability. Accordingly, cemented rocks may not offer much potential to produce groundwater.

2.5. Unconfined and Confined Conditions

Unconfined aquifers are those in which the water table forms the upper boundary of the aquifer and is not confined by an impermeable layer. The groundwater surface in an unconfined aquifer is referred to as the "water table". Confined aquifers are those in which the water level in the aquifer rises above the top of the aquifer and is confined in the aquifer, under pressure, by an impermeable layer. The level to which water will rise in a well penetrating through the confining layer and into the aquifer is referred to as the "potentiometric surface". The potentiometric surface is analogous to the water table but represents a pressure surface whereas the water table is a physical surface. Both terms represent the hydraulic head in the aquifer and when water level elevations from either type of system are plotted on a map and contoured, the resultant map is called a water-table surface or potentiometric surface, as appropriate, and provides an indication of the directions of groundwater flow in the aquifer.

3. GEOLOGIC HISTORY

The PSWID is located on the south-facing slope of a topographic feature called the Mogollon Rim. The Mogollon Rim is an escarpment with as much as 2,600 feet of vertical relief, about 1,475 feet at Pine and Strawberry, comprising the southern flank of the Colorado Plateau in northern Arizona and is the northern limit of a transition zone from the Colorado Plateau structural province to the Basin and Range structural province of southern Arizona. The Colorado Plateau area to the north of Mogollon Rim has been one of the more geologically stable

parts of the earth's crust in the western United States, a fact described by Baars (1962; p. 150), as follows:

> "***The Colorado Plateau physiographic and structural province is a high semi-arid plateau and canyon land that includes most of eastern Utah, the northern third of Arizona, northwestern New Mexico, and the southwestern corner of Colorado . . . The area is typified by sparse desert vegetation and rugged topography developed on generally horizontal sedimentary rocks. Tectonically, the plateau is relatively stable compared with the Basin-and Range structural province on its southern and western boundaries and the Rocky Mountain province of the northern and eastern margins.***"

Thus, the sedimentary strata deposited on that portion of the earth's crust under the western United States have been preserved in the area now known as the Colorado Plateau whereas the same strata in the areas surrounding the Colorado Plateau have been greatly deformed and displaced. The geologic strata of the Colorado Plateau comprise the framework containing the groundwater resources available to the PSWID. Although the PSWID is located on the very edge of the structural plateau, where structural movements have caused the sedimentary strata to be displaced downward along faults, the PSWID is located on the truncated face of the relatively stable strata north of the major displacements along faults. Therefore, the geologic factors controlling the distribution and availability of groundwater within the PSWID area are very similar to those applying to the Colorado Plateau to the north.

Over geologic time, structural warping of the continental plate under the western United States caused repeated advance and retreat of oceans across the area, including that part now preserved as the Colorado Plateau. As much as several thousand feet of sediments were deposited over geologic time representing hundreds of millions of years (Bills et al, 2000). Lithification processes consolidated the thick sequence of sediments into the rock strata presently underlying the Colorado Plateau. Table 3-1 shows the geologic time scale.

Crustal deformation of the western United States started in late Cretaceous time and continued through the early Tertiary in several phases, generally ending in the Paleocene. Geologists call a period of mountain building an "orogeny". The crustal deformation starting in late Cretaceous time was a period of mountain building along the entire western part of the north-American continent and is referred to as the Laramide Orogeny. Compressive forces resulting in folding and faulting of the continental strata were accompanied by emplacement of intrusive rocks and ore bodies in the subsurface and emanation of volcanic materials onto the land surface.

Table 3-1: Geologic time scale.

Eon	Era	Period		Epoch	Time Starting (millions of years)
Phanerozoic	Cenozoic	Quaternary		Holocene	0.01
				Pleistocene	1.6
		Tertiary	Neogene	Pliocene	5.3
				Miocene	23.7
			Palaeogene	Oligocene	36.6
				Eocene	57.8
				Paleocene	66.4
	Mesozoic	Cretaceous		late Cretaceous	97.5
				early Cretaceous	144
		Jurassic		late Jurassic	163
				middle Jurassic	187
				early Jurassic	208
		Triassic			245
	Palaeozoic	Permian			286
		Carboniferous		Pennsylvanian	320
				Mississippian	360
		Devonian			408
		Silurian			438
		Ordovician			505
		Cambrian			570
Proterozoic	Precambrian				4,600
Archaean					

The Laramide Orogeny (and earlier crustal movements) resulted in uplift of the area south of the Mogollon Rim to form a highland consisting of Precambrian granite and quartzite. The same crustal compression, from late Cretaceous through Paleocene time, raised the southern end of the Colorado Plateau structural province to essentially its present elevation, tilting the flat-lying sedimentary rocks 1-2° to the east and north (Bills et al., 2000). Compression and uplift were accompanied by deformation of the sedimentary strata on the Colorado Plateau into broad regional faults and folds. Continued movement along deep seated faults separated the sedimentary strata on the plateau from the Precambrian strata supporting the highlands to the south, thus forming the structural boundary of the south end of the Colorado Plateau.

At the end of compression and uplift, a continuous erosion surface, draining to the northeast, developed across the Precambrian granite and quartzite in the highland to the southwest, and continued across the contemporary Mogollon Rim area, well into the central Colorado Plateau region. Although sediments from this erosion surface are not present in the PSWID portion of the Mogollon Rim, their presence to the east provides the basis for dating the development of the

Mogollon Rim. The clastic debris deposited on the erosion surface have been referred to historically as the "Rim Gravels"; however, Potochnik (1989) proposed the name "Mogollon Rim Formation" for these deposits and described their significance as follows:

> "***The Mogollon Rim formation is an alluvial braidplain deposit that blanketed part of the southern Colorado Plateau and Transition Zone province in east-central Arizona during the Eocene. These coarse clastics were shed northeastward off the flanks of the actively rising Laramide Mogollon highland onto a locally channeled but regionally flat erosion surface that bevels increasingly older Tertiary(?) through Precambrian rocks towards the southwest. Evidence for contemporaneous uplift is recorded by facies relationships across several northwest–trending intrabasinal faults that cross the Transition Zone. Regional transport of sediment was generally eastward toward the Baca Basin in New Mexico. At least three large trunk streams from the Mogollon highland distributed discrete lithologic suites of clasts across a broad alluvial braidplain. The source area extended west and southwest beyond the present Tonto basin and Globe-Miami mining district. Deposition began with the widespread distribution of a coarse boulder conglomerate across the moderately channeled bedrock surface. As bedrock lows were filled, clast size diminished, and arkosic sand dominated the rivers. The alluvial plain was deposited in a semiarid climate, but the source area was sufficiently humid to support large-volume rivers. Paleocurrents suggest a 31° northward rotation of paleoslope following deposition of the basal conglomerate. Increasingly tuffaceous sandstones in the upper member signal incipient mid-Tertiary magmatism in latest Eocene time. The basal contact serves as a datum or post-depositional structural lowering of the Transition Zone. The previously active northwest-trending faults in the area were later reactivated with the opposite sense of movement, causing the Mogollon Rim formation in the Transition Zone to be downfaulted and downwarped at least 760 m to the south.***" (Potochnik, 1989; abstract)

Thus, Potochnik (1989) documents that reactivation of the faults that resulted in the Mogollon Rim occurred sometime after the Eocene. Peirce et al. (1979) date the minimum age of volcanics overlying the rim gravels at 28 million years ago, suggesting the reactivation of the faults resulting in the Mogollon Rim occurred in the Oligocene.

Mayer (1979) states that the Diamond Rim fault was active from 25 to 15 million years ago, indicating local reactivation of the faults along the south end of the Colorado Plateau started in the Oligocene. The reactivated faults are high-angle, deep-seated faults in the Precambrian that developed well before the Laramide Orogeny. As late-Tertiary crustal movement lowered the area south of the Colorado Plateau and the Basin and Range structural province developed, the drainage of the former Eocene erosion surface across the region was reversed along the structural Transition Zone between the Colorado Plateau and the Basin and Range. The ancestral drainage divide, now represented by the Mogollon Rim, was south of the present Mogollon Rim and aligned along the Diamond Rim fault. Continued lowering the Basin and Range province south of the ancestral Mogollon Rim lowered base levels so that the ancestral rim at the southern end of the Colorado Plateau was modified by erosion. Mayer (1979) describes the headward retreat of the escarpment as follows:

> "***The evolution of the Mogollon Rim near Pine, Arizona can be outlined from the data presented above . . . Prior to 30 m.y. ago, drainage was flowing north-northeast from the Basin and Range onto the Colorado Plateau (Pierce et al., 1978). By about 25 m.y. ago the drainage had been reversed, at least locally and a drainage divide established near the present Mogollon Rim. Development of erosional relief followed the drainage reversal. Other separate escarpments may have existed due to resistant formations capping the Supai Formation.***
>
> ***Between 25 and 15 m.y. ago faulting along the Diamond Rim fault superposed a new escarpment on the previous relief. Pedimentation and retreat of this escarpment followed. About 12 m.y. ago, basalts flowed onto the pediment and across the fault. From 12 m.y. ago to the present, the Rim continued retreating while canyon cutting began on the pediment by headward erosion from the south.***
>
> ***The absence of thick fan deposits underneath the basalts suggests that the sediment was transported further to the south. Pine Creek, may have been a tributary to the Tonto drainage system. This supports the work of Pederson and Royse (1970) who believe the East Verde River to have been part of the Tonto drainage system in Miocene time. Therefore, the lowering of the base-level represented by the initial drainage divide and the younger escarpment was due to the combined effect of local faulting and base-level lowering south of the present Mogollon Rim.***" (Mayer, 1979; pp. 54-55)

Mayer (1979) estimates the rate of retreat of the younger rim to its present location as the Mogollon Rim at 354 – 857 meters (1,160 – 2,800 feet) per million years. Mayer (1979) also shows that after retreat of the Mogollon Rim away from the Diamond Rim fault, basalt flowed onto the erosion surface between the Rim and the Diamond Rim fault, forming Buckhead Mesa. Other volcanic deposits are present on different ages of erosion surfaces below the Mogollon Rim at locations such as Hardscrabble Mesa. Volcanic deposits on Strawberry Mountain and Milk Ranch point, however, are above the ancestral Mogollon Rim over which the basalts flowed down onto the erosional surface below the retreating rim.

Weisman (1984) cites several sources of information in describing the relationship between the volcanics and the ancestral Mogollon Rim:

> "***In the Fossil Creek Canyon area, Twenter (1962) reported that the ancestral Mogollon Rim lies preserved against 3,000 to 4,000 feet of Tertiary basalt flows and ash fall deposits. In this area the existence of the ancestral scarp obviously pre-dates the oldest volcanics, although no basal flows were dated. Younger volcanics from the upper slopes of the canyon, however, have been dated by Peirce and others (1979) as 10.16 and 9.3 million years old.***" (Weisman, 1984; p.70)

and,

> "***Volcanic rocks in the study area have been dated as 11.4±0.27 million years old on Baker Butte (Peirce and others, 1979) and 14.23±0.74 million years old on Milk Ranch Point (Peirce and Shafiqullah, 1982, personal commun.) However, these are dates from the top of flows and , thus, are minimum ages. In this study area*** (portions of the Pine and Buckhead Mesa Quadrangles)***, as in Fossil Creek, the rim pre-dates the oldest known volcanics. The thick pile of volcanic rocks that filled the ancestral valley building up and covering the edge of the ancestral rim in Fossil Creek (Twenter's Fig.2, 1962) has no analog in nearby areas. In this study area, basalt either flowed down the southward-dipping erosional ramp*** (from the top of the Mogollon Rim) ***stopping short of the edge or spilled off the ancestral escarpments formed on the southern boundaries of Strawberry Mountain and Milk Ranch Point.***" (Weisman, 1984; p.71)

Weisman (1984) therefore concludes that both Milk Ranch Point and the south end of Strawberry Mountain are remnants of the ancestral Mogollon Rim, preserved from headward erosion and retreat by resistant caps of basalt.

As shown by the brief summary presented above, a significant event in the geologic history of the PSWID area and surrounding area at the southern extent of the Colorado Plateau was the change from deformation and uplift, due to compression, to down-dropping of the Basin and Range province under extension. As previously mentioned, fractures formed under compression may offer less favorable conditions for groundwater flow than fractures formed under tension.

Mayer (1979) summarizes a number of primary references from which he draws the inference that prior to about 30 million years ago, forces between colliding plates of the earth's crust resulted in compression of the continental crust and associated crustal shortening, including the uplift of the Laramide Mogollon highland and the Colorado Plateau, as well as uplift of much of the eastern Rocky Mountains. After about 30 million years ago, development of the San Andreas transform fault realigned the stress directions between the tectonic plates, allowing the western part of the continental plate to change from compression to extension. Formation of the Basin and Range province south of the Colorado Plateau resulted from extension of the crust and continues today.

As summarized in Bills et al. (2000), all the faults in the part of the Colorado Plateau between the Mogollon Rim and Flagstaff are younger in age than the pre-Laramide faults, but include faults formed under both compression and extension. Most of the faults in the PSWID area appear to displace the volcanics as well as the underlying strata, thus indicating they formed in the post-Laramide period of extension and down dropping of the Transition Zone and Basin and Range provinces south of the Mogollon Rim. In explaining the significance of the different ages of faults, Bills et al. (2000) state:

> "***In the study area*** (the Lake Mary area south of Flagstaff and other areas around Flagstaff, all on the Colorado Plateau north of Pine and Strawberry)***, the two principal strikes of faults are north-northeast and north-northwest. The north to northeastward-striking faults are interpreted as reactivation of structure that originates deep in the Precambrian unit by compressional stresses . . . The Oak Creek Fault, which is the principal fault of this type, currently has offsets of 200 to 500 ft along the strike of the fault. In the study area, most of the faults strike north to northwest. The north- to northwest-striking faults are one of the youngest structural features on the Colorado Plateau. Some of these faults are the result of basin and range extension that postdates the Laramide orogeny. Many of these features are within the still active Cataract Fault zone. A few of these faults extend through the volcanic rocks and recent alluvial material, which indicates they are still active. The mechanism for these faults and associated fractures are***

current extensional stress fields and processes now active on the Colorado Plateau . . .

Sedimentary rocks of the regional aquifer are all fractured and folded to varying degrees. Most of the fracturing is related to major fault zones. Although most faults extend through the whole aquifer thickness, other fractures may be formation specific. Thus, these fractures can act as either conduits or barriers to ground-water flow. Shattered rock in these fractured zones is permeable; however, gouge zones, which consist of fine-grained to clay-sized material produced by grinding along the fault plane, are impermeable. In addition, the Kaibab Formation is brittle and contains many joints, solution channels, and other openings that can act as conduits for the flow of water. The lithology of the regional aquifer changes from formation to formation and also vertically and laterally within the formations. The most productive water-bearing material tends to be the fine- to medium-grained sandstones. Because of these structural and lithologic characteristics, the regional aquifer is heterogeneous and anisotropic and has a complex ground-water flow system." (Bills et al., 2000; pp.28-29)

Although faults and fractures formed under tension, during structural extension of the area, may offer better conditions for groundwater flow than faults and fractures formed under compression, it is important to note that faults originally formed under compression may have been reactivated under extension. Accordingly, northeastward-striking faults may also offer good conditions for groundwater flow as described by Bills et al. (2000):

"***These researchers*** (G.M. Mann and Dr. A.E. Springer, geologists at Northern Arizona University) ***found that (1) north-to northeastward-striking fractures originate from compressional stress, (2) north- to northwestward-striking fractures originate from and are related to tensional stresses, and (3) some northeastward-striking fractures are related to reactivation of deep-seated faults caused by regional extension. . . . Northeastward-striking fractures generally parallel the direction of ground-water flow and surface drainage. Surface drainage may be better developed along these older structural features, and dissolution of formational material may have increased ground-water flow along these structures.***" (Bills et al., 2000; p.30)

Obviously, this brief summary of the geologic history of the PSWID area refers to only a small portion of a large body of research about the Colorado Plateau,

development of the Basin and Range structural province, and the formation of faults in the PSWID area. The summary is provided to give the lay reader an overview of the processes that resulted in the contemporary geologic terrain and produced the conditions that affect modern efforts to develop groundwater resources in the area.

4. HYDROGEOLOGIC UNITS

Figure 4-1 shows the generalized stratigraphic section of rock units in the PSWID area. Figure 4-2 is a geologic map showing the distribution of outcrops of the various strata at the land surface. The strata shown on Figures 4-1 and 4-2 include water-bearing materials that function as aquifers as well as relatively impermeable materials that function as confining layers between the aquifers, except where they are fractured.

The water-bearing strata can be generally grouped into three aquifer systems wherein associated strata act collectively as one aquifer, although with different hydraulic properties in the different layers in the system. The three aquifer systems are the Perched Aquifer, the Regional Aquifer, and the Limestone Aquifer.

4.1. Perched Aquifer

As shown on Figure 4-1, the uppermost aquifer system is contained in basalts where groundwater is perched on interbeds of sediments and volcanic ash that prevent the water from draining through the volcanics into the underlying Kaibab and Coconino units. The perched aquifers discharge water around the margins of the volcanics as contact springs. In that part of the Mogollon Rim above Pine and Strawberry, the basalts may be observed resting on an eroded surface cut into Kaibab limestone, Coconino sandstone, and at the southern ends of Milk Ranch Point and Strawberry Mountain the basalt rests on eroded Supai.

Not all of the basalts may contain perched groundwater. In some of the area, recharge entering the basalt probably flows through the basalt to recharge the Kaibab and/or Coconino units. The basalts offer a receptive surface for infiltration of precipitation and runoff and may play an important role in collecting recharge that ultimately enters the underlying Kaibab and Coconino units. The basalt strata are generally located outside of the areas of private property available for development and are therefore not a potential source of water to the PSWID, notwithstanding the issues of low yield and seasonal reliability. An exception is the westernmost end of the private property extending onto the area west of Strawberry Valley. The thickness of Tertiary volcanics in this area may be as much as 1,300 feet or more and is part of the area where Twenter (1962) described several thousand feet of Tertiary basalt flows and ash deposits preserving the ancestral scarp of the Mogollon Rim.

Figure 4-2: Geologic map.

Qal = Modern Alluvium
Qc = Collumium
Tv = Volcanics, mostly basalt
Pk = Kaibab Formation
Pco = Coconino Sandstone
Pshu = Corduroy Member, Schnebly Hill Fm.
Psfa = Fort Apache Member, Schnebly Hill Fm.
Pshl = Bell Rock/Rancho Rojo Mbrs., Schnebly Hill Fm.
Psu = Upper Supai Formation
Psl = Lower Supai Formation
PPn = Naco Formation
Mr = Redwall Limestone
pCm = Mazatzal Quartzite

Private Land Boundary (Approx.)
PSWID Boundary (Approx.)
Geologic Contact (Approx.)
U / D Fault - U = Up; D = Down
Dashed where projected

Geologic contacts not field checked.

Geology modified from: Weir and Beard (1984)
Weisman and Weir (1990)

3813000 3812500 3812000 3811500 3811000 3810500 3810000 3809500 3809000 3808500 3808000 3807500 3807000 3806500 3806000 3805500 3805000 3804500 3804000 3803500 3803000 3802500 3802000

449000 449500 450000 450500 451000 451500 452000 452500 453000 453500 454000 454500 455000 455500 456000 456500 457000 457500 458000 458500 459000 459500 460000 460500 461000 461500 462000 462500 463000 463500 464000 464500 465000 465500 466000

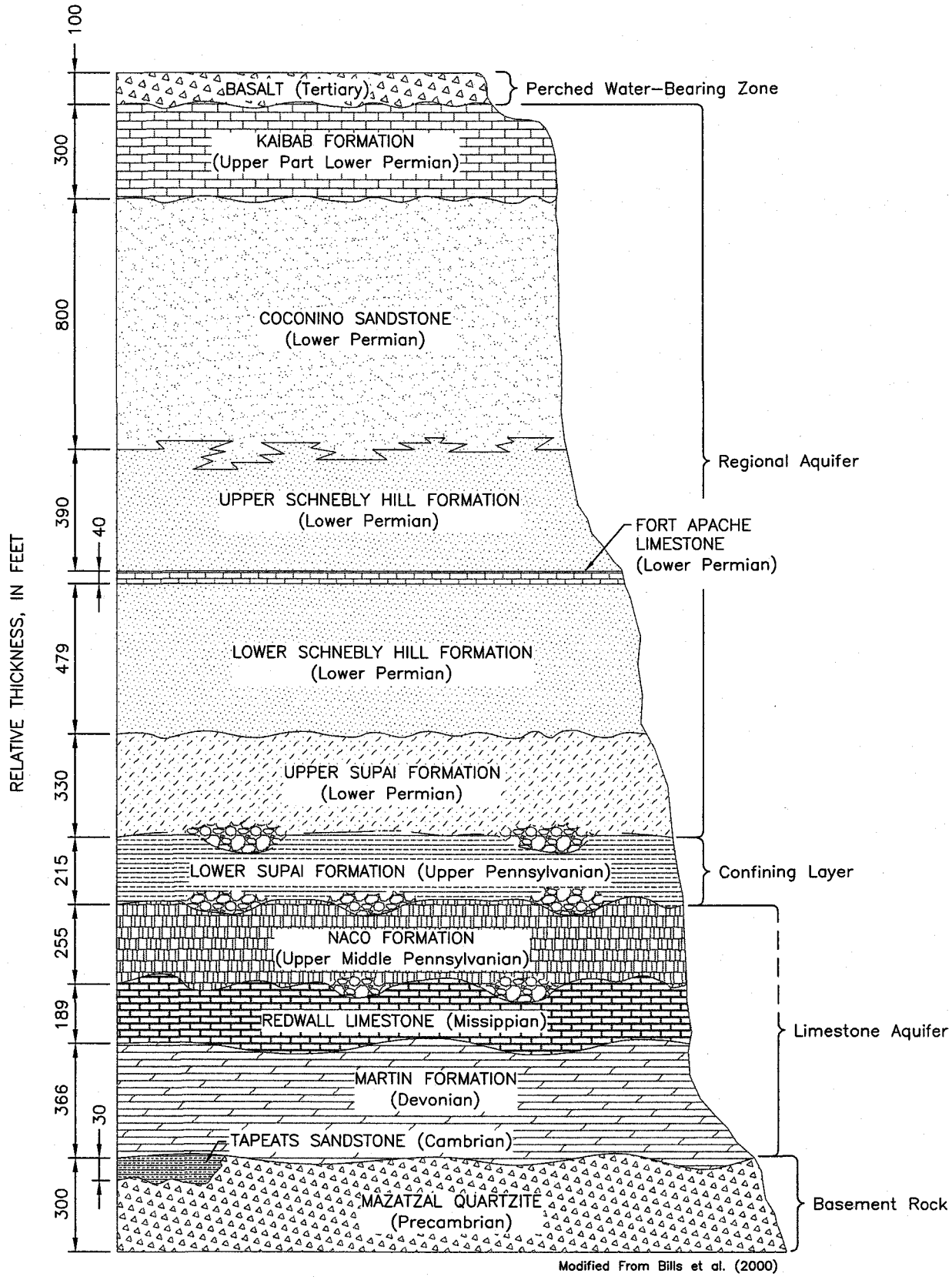

FIGURE 4-1: Generalized Stratigraphic Section in PSWID Area

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4.2. Regional Aquifer

The Kaibab limestone (where present), the Coconino Sandstone, the Schnebly Hill Formation, and, where sufficiently fractured, the upper Supai Formation act collectively as an aquifer system (Figure 4-1). The principal water-bearing zones in the Regional Aquifer are the Kaibab, Coconino, and Schnebly Hill strata. This aquifer system is the source of water to the well fields for Flagstaff, Arizona, and was named the "Regional Aquifer" by Bills et al. (2000), although the Regional Aquifer of Bills et al. (2000) includes middle Supai that is not distinguished separately in the PSWID and regards the lower Supai as a confining unit. The lower Supai probably acts as the main confining unit above the Limestone Aquifer at Pine; however, it will yield water from fractures.

The Kaibab limestone is highly jointed and contains considerable solution cavities that allow water to move rapidly through the formation, where it is present below the water table. It is a receptive surface to receive recharge where it is present at the land surface above the regional water table. The Coconino Sandstone and parts of the Schnebly Hill Formation offer the best primary porosity and hydraulic conductivity to store and transmit groundwater whereas the upper and lower Supai Formation offer limited hydraulic conductivity due to their fine-grained and cemented nature, but they do contribute water to wells from fractures.

Based on the geophysical logs from the test well drilled in Strawberry in 2000, referred to as the Strawberry Borehole, and based on measured geologic sections in Fossil Creek Canyon by Blakey (1990), the generalized thick nesses of the Schnebly Hill and Supai Group in the PSWID area are 909 feet of Schnebly Hill, 330 feet of upper Supai, and 215 feet of lower Supai. The Fort Apache Limestone is located midway in the Schnebly Hill Formation and averages about 40 feet thick with about 390 feet of Schnebly hill sandstone above and about 479 feet of sandstone below the 40-feet thick limestone unit. The approximate distribution of exposures of these strata on the land surface in the PSWID is shown on the geologic map of bedrock outcrops on Figure 4-2.

It is apparent from Figure 4-2 that wells started on the floor of the Strawberry Valley will penetrate 450 to 479 feet of lower Schnebly Hill sandstone, depending on the amount of erosion and alluvial infilling in the valley floor. The amount of Schnebly Hill sandstone (and limestone) available for penetration by wells increases to essentially the entire 909 feet of Schnebly hill in the area between the valley floor and the northern extent of the private lands in Strawberry. The amount of Schnebly Hill sandstone available at the southern boundary of the private lands in the Strawberry Valley probably averages about 400 feet. The lower sandstone of the Schnebly Hill Formation is present under most of the Strawberry Hollow, with about 479 feet of thickness available at the top of the pass between Strawberry and Pine, thinning to zero feet where it is truncated by

the terrain at an elevation of about 5640 feet two-thirds of the way from the pass towards Pine.

Figure 4-2 indicates the strata in the subsurface of Pine are considerably different than at Strawberry. Pine is almost entirely located on upper and lower Supai strata. The only Schnebly Hill Formation in the subsurface of Pine is a narrow zone under the uppermost elevations of the various Portals subdivisions on the west side of Pine Creek where probably less than 200 feet of the unit is available for penetration by wells. For example, the Portals IV Well 1 (Manera, 1994) appears to penetrate 215 feet of Schnebly Hill Formation with the remaining 165 feet of the 380-feet deep well completed in upper Supai strata. The southernmost part of Pine is located over Naco Formation (as defined by Blakey (1990)) less than 200 feet thick and which might be mistaken on well logs for Redwall Limestone due to the predominance of limestone in the Naco.

Thus, the hydrogeologic conditions in the uppermost 400-500 feet of strata underlying Strawberry are much more favorable to groundwater development than any of the subsurface material underlying Pine. This is because the Schnebly Hill Formation underlying Strawberry is a somewhat more permeable sandstone unit than the finer-grained strata of the Supai underlying most of Pine. It is possible that sandstone layers within the Schnebly Hill Formation yield groundwater to wells in the absence of fractures whereas the composition of the Supai strata underneath Pine indicates well yields must likely depend on groundwater flow from fractures.

4.2.1. Kaibab Formation

Weisman (1984) indicates about 300 feet of Kaibab Formation is present in the area above the Mogollon Rim north of the PSWID and divides the formation informally into three parts consisting of an upper porous, fine-grained sandstone; a middle sandy limestone and dolomite; and a basal calcite and silica cemented, soft, fine- to very fine-grained sandstone. Weisman (1984) does not indicate the thick nesses of the individual parts of the Kaibab. The Kaibab is typically quite jointed and exhibits considerable porosity in the carbonate section.

4.2.2. Coconino Sandstone

The Coconino Sandstone is a pale orange to light brown or white, cross-stratified, fine- to medium-grained sandstone consisting of about 95 percent grains of wind-deposited quartz grains. Secondary overgrowths of silica cement are typical in the rock, providing reflective surfaces that give the rock surface a distinctive sparkle in sunlight. The Coconino is relatively porous sandstone and is the principal water-bearing unit of the Regional Aquifer. Although the Coconino exhibits sufficient hydraulic conductivity to provide good yields of water to wells, the highest yields to wells are obtained from fracture zones where permeability is greatest. The Coconino Sandstone along the northern edge of

the Mogollon Rim above the PSWID is at the top of the recharge area for aquifers in the region and therefore is saturated through only part of its thickness and offers only limited groundwater storage due to the fact most of the aquifer is located down-gradient from the Rim. The thickness of the Coconino in the PSWID area was not determined by this investigation; however, interpretation of the geologic contacts plotted on the topographic map base in the vicinity of Pine Creek Canyon suggest about 800 feet of Coconino Sandstone in that area.

4.2.3. Schnebly Hill Formation

The Schnebly Hill Formation is a stratigraphic classification proposed by Blakey (1990) for a sandy red-bed sequence included in the upper part of the Supai by previous investigators. Based on a measured section along Fossil Creek, Blakey (1990), the Schnebly Hill Formation is assigned a thickness of 909 feet for the purpose of this investigation. The Fort Apache Limestone, a prominent ledge-forming unit on the face of the Mogollon Rim above the PSWID area, is located midway in the red-bed sequence. In the PSWID vicinity, Blakey (1990) divides the formation into five members.

4.2.3.1 Sycamore Pass Member

The uppermost member, called the Sycamore Pass Member is less than 150 feet thick at Fossil Creek and thins abruptly to the southeast. The unit consists of nearly 100 percent cross-stratified quartz sandstone and forms cliffs which make the unit hard to distinguish from the overlying Coconino Sandstone with which it interfingers.

This investigation did not identify the thickness of the Sycamore Pass Member in the PSWID; however, plotting of the entire thickness of the members above the bass of the Fort Apache Member on Figure 4-2 places the top of the Schnebly Hill Formation at the base of the cliffs formed by the Coconino Sandstone. This suggests the Sycamore Pass Member thins from nearly 150 feet in Fossil Creek to essentially zero in Pine Canyon. Accordingly, the Corduroy Member appears to comprise the materials between the base of the Coconino and the top of the Fort Apache Member in the PSWID area. If the Sycamore Pass Member is present in Pine Canyon, it has not been distinguished from the Coconino Sandstone; however, projection of the Schnebly Hill Formation thickness from Fossil Creek into the PSWID area on Figure 4-2 suggests the Sycamore Pass Member simply thins out between Fossil Creek and Pine Canyon. Weisman (1984) describes the contact between the upper part of the Schnebly Hill Formation (Weisman's upper Supai) and the Coconino as follows:

> "*. . . the unit is predominantly siltstone and very fine-grained sandstone (with minor limestone) that becomes slightly more coarse-grained toward the top of the unit. (The base of the transition zone, which is marked by 100 to 150 foot cliffs, is*

included in the Lower Coconino Sandstone on the field map because basal cliffs were easier to locate for field identification than to determine where a gradational zone terminates.)" (Weisman, 1984; pp. 52-53)

4.2.3.2 Corduroy and Fort Apache Members

The Sycamore Pass Member overlies and intertongues with the Corduroy Member that consists of siltstone, mudstone, gypsum, and thin carbonates. The Corduroy Member overlies the Fort Apache Member consisting of about 40 feet of limestone and dolomite with a medial limey siltstone sandwiched between the upper and lower carbonate layers and one to two feet of a basal limey siltstone unit.

Weisman (1984) characterizes the Schnebly Hill Formation above the Fort Apache Member as calcareously cemented, including infilling of small fractures with calcite, but other parts of the unit are not cemented or only partly cemented. Weisman (1984) also describes two limestone units, 10-25 feet thick, in the upper Schnebly Hill, above the Fort Apache Member. The predominately fine-grained sandstone and siltstone nature of the Schnebly Hill strata above the Fort Apache Member, combined with the observed cementation, suggests the Corduroy Member is not a major aquifer zone in the PSWID area, but can yield water to wells where fractured. The principal implication of these characteristics is that the bulk of the rock is not favorable to the storage or flow of large amounts of groundwater and must be fractured to yield significant amounts of groundwater to wells.

4.2.3.3 Bell Rock Member

Most of the Schnebly Hill Formation below the Fort Apache Member in the PSWID area is comprised of the Bell Rock Member (Blakey, 1990), consisting predominantly of ripple-laminated, very fine-grained sandstone and silty sandstone. Weisman (1984) and Weisman and Weir (1990) included this unit in their lower Supai unit.

The Bell Rock Member, while part of the Regional Aquifer and favorable to groundwater storage and slow groundwater flow, is fine-grained and is not likely to provide large yields to individual wells except where enhanced by fractures. Although the Schnebly Hill strata in the Regional Aquifer between the PSWID area and Flagstaff are described collectively as yielding considerable groundwater (Bills et al., 2000), much of the groundwater production in the latter area is probably from to the relatively thick (up to 740 feet) of Sycamore Pass Member in that area. The apparent absence of the Sycamore Pass sandstone in the upper Schnebly Hill in the PSWID area indicates the Schnebly Hill, while perhaps more porous, permeable and productive than the Supai, is not a high-

yield aquifer like the Coconino Sandstone and may provide adequate yield to wells only where fractured.

However, the relatively greater porosity and permeability the Bell Rock Member, relative to the Supai, offers groundwater storage that is apparently not present in the fine-grained and calcareous-cemented Supai beds. The groundwater stored in the Bell Rock Member strata, while able to move only slowly through the fine-grained materials, provides a source of groundwater storage that can be released to fractures penetrated by wells, thus sustaining pumping production and greatly improving the reliability of such wells, as compared to wells penetrating fractures in the Supai where the only available storage is within the fractures themselves. Accordingly, it may be anticipated that water wells penetrating fractures in the Bell Rock Member in the lower part of the Schnebly Hill Formation will offer greater reliability during continuous pumping than wells penetrating similar fractures in the Supai.

4.2.3.4 Rancho Rojo Member

Blakely (1990) proposed a new member in the Schnebly Hill, based on a type section at the Rancho Rojo Subdivision about 8 miles south of Sedona. About 25 to 30 feet of the unit are exposed in Fossil Creek Canyon. The Rancho Rojo Member consists of cross-stratified, very fine-grained sandstone that typically forms a distinctive light orange cliff and is mappable as an individual stratigraphic unit across broad areas. The unit was lumped into the lower Supai unit of Weisman (1984) and Weisman and Weir (1990). The porosity of the fine-grained unit may be another source of groundwater storage to be released into fractures to sustain the reliability of production from wells completed into the lower Schnebly Hill Formation.

4.2.4. Supai Formation

The Supai Formation is a thick sequence of very fine-grained red beds that include minor amounts of conglomerate and a few layers of limestone. Weisman (1984) in attempting to describe the unit, made the following statements:

> "***The lower Supai is characterized by a conglomerate sequence, 250 to 270 feet (72-82 m) thick, that is overlain by 570 to 670 feet (174-204 m) of reddish-orange to reddish-brown siltstone*** (Weisman included the lower part of the Schneby Hill in the upper part of this unit). ***The limestone-siltstone pebble conglomerate beds are interstratified with beds of sandstone, siltstone, and minor shale and limestone, . . .***" (Weisman, 1984; p. 40)

and,

> "***No recognizable divisions in the Supai Formation (with the exception of the Fort Apache Member) could be discerned in the field area although Ron Blakey (1984, personal commun.) states that units corresponding to his descriptions of the Supai of central Arizona (1980) are evident in Calf Pen Canyon. . . . The siltstones are calcareous, occasionally micaceous, and predominantly orange red to dark red to pale gray (rarely) in color. Bedding characteristics range from massive (unbedded) to thinly laminated. . . .***" (Weisman, 1984; p. 40)

Separating the Schnebly Hill Formation from the upper part of the sequence described by Weisman (1984) as Supai beds, the lower part of her sequence may be summarized as reddish-orange to reddish-brown siltstone with no recognizable divisions but with lesser amounts of interbedded sandstone, shale and limestone. The most important aspect of this description is that the unit is predominantly siltstone and is predominantly cemented with calcareous cement. The conglomerate beds are described by Weisman (1984) as lenses ten's of feet in extent but laterally discontinuous, and horizontally and vertically gradational with the surrounding siltstone and sandstone.

The description provided by Weisman (1984) of that part of the Supai corresponding to the definition of the Supai by Blakey (1990), is consistent with the characteristics of the upper and lower Supai described by Blakey (1990) when it is recognized that the upper part of the Supai unit of Weisman (1984) is actually the Schnebly Hill Formation. The Schnebly Hill Formation is also included as part of both the upper and lower Supai in Weisman and Weir (1990). Recognizing the Schnebly Hill Formation as a separate and distinct unit, Blakey (1990) divides the Supai into an upper and a lower unit in the PSWID and surrounding area, as follows:

> "***The Supai Formation consists of a poorly studied red-bed sequence and has been inconsistently subdivided and assigned to various stratigraphic units . . . The treatment of the unit herein is considered a compromise, because further detailed study will likely result in more precise definition, correlation, and subdivision.***
>
> ***Two parts can generally be recognized in the central and eastern Mogollon Rim. The lower part . . . consist***(s) ***chiefly of limey and nodular very fine-grained structureless sandstone, trough cross-stratified sandstone and conglomerate, and limey mudstone to the west with addition of micritic*** (finely crystalline) ***and calcarenitic*** (sandy) ***limestone to the east. The unit is primarily reddish gray to reddish brown to locally pale grayish orange in color and forms ledges, steep slopes, and***

> ***local cliffs. T hickness a verages 90 m (300 f t). L ocal l arge-scale, cross-stratified, calcareous sandstone of possible eolian*** (wind deposited) ***origin is present in parts of the Fossil Creek area.*** (Blakey, 1990; p. 1205)

and,

> "***The upper part of the Supai Formation is a complex assemblage of red beds. Sandstone and conglomerate content, composition of conglomerates, and bedding styles vary across the region. . . . To further confuse matters, a complex of fluvial channels, bleached sandstone and mudstone, carbonaceous material, and anomalous high radioactivity is present near the middle of the Supai Formation, probably at or near the Pennsylvanian-Permian boundary. Peirce and others (1977) described and correlated this interval throughout the central and eastern Mogollon Rim and into the adjacent subsurface. At Fossil Creek, the complex fills a northwest-trending channel roughly 1 km wide and 10-25 m deep. This channel, or paleovalley, is filled with fine- to very fine-grained quartz sandstone and limestone-pebble conglomerate. . . . The complex overlies several conglomerate units, one of which is very prominent in the area, and is overlain by several more conglomerate beds.***" (Blakey, 1990; pp. 1205-1206)

Recognizing that Weisman (1984) evidently assigned about 130 feet of red beds at the base of the Supai as defined by Blakey (1990) to the Naco Formation and considered the lower Supai to be 250 to 270 feet thick, the conglomerates described by Blakey (1990) as in the middle of the Supai were described by Weisman to be the lower Supai. Thus, much of what Weisman (1984) described as lower Supai is equivalent to the medial channel sands and conglomerate and upper Supai of Blakey (1990) as well as including that part of the Schnebly Hill Formation located below the Fort Apache Member. Weisman (1984) incorporated into her definition of the Supai everything from the base of the Coconino Sandstone to approximately 130 feet above the top of the interbedded limestone and shale in the Naco Formation. Refinement of the stratigraphy by Blakey (1990) divides the Weisman (1990) Supai sequence into the following units:

Schnebly Hill Formation	909 feet
upper Supai including medial conglomerates	330 feet
lower Supai including about 130 feet of red beds assigned to the Naco by Weisman	215 feet
Total Thickness	1,454 feet

It is important to separate the Schnebly Hill Formation from the Supai Formation, because the two units appear to offer significantly different properties for storing and transmitting groundwater. It is probably less important to separate the upper Supai from the lower Supai; however, the presence of conglomerates and the fine-grained quartz sandstone described by Blakey (1990) at Fossil Creek, and by extension, in the PSWID by Weisman (1984), may offer more favorable conditions for groundwater storage and transmittal in parts of the upper Supai than in the lower Supai.

It is anticipated the generally fine-grained siltstone particle size and pervasive calcareous cementation of the Supai strata limit storage and transmittal of groundwater essentially to fracture openings with little or no significant storage of groundwater in the pores of the rock. This is significant in that wells abstracting water from the fractures must rely solely upon the groundwater stored in the fractures with little or no recharge of the fractures from groundwater stored in the host rock surrounding the fractures. By comparison, the characteristics of the overlying Schnebly Hill Formation suggest depressuring of fractures by wells will result in release of groundwater from storage in the pores in the rocks surrounding the fractures, thus providing much greater reliability to wells completed in fractures in the Schnebly Hill Formation as compared to those completed in fractures in the Supai strata.

4.3. Naco Formation

A good description of the Naco Formation was not found during the literature research for this project. Blakey (1990), summarizing information from Huddle and Drobovolny (1945), describes the unit as ledge and slope forming light gray limestone; nodular bluish-gray to pinkish limey mudstone; gray to purplish to locally reddish sandy mudstone, and rare tan to pinkish sandstone. An outcrop of Naco Formation exposed along Highway 87, north of the East Verde River, includes a lower member consisting of chert breccia, structureless mudstone, and purplish-brown sandy mudstone and sandstone (Huddle and Drobovolny, 1950; p. 89). The thickness of the basal unit is not known, but at least 30 to 40 feet of the materials appear to be present. Exposed above the basal unit is an unknown thickness of alternating beds of limestone, two to three feet thick, interbedded with two- to three-feet thick beds of soft, calcareous mudstone and siltstone.

The location of the contact between the base of the Supai and the top of the Naco Formation on Figure 4-2 is based on structural projection of the unit thicknesses previously described, using the base of the Fort Apache Limestone as the control elevation. The resultant location of the Supai/Naco contact is significantly different than that shown on the U.S. Geological Survey geologic map of the Pine Quadrangle (Weisman and Weir, 1990). The map by Weisman and Weir (1990) locates the top of the Naco at about the location of the top of the upper Supai on Figure 4-2. The reason for the large difference between the location of the Naco contact on the two maps is due to differences in the definition of the top of the Naco Formation as selected by Blakey (1990) in the Fossil Creek measured section and the top of the Naco Formation as mapped by Weisman and Weir (1990) and by Weir and Beard (1984). Weisman (1984) sums up the problem as follows:

> "***Apparently every researcher who investigated the Naco Formation formulated Naco-Supai boundary criteria that best accommodated their own field area conditions. Consequently, there are nearly as many boundaries defined as there are researchers.***" (Weisman, 1984; p.29)

Weir and Beard (1984) described the Naco Formation as about 400 feet thick in Fossil Creek Canyon compared to about 200-250 feet indicated by Blakey (1990). Weisman and Weir (1990) described the Naco as 200-300 feet thick in the Pine quadrangle, where the unit is poorly exposed, but do not state their basis for this conclusion. Weisman and Weir (1990) describe their selection of the top of the Naco as follows:

> "***The boundary between the Supai Formation and the underlying Naco Formation lies in a poorly exposed, gradational sequence of limestone and clastic beds. In this quadrangle the contact was arbitrarily mapped at the base of the lowest limestone-pebble conglomerate. This placement of the contract, judging from the few outcrops observed, is higher than or about the same as that used by Brew (1965, p.81), who placed it at "***the top of the uppermost grayish-red and light-gray mottled calcilutite overlain by a thick, slope-forming, pale-red siltstone and sandstone sequence.***"

Brew (1965) defined the Naco to be 330 feet thick at Fossil Creek. However, other researchers (Huddle and Dobrovolny, 1945) restricted the Naco at Fossil Creek to the ledge and slope-forming light gray limestone and intercalated nodular bluish-gray to pinkish limey mudstone and did not include the upper clastic beds included in the unit by Brew (1965). Blakey (1990) followed the convention of Huddle and Dobrovolny (1945), limiting the Naco Formation to about 200 feet of predominantly gray and purplish-gray limestone and mudstone

and assigning about 130 feet of overlying reddish-brown sandstone and mudstone to the Supai.

Corkhill (2000) identified 255 feet of Naco on the geophysical log of the Strawberry Borehole, putting the Supai/Naco contact at 1,040 feet, but did not explain his reasons. The first major deflection of the Gamma Ray log of the Strawberry Borehole in the interval between 1,040 and the top of the Redwall at 1,295 feet occurs at 1,110 feet, indicating the first mudstone layer in the Naco. This suggests the contact could be placed anywhere between 1,040 and 1,110 feet on the geophysical log. Blakey (1990) makes the following statement in regards to selecting the upper contact of the Naco:

> "***The 40-70 m of rocks in question*** (the upper 130 feet of reddish-brown sandstone and mudstone at Fossil Creek), ***variously assigned to the Supai Formation, Earp Formation, Naco Formation or B-2 . . . is a complicated, very poorly exposed sequence of sandstone, limestone, and fine-grained red beds. Their age (based on a late Virgilian fauna), stratigraphic position, and lithologic character suggest both Supai and Naco affinities. The preference herein to assign the rocks to the Supai Formation (lower part) is perhaps a moot point, given the poor outcrops and difficulty of establishing mappable contacts.***"

Based on the foregoing considerations, the Naco was assigned a thickness of 255 feet for compilation of Figures 4-1 and 4-2. Reducing the thickness from the 255 feet assigned by Corkhill (2000) to the 200 feet measured by Blakey (1990) in Fossil Creek Canyon would be an arbitrary decision under the circumstances and would not resolve the difference between the upper Naco contact on Figure 4-2 and that shown by Weisman and Weir (1990).

Perhaps the best available information is the fact that the Strawberry Borehole began penetrating voids at a depth of 1,041 feet, suggesting that the first limestone units below the Supai red beds probably occurred at that depth. This interpretation is supported by the open-hole geophysical logs of the Strawberry Borehole and is likely the reason for Corkhill's selection of 1,040 feet depth as the top of the Naco at the borehole. If this assumption is correct, the selection of the contact at 1,040 feet by Corkhill (2000), presumably at the first limestone layer, is consistent with Blakey (1990) who excluded the overlying red beds and interbedded thin limestones, and puts the contact at the top of a limestone layer that might be more readily identified in the field than the top of the relatively softer red beds.

The role of the Naco as an aquifer is not well known; however, the log of the Strawberry Borehole indicates 14 intervals where the drilling rods dropped through voids as the borehole was drilled through 255 feet of Naco Formation. It

is not known if the voids were open fractures or solution cavities. They were all above the water table, thus rendering moot the question of aquifer potential in the Naco under Pine or Strawberry; however, the voids suggest the unit could transmit large amounts of groundwater, assuming it were below the water table and the voids are interconnected. As described later in this report, the Naco remains above the potential water table throughout most of the area where water wells might be drilled into the unit on private lands in Pine and Strawberry. As indicated on Figure 4-1, the Naco is considered to potentially act as an aquifer, where it is below the water table, in concert with the Redwall Limestone and Martin Formation.

4.4. Limestone Aquifer

The third aquifer system in the PSWID, in addition to the perched aquifer and the Regional Aquifer, is the so-called limestone aquifer consisting of the Redwall Limestone, the Martin Formation, and potentially, parts of the Naco Formation. Only a small part of the Redwall Limestone is exposed in the PSWID area where a fault brings the unit to the surface at the south end of Pine. The Martin Formation is not exposed at the surface in the PSWID but can be viewed in the East Verde Canyon along the road between Pine and Payson, just north of the river, and in other areas where the East Verde River cuts through the Little Diamond Rim south of Control Road.

Little is known about the Limestone Aquifer in the PSWID area. Wells penetrating either the Naco Formation or the Redwall Limestone in Pine penetrate empty voids above the water table. This has the effect of allowing water flowing into the well bores from the overlying Supai strata to drain down the well and be lost into the empty voids in the Limestone Aquifer. This phenomena is described by Hix (1978) as follows:

> "***An open fracture and solution channel*** (in the Redwall Limestone) ***can be seen just south of Pine along the east side of Highway 87. A crevice about 18 inches wide and dipping steeply downward to the north can be found along the north bank of the stream . . . One mile north and slightly west of this entrance, a dry water well was observed. This well is reported to be 910 feet deep. An unsuccessful attempt was made to sound this well. Over 400 feet of wire did not reach water. This writer observed and noted the well to be blowing air with a definite musty, damp smell. This well may have intercepted a branch of a fracture in the Redwall.***
>
> ***There have been reports of water wells within the Pine area that have been lost when dynamite was used to loosen the rock. This is what would be expected of a formation I which***

the water was controlled by solutions channels rather than a consistent permeability. . . . (Hix, 1978)

The above commentary by Hix (1978) is consistent with the geologic structure of the Pine area. The Redwall Limestone, which is exposed at the south edge of the community, and the overlying Naco, which may contain solution channels, are well above the local water table in the Limestone Aquifer of about elevation 4,365 feet, as measured in the Strawberry Borehole. A well penetrating to a depth of 910 feet in the southern part of Pine would have a bottom elevation of 4,500 to 4,600 feet, well above the water surface elevation of 4,365 feet measured in the Limestone Aquifer at the Strawberry Borehole.

In order to develop groundwater from the Limestone Aquifer, it will be necessary to locate wells down dip, along the north side of Pine or Strawberry. An analysis of the factors that must be considered to site such wells is provided later in this report.

4.4.1. Redwall Limestone

Huddle and Dobrovolny (1952) measured 189 feet of Redwall Limestone along Highway 60 at points 3.7 to 11 miles north of the bridge over the East Verde River, more than 100 feet of Redwall in Fossil Creek Canyon where the base is not exposed, and 67 feet in a draw about a half mile east of the bridge where Highway 60 crosses the East Verde River. At the latter section, the Redwall consisted of white and gray, coarsely crystalline limestone with a few nodules of gray, dense chert. The limestone was mainly in loose blocks with fracture and void fillings of red sandy mudstone from the overlying Naco Formation. Hix (1978) and Weisman (1984) observed the Redwall resting directly on Precambrian quartzite along Highway 60 just south of the junction with Control Road. Accordingly, it is clear the thickness of the Redwall Limestone under the PSWID area may be different from one location to another, depending on whether or not islands of Precambrian rock protruded above the level of deposition in the Redwall sea.

In what appears to be a composite section described as "Measured along United States Highway No. 60, at point 3.7 to 11 miles north of bridge over river", a total thickness of 189 feet of Redwall consists of an upper 108 feet of limestone in beds 10 to 38 feet thick, 2 feet of red mudstone cavity filling, 17 feet of limestone solution breccia, 5 feet of sandstone solution cavity filling, and 57 feet of limestone in beds ranging from 5 to 27 feet thick. Chert nodules and beds of gray- and white-banded chert are present in a number of intervals. Huddle and Dobrovolny report solution breccias and collapse breccias as well as cavern fillings at the top of the Redwall.

The geologic history of the Redwall Limestone includes development of caverns, sink holes and a system of underground or internal drainage through solution-

enlarged channels in the limestone, prior to burial of the Redwall by Naco strata. The fossil caverns and sinkholes are now filled with red sandy mudstone and clay or with collapse breccia in a sandy red clay matrix. Large deposits of travertine (calcium carbonate rock deposited by precipitation of calcite from groundwater discharged out of springs in the Redwall) downstream from Redwall springs such as Fossil Creek Springs indicate that solution channels have continued to develop in the limestone. Wells penetrating solution channels in the Redwall presumably could obtain relatively high yields where the solution channels are below the groundwater level. In order for such wells to be reliable in the PSWID area, it is necessary to drill them as far north as possible so that they will penetrate a part of the Limestone Aquifer offering as much groundwater storage as possible to support pumping of the wells.

The open-hole Gamma Ray log of the Strawberry Borehole from year 2000 and the cased-hole log from 2003 indicate the top of the Redwall is at 1,295 feet in the borehole. The same logs suggest the base of the Redwall may be at about 1,400 feet of depth, indicating about 105 feet of Redwall Limestone are penetrated by the exploratory borehole. However, an alternate interpretation is that the Gamma Ray response at 1,400 feet and below corresponds to cavity fillings in the Redwall. Another large response of the Gamma Ray from about 1,560 to 1,610 feet could also be interpreted to represent the uppermost green shale unit or the entire upper member of the Martin Formation. The latter interpretation would make the Redwall Limestone 265 feet thick at the Strawberry Borehole. The interpreted range of thickness of 105 to 265 feet, based on the geophysical logs, brackets the thickness of as much as 189 feet measured in outcrops south of Pine.

The static water level measured in the borehole January 17, 2003 was at a depth of 1,382 feet, 18 to 180 feet above the bottom of the Redwall Limestone, depending on which interpretation of the geophysical logs is used to identify the base of the Redwall.

4.4.2. Martin Formation

Huddle and Dobrovolny (1952) provide the best description of the Martin Formation and divide the formation into three members. They describe the members as somewhat arbitrary and grading into one another with a total thickness ranging from 300 to 400 feet. They describe 366.4 feet of Martin Formation in exposures along Highway 60 south of Pine.

4.4.2.1 Upper Martin Member

The upper member consists of calcareous sandstone, limestone, and shale ranging in thickness from 32 to 194 feet. The 194-feet thick section is displayed in a canyon about one-half mile east of where Highway 60 crosses the East Verde River. Another section between the East Verde River and Pine, along

Highway 60, displays 103.5 feet of the upper member. A green shale unit is often present at the top of the upper member, but may have been removed by erosion in some areas. The green shale ranges from 6 to 75 feet in thickness (Huddle and Dobrovolny, 1952; p. 76).

The open-hole Gamma Ray log of the Strawberry Borehole from year 2000 provides a strong response beginning at a depth of about 1,400 feet, possibly corresponding to the green shale at the top of the Martin Formation, and indicating about 40 to 50 feet of shale. An alternate interpretation is that the upper member of the Martin is indicated by a strong Gamma Ray response beginning at about 1,560 feet, as previously discussed in regards to the thickness of the Redwall Limestone.

4.4.2.2 Middle Martin Member

The middle member of the Martin consists of a cross-bedded sandstone and a cliff-forming limestone that collectively range in thickness from 50 to 77 feet (Huddle and Dobrovolny, 1952; p. 75). The sandstone ranges from zero to 90 feet thick and includes interbedded sandy shale and sandy limestone. The limestone unit above the sandstone ranges from 38 to 98 feet thick and is characteristically a thick-bedded cliff-forming unit, although it may grade laterally into sandstone locally. The outcrop one-half mile east of where Highway 60 crosses the East Verde River contains 51.3 feet of the middle unit including 13.5 feet of sandstone at the base.

4.4.2.3 Lower Martin Member

The upper part of the lower member of the Martin consists of 77 to 138 feet light buff-weathering beds of thin- to medium-bedded dense dolomitic limestone containing a few chert nodules and interbedded with very thin layers of green shale (Huddle and Dobrovolny, 1952; p.75). The middle part of the lower member consists of 20 to 53 feet of dark-brown or black to light-gray dolomitic limestone that weathers brown and gives off a fetid petroleum odor when freshly fractured. The lower three feet of the middle unit are a transition into the underlying sandstone and consist of dark-gray sandy dolomitic limestone with interbedded sandstone and green to black shale in beds 0.01 to 0.1 foot thick (Huddle and Dobrovolny, 1952; p. 74). The lowermost part of the lower Martin member is a basal sandstone consisting of 10 to 20 feet of light yellow-brown conglomeratic sandstone characterized by granules and pebbles of quartz and quartzite embedded in a fine- to coarse-grained matrix (Huddle and Dobrovolny, 1952; p. 74). Angular boulders are present in the basal sandstone at Natural Bridge.

4.5. Older Strata

The Precambrian strata in the subsurface of the Pine/Strawberry area consist of a quartzite locally called the Mazatzal Quartzite. The quartzite is crystalline and non-porous and will not store or transmit groundwater except in fractures and is therefore not considered to be a significant aquifer for the purposes of this investigation. Erosion of the Precambrian rock surface resulted in considerable relief. Accordingly, different stratigraphic units may be found resting on the Precambrian rocks at different locations.

Strata older than the Martin Formation, are present in low parts of the erosional surface on the Precambrian. Weisman (1984) provides a good discussion of the age and origin of these units. For the purpose of simplification in this report, the units are considered to be the Tapeats Sandstone or an equivalent and consist of a basal conglomerate overlain by a sandstone unit. If these strata are present under the PSWID, their significance to groundwater development is nil; however, they may be hydraulically and hydrologically associated with the Limestone Aquifer, if they offer any potential to store and transmit groundwater. Exposures of these strata along the East Verde River near Highway 87 suggest the strata are not particularly porous and groundwater flow may be limited essentially to fractures.

5. HISTORIC WATER SUPPLY DATA

The request for proposals for this project, RFQ&P/PROJECT NUMBER: P/S 2002-01, required in the scope of work a review of historic documentation in the PSWID files, stating under Desired Outcomes:

> "2. ***Evaluate and establish a baseline reference of prior information and data, including that presently held by PSWID, for new exploration and development of water resources. The list of documents held by PSWID may be found in the Appendix, "Preliminary List of Studies for Pine-Strawberry area."***

This part of the report is provided in response to the requirement for review of historic documentation.

Very little historic information is available about water supply or water demand in the Pine/Strawberry areas. However, the sparse information available documents a history of increasing demand for water in the face of inadequate sources of supply as the population in the communities grew. The historic record suggests the groundwater sources developed by the communities, to supplement the original surface water source in Pine Creek, were vulnerable to drought and/or seasonal fluctuation. The record also indicates the wells in the Strawberry area continued to produce water when many of the wells in the Pine area had

failed. The historic perception that the groundwater sources are sensitive to drought implies that the groundwater systems supplying the wells and springs do not contain adequate storage of groundwater to support demands during periods of diminished recharge or increased pumping duration.

Accordingly, the historic documents blame shortages on drought conditions or, implicitly, on improper management and maintenance of wells and pumps, and do not consider any other possibilities, namely that the local aquifer hydraulic performance may be inadequate to support long-term sustained pumping regardless of recharge conditions related to drought or above average moisture conditions. The inadequacy of the aquifer to support demand was evidently not considered because all of the historic documentation found in the PSWID files indicates the volume of the groundwater resource greatly exceeds the projected demands for water. The historical calculations that water resources availability exceeded demand implied that shortages were either caused by drought or by poor maintenance of the pumping and distribution systems. However, this investigation finds that the historical calculations of water resources availability are highly optimistic and, not only is the available resource likely to be much smaller than estimated historically, the hydraulic characteristics of the aquifers provide inherently limiting conditions that dictate wells will experience loss of yield when subjected to continuously sustained pumping over long periods of time.

The historic record includes hydrogeologic analyses that provide calculations showing the flow of groundwater (groundwater "flux") beneath specific residential developments, combined with groundwater storage, is adequate to supply the anticipated demand for residential water use for 100 years. Yet the historic documents also show that wells in the Pine area in particular have repeatedly lost yield during the summer months. The contradiction between the hydrogeologic predictions of adequate groundwater resources, based on tests of the groundwater system, and the history of inadequate groundwater production, indicates that factors in addition to groundwater recharge and storage influence the reliability of wells in the area.

The following sections of this chapter discuss the historic documentation in detail and provide analyses showing the hydraulic properties of the local aquifer system in the PSWID area, as determined from local pumping tests, have been incorrectly determined with the result that the availability of groundwater has been overestimated and the inherent hydraulic limitations in the aquifer system have not been recognized. The fundamental error in the historic calculations has been the failure to recognize that groundwater flow to the pumped wells, and through the Schnebly Hill and Supai strata in general, is profoundly influenced by fractures.

The calculation of the groundwater flow under the Portal I and Portal II subdivisions (Manera, 1979), the Arizona Department of Water Resources

estimate of 100-year groundwater supplies at Pine and Strawberry (ADWR, 1987), the 1994 calculation of the 100-year groundwater supply for the Portal IV subdivision (Manera, 1994), and the 2002 water resources study of the Pine Water Company and Strawberry Water Company service areas (Glotfelty, 2002) are all based on the assumptions that (1) the aquifers tested exhibited radial flow of groundwater through porous media to the pumped wells and (2) the hydraulic parameters of the aquifers calculated with analytical methods for radial flow are representative of groundwater flow conditions throughout the areas studied.

Reexamination of the latter historic pumping test information and groundwater flow calculations finds that groundwater flow through the aquifer system underlying the PSWID area, in the Schnebly Hill and Supai Group, is not radial flow. The pumping test responses reviewed in the historic documents are diagnostic of groundwater flow restricted to highly bounded flow paths in linear fractures of limited lateral extent, not radial flow through a porous media of widespread extent as assumed in the analyses presented in the historic documents. Consequently, three conclusions are inevitable: (1) the radial flow analytical methods applied to the pumping test interpretations were not appropriate analyses for the type of aquifer response obtained; (2) the values of aquifer transmissivity determined by the inappropriate radial flow analyses and used to calculate groundwater flow are incorrect and are not representative of the hydraulic properties controlling the amount of groundwater flow through the areas studied, and (3) the inherent limitations imposed on long-term well yield by the hydraulic characteristics of linear flow in fractured rock were not recognized.

The foregoing considerations explain the vast difference between the historic analytical predictions of adequate groundwater supplies, exceeding reasonable demand, and the ongoing experience of water shortages in the PSWID area.

The lithology of the Schnebly Hill and Supai strata, described in the previous chapter on the hydrogeologic units in the PSWID area, indicates the capacity of the rocks, consisting of fine- and very fine-grained sandstone and siltstone, to store and transmit groundwater is very limited and, in general, should not be realistically expected to provide the range of yields experienced by water wells in the area. This observation alone is sufficient reason to suspect that the principal source of flow to the wells is through fractures that significantly enhance the hydraulic capacity of the rocks.

However, dependence on groundwater flow through fractures is not sole justification to assume that the hydraulics of the aquifer systems place limitations on groundwater storage, well yield, or distribution of transmissivity throughout the aquifer. Likewise, the presence of a fractured rock aquifer is not sole justification to assume that analytical solutions for radial flow are not appropriate. Sufficient fracturing of a rock mass can provide a fractured rock aquifer that mimics the hydraulics of a porous media, providing an aquifer response to pumping controlled by radial flow. The latter type of fractured rock aquifer does not

impose the hydraulic limitations on groundwater flux and long-term well yields inherent in linear flow controlled by discrete fracture systems that are essentially planar in nature and therefore impose strong boundaries that limit the area of groundwater flow through the rock mass. Accordingly, it is necessary to interpret pumping test data, using conventional analytical methods, to determine if the aquifer response obtained is for radial flow or for linear flow. Application of conventional methods to the pumping test data provided in the historic documents listed above indicates linear flow conditions controlled the test responses.

It is well beyond the scope of this report to explain the highly technical considerations of aquifer test interpretation. However, a brief summary of analytical methodology is appropriate herein to explain the conclusions of this report that the historic pumping test data were not correctly interpreted and to document the primary sources of the conventional methods for analyzing groundwater flow in pumping tests. The fundamental analytical solution for transient groundwater flow conditions was provided by Theis (1935) and expanded on by Theis (1940). The solution is referred to as the Theis non-equilibrium equation or the Theis "type curve", and is applicable to radial flow through a homogenous porous media of essentially infinite extent compared to the area affected by pumping. It was the first non-steady state solution for radial groundwater flow incorporating the concepts of groundwater storage (storativity) and pumping duration (time), thus allowing a solution for transient flow conditions when the rate of drawdown is changing significantly during the early part constant rate pumping, i.e., when the cone of depression is rapidly expanding.

It was soon recognized that after a sufficient duration of constant rate pumping, the rate of drawdown was changing very slowly such that it was essentially steady state or in "equilibrium" with the pumping rate. This simply meant that the cone of depression was no longer expanding rapidly. Cooper and Jacob (1946) developed a modified version of the Theis equation, applicable to the late part of a radial flow response when the rate of drawdown is "stabilized" or in "equilibrium". Use of the term "stabilized" to describe steady state drawdown has caused some confusion to laymen because it does not mean that drawdown has ceased increasing, only that it is increasing at a constant rate. The so-called Cooper-Jacob solution or "modified non-equilibrium equation" is therefore a special condition of the Theis solution and can be applied only when flow to the pumped well is radial and after pumping duration is sufficient to result in steady state drawdown late in a test.

Manera (1994) and Glotfelty (2002) used the Cooper-Jacob solution to analyze the pumping test data in the PSWID area. Presumably, Manera (1979) also used the Cooper-Jacob method; however, the analysis was not available to this investigation for review. Application of standard analytical methods to determine if the historically documented pumping test responses were that of radial flow or linear flow were not applied. Reexamination of the test data by this investigation,

using the standard methods, found that the test responses were those of linear flow.

Contemporary standard methods for distinguishing between radial flow, linear flow, and a host of other potential flow conditions in an aquifer were summarized by Gringarten (1982) with a history of their derivation from groundwater research and petroleum reservoir analysis. The bibliography of the paper by Gringarten (1982) provides an abundance of primary research citations. Boehmer and Boonstra (1986) provided further clarification of the mathematics of linear groundwater flow and presented simple concepts for distinguishing between radial flow and linear flow as well as between different types of linear flow, expanding on the concepts summarized in Gringarten (1982). A comprehensive summary of standard analytical methods for groundwater flow analysis and pumping test interpretation is provided in Kruseman and de Ridder (1991), or in more recently revised editions of that text. The analytical methods used in this investigation to reexamine the historically documented pumping test data were drawn from the foregoing sources of standard methods.

Recognition that groundwater flow to wells in the PSWID area is controlled by linear fractures that constrain groundwater flow to narrow flow paths, relative to the width of the PSWID area, greatly changes the perception of how the available resource must be estimated. Water wells developed in bedrock aquifers that store and transmit groundwater primarily through fractures often exhibit initially high yields that progressively decline with increased pumping duration. The declines in well yields penetrating these types of fractured rock systems are simply a function of the hydraulic factors controlling the flow of groundwater through the fracture systems to the pumped wells and are not necessarily related to seasonal or long-term absence of recharge, although a lack of recharge exacerbates the hydraulic limitations and decline of well yields. Cessation of pumping until groundwater levels recover will restore the well yields in these systems, if inadequate recharge is not an accessory factor. Typically, the time required for groundwater levels to recover may be considerably longer than the preceding pumping duration.

The aquifer hydraulic parameters, such as transmissivity and storativity, determined by pumping tests conducted where fractures control groundwater flow in the rock mass, apply only to the fractures in the rock, not to the surrounding rock mass. Since most of the rock mass in an area being investigated may not be fractured, use of the fractured rock aquifer hydraulic parameters to estimate groundwater flow through the entire width of the area of investigation will greatly overestimate the flow of groundwater through the area, i.e., the "flux" referred to in many of the historical studies, because the flow is limited to the width of the fracture, not the width of the entire area. Likewise, variations in fractured rock hydraulic properties from one test well to another must be taken into account in applying the values in estimates of groundwater flow through an area. Accordingly, the calculation of groundwater flow across a

broad area, based on hydraulic parameters that are applicable only to the limited area of a localized fracture system surrounded by less permeable materials, is a major factor in the difference between historic predictions of adequate water supply and the subsequent shortages experienced.

Wells penetrating fractured rock aquifers that constrain flow to the wells along linear flow paths in the bedrock typically exhibit relatively high yields in the spring and early summer. Well yields decline during summer due to high demands for water and relatively long pumping durations. As demand for water declines in the fall and winter, the pumping durations become small or the wells are not used and the water levels at the wells recover in the absence of long-term sustained pumping. The recovery of the water levels restores the yield of the wells. The pattern of initially high well yields in the spring followed by progressive loss of well yield is typically interpreted to be the result of seasonal recharge patterns with groundwater levels declining due to lack of recharge in the summer. However, in many fractured rock aquifers, the seasonal pattern is controlled by the hydraulics of the fractured rock system and will occur irrespective of the seasonal recharge pattern. Declining groundwater levels in the absence of recharge, of course, aggravates the pattern of declining well yield during times of increased pumping duration, but the primary factor causing the loss of yield is the inherent aquifer hydraulic properties in fractures that cause declining well yield during periods of prolonged pumping, regardless of recharge conditions.

Accordingly, the historic record, although not overly abundant in details, provides conclusive information about the properties of the aquifer system currently utilized by private and public wells in the Pine/Strawberry area. The recognition of linear flow in highly constrained fracture systems, combined with recognition of the distinction between aquifer response in Schnebly Hill strata versus that in Supai strata, provides an explanation for the various conditions historically experienced in the PSWID wells. In addition, comparison of the sparse record of monitored groundwater levels to historic precipitation trends suggests the aquifer system in the Schnebly Hill and Supai strata does not contain sufficient stored groundwater to provide reliability during multiple years of below normal precipitation and recharge, even though historic loss of well yields might be explained solely by fractured rock aquifer hydraulics.

Some of the historic records contained in the PSWID files are discussed below. The records exhibit some of the contradictions mentioned above and document a history of water supply problems. The history of problems is consistent with the anticipated performance of a fractured rock aquifer system, as documented by the available test data. The records discussed may not be comprehensive of all of the history of water supply development and shortages in the PSWID; however, they are comprehensive of the data contained in the PSWID files and are adequate to support an expert opinion about groundwater conditions in the PSWID area.

5.1. Tonto National Forest Report

In 1967, the Tonto National Forest approved an unpublished internal document presenting an analysis of hydrologic conditions in the Pine Canyon watershed. Although this report is not particularly significant to interpretation of groundwater conditions in the PSWID area, it provides some historic insight into development of the water resources in the area. Page 6 of the document, referring to the Pine Creek channel upstream from a diversion structure described as "the Pine Detention dam", states:

> ***"The base flow of this perennial stream approaches 0.5 cfs. At least as much is lost to deep seepage. At 1.0 cfs,*** (cubic feet per second) ***some fraction of flow still runs over the detention dam with the intake closed."*** (Tonto National Forest, 1967; p.6)

Page 24 of the same document provides a summary of stream flow measurements along the length of Pine Creek from an unknown location upstream from Parsnip Spring to the historic diversion structure on Pine Creek. The stream flow measurements are evidently crude measurements based on observation of surface flow rate velocity multiplied times the cross-sectional area where flow rate equals velocity times area. Nonetheless, the measurements reflect an increase in surface water flow from 0.8 cfs at the upstream measurement to 1.3 cfs just above the diversion dam on May 25, 1966. The increase in baseflow on May 25, 1966 is apparently due to groundwater draining from the Coconino Sandstone and the Schnebly Hill Formation. The basis for the conclusion that base flow is about 0.5 cfs is not stated. The measurements showing an increase in flow between the upstream area and the diversion dam indicate the loss to "deep seepage" is in the channel downstream from the dam, not in the channel above the dam, at least at the time of the measurements. This suggests the loss was into the alluvium along the channel, and potentially into the Naco Formation or Redwall Limestone.

The Tonto National Forest report provides the following description of the municipal water supply system for Pine:

> ***"The detention dam is constructed of rubble-masonry and is about four feet deep (total height). . . . The dam was constructed in 1965 and is capable of diverting up to 200 miners inches of water (5 cfs) through a 12" diameter controlled intake. The total capacity of this inlet, with frictional losses considered, approximates four to five cfs (see Appendix p.28). The collecting and distributing system is adequate to keep the 10,000 gal. tank full most of the year, or the present domestic and irrigation needs of Pine satisfied during normal years (about 140 people). A separate system dependent on two wells is used by the subdivided*** (sic)

> ***property owners. George Randall, the Pine Water System manager, is certain that future needs for Pine will require water beyond present storage capacity.***
>
> ***Six months out of twelve (approximately November through May), Pine Water*** (sic) ***consumption (irrigation and domestic use) amounts to only 80% of the total natural stream flow on the average. During June, most of July and October, the full stream flow and more (in storage) is being used. During the other three months*** (sic)***, use averages about 80% of the natural stream flow. This*** (sic) ***data was provided by Mr. Randall."*** (Tonto National Forest, p. 9)

The foregoing commentary implies that in 1966-1967, all of the stream flow in Pine Creek, as augmented by 10,000 gallons of storage, was needed to meet the demands of a population of 140 people in the months of June, July, and October. Why 80 percent of the stream flow was adequate to satisfy demand in August and September is not stated; however, those are months of summer thunderstorm activity and stream flow in August and September may therefore have been greater than in June, July, and October.

The statement that "the full stream flow and more" was used in June, July and October suggests the stream flow was marginally adequate for the population of 140 people. However, a base flow "that approaches 0.5 cfs" is a flow that approaches 224 gpm. A flow of 224 gpm is far more than needed to satisfy municipal water requirements for a population of 140 people, a consideration that suggests the 1967 Tonto Forest report does not provide all the facts. Either the stream flow that could be diverted in June, July and October was much less than 0.5 cfs or, more likely, a significant part of the diverted flow was used for non-residential irrigation rather than for domestic use including residential lawns and gardens. Otherwise, use of 100 percent of a base flow of 0.5 cfs for residential use for 140 persons is equivalent to 2,308 gpd/c (gallons per day per capita).

5.2. Hydrologic Evaluation of the Portal Subdivisions

A report prepared by Manera and Associates, Inc. (Manera, 1979) provides some insight into water use in the PSWID area in the 1970s as follows:

> ***"There are presently 51 residential units in the subdivisions*** (Portal I, II, III and Canyon Shadows)***. Twelve units (24%) are full time water users with the remaining 39 units (76%) being part time or weekend water users. A seven year history shows that the average water usage is 3010 gallons per month for the full time residents and 648 gallons per month for the part time or weekend users."*** (Manera, 1979; p. 1)

In addition, the report describes the results of aquifer tests and provides well depth and yield data strongly indicating well yields were controlled by highly bounded fractured rock flow. However, the calculation of groundwater flow through the area, groundwater "flux", was based on the concept that aquifer hydraulic constants derived from radial flow interpretation of the pumping tests were representative of groundwater flow conditions across the width of the groundwater flow path, taken to be equal to the width of the subdivision, not the limited width of a fracture system.

5.2.1. Water Use

The data provided by Manera (1979) indicates a water use of about 100 gpd (gallons per day) per home for full time residents. Although Manera (1979) does not indicate the number of residents per home, an assumption that residency ranged from 2.0 to 2.5 residents per home provides a water use of 40 to 50 gpd/c for full time residents. Although the foregoing per capita statistics are assumed, they are not an unreasonable range of assumption for the area. By comparison, if one assumes four weekends per month or 8 days of occupancy per month for 2.0 to 2.5 people per home for part time or weekend users, the water use is 81 gpd per home or 32.4 to 40.5 gpd/c. This is not inconsistent with the use by full time residents but does not support the currently prevailing perception that per capita water use by part time residents is much greater than by full time residents, at least not as of 1979.

5.2.2. Water Well Data

Minera (1979) summarizes statistics for five wells drilled in the NE quarter of section 25 and one well drilled in the SE quarter of section 24, T12N, R8E. Figure 5-1 shows the location of the wells. Well depths ranged from 177 to 480 feet and well yields ranged from 8 gpm to 95 gpm. There was not a correlation between well depth and well yield despite the fact all six wells were drilled in geologically similar terrain along the west side of Pine Creek canyon. The Myers-Portal I, Well 1, and the Myers-Portal II, Wells 2, 3, and 5 wellheads are below the top of the upper Supai, defined in this report to be about 330 feet thick. Accordingly, the latter wells are completed in upper Supai, as used herein, and Wells 3 and 5 may penetrate slightly into the lower Supai. The Meyers-Portal III well in Section 24 and the Portal II Well 4 wellheads are near the middle of the lower part of the Schnebly Hill Formation and the well depths of 480 and 405 feet, respectively, indicate these wells penetrate through the Schnebly Hill and into the upper Supai. The static water levels of 202 and 167 feet, respectively, are at or above the estimated base of the Schnebly Hill Formation at these locations; therefore, it is not possible to determine if the water came from the Schnebly Hill, the upper Supai, or a combination thereof.

Figure 5-1: Locations of wells from Manera (1979).

Qal = Modern Alluvium
Qc = Collumium
Tv = Volcanics, mostly basalt
Pk = Kaibab Formation
Pco = Coconino Sandstone
Pshu = Corduroy Member, Schnebly Hill Fm.
Psfa = Fort Apache Member, Schnebly Hill Fm.
Pshl = Bell Rock/Rancho Rojo Mbrs., Schnebly Hill Fm.
Psu = Upper Supai Formation
Psl = Lower Supai Formation
PPn = Naco Formation
Mr = Redwall Limestone
pCm = Mazatzal Quartzite

Private Land Boundary (Approx.)
PSWID Boundary (Approx.)
Geologic Contact (Approx.)
Well 3 Well from Manera (1979)

Well locations not field checked.

Myers-Portal III
Well 4
Well 3
Well 1
Well 2
Well 5

Geology modified from: Weir and Beard (1984)
Weisman and Weir (1990)

The lack of correlation between the well depths and the well yields implies that the water-bearing zones are not related to individual layers within horizontally bedded strata. Likewise, there is no evident relationship between well yield and whether the wells were completed in the Schnebly Hill Formation or upper Supai. Therefore the availability of water to the wells was controlled by other factors, probably the number and openness of fractures penetrated by the well bores. This interpretation is consistent with the fine-grained nature of the Schnebly Hill and upper Supai strata, as previously described.

Manera (1979) used the historic water demand of 3,010 gallons per month per household cited above as the basis to predict a water demand of 31 gpm or 50 acre-feet per year (ac-ft/yr) for full time residency of 443 units in the subdivision areas. He performed pumping tests on several of the Portal wells and analyzed the data from one well. Based on the aquifer transmissivity determined from the pumping test and the hydraulic gradient across the area determined from groundwater elevations in the six wells, Manera (1979) calculated that the flow of groundwater under the property was 167 gpm as compared to the demand of 31 gpm.

Unfortunately, the pumping test data compiled by Manera (1979) are missing from the PSWID records. Review of the Manera (1979) report indicates the tested well from which transmissivity was calculated was the well referred to as the Myers-Portal III well in the SW, NE, SE, Sec 24, T12N, R8E, that penetrates about half of the lower Schnebly Hill Formation and most of the upper Supai. The well was reportedly cased to its total depth of 480 feet. The static water level was 202 feet in February 1979. Manera (1979) states that when the well was tested at 80 gpm, the pump broke suction after 1080 minutes of pumping. The pumping rate was then reduced to 60 gpm, after allowing the well to recover to static, and after 1160 minutes at 60 gpm, the pumping water level stabilized at about 322 feet (about 119 feet of drawdown) for an additional 1000 minutes of pumping.

5.2.3. Hydrogeologic Interpretation

The Manera (1979) report offers a number of insights into the aquifer conditions in the Schnebly Hill and upper Supai, even without the test data. The first insight is provided by the description of the test discharge rate. Typically, some initial pumping is performed prior to the accomplishment of the constant rate test. The initial pumping is usually a stepped rate test to evaluate the well hydraulics (as opposed to the aquifer hydraulics), but may be some short tests to establish a simple relationship between the pumping rate and the drawdown. This relationship is referred to as the specific capacity of the well and may be expressed as the gallons per minute rate divided by the drawdown in feet. The relationship, combined with some judgment, is used to select a pumping rate that can be sustained for the planned duration of the test, without the pumping water

level in the well declining to a depth where the test pump breaks suction due to inadequate submergence.

The steps taken to determine that an initial pumping rate of 80 gpm was appropriate are not described by Manera (1979); however, the fact that 80 gpm was sustained for 1080 minutes before drawdown became excessive for the test pump setting, rather than in a few hours or less, suggests the 80-gpm rate was selected on the basis of careful consideration of the early time-drawdown response in the well. After the 80-gpm rate proved excessive, the well was allowed to recover and was pumped at 60 gpm. Manera (1979) describes drawdown as "stabilized" after 1160 minutes of pumping at 60 gpm.

The water level in a pumped well does not stabilize unless there is a source of recharge such as a lake or stream contributing recharge that offsets the need for the pumped water to be derived from stored groundwater. Without a source of immediate recharge, the pumped water must necessarily be derived from stored groundwater and drawdown must continue as groundwater is removed from storage in the aquifer. Therefore, when Manera (1979) states that drawdown stabilized for the last 1,000 minutes of the test, that is a strong clue that the 60-gpm test rate in the last 1,000 minutes was actually in a slow decline such that the pumping water level stayed nearly constant. This is a very typical condition where the discharge rate is not maintained constant, but is allowed to decay slowly so that the decreasing rate of discharge and the time-drawdown response in the well meet at a stabilized pumping level that may be maintained for a long period of time with submergence of the pump inlet marginally adequate to prevent a complete break in suction at the pump. The discharge rate continues to decrease under such conditions; however, at a very slow rate of decrease.

The description of the problems with the pumping test rate and the description of stabilized drawdown provided by Manera (1979) therefore indicates a situation in which the best projections of the drawdown rate, by experienced personnel, were not successful in preventing excessive drawdown within the duration of the pumping test, at either 80 gpm or 60 gpm. The descriptions provided by Manera (1979) appear to be a classic example of a well in an aquifer where the flow of water to the well is controlled by linear flow along fractures rather than by radial flow through a porous media. Preliminary projections of drawdown in such wells, based on radial flow concepts, always underestimate the rate of drawdown and result in excessive drawdown during pumping tests. Thus, the experience with pumping rate and drawdown described by Manera (1979) is a strong clue that the well was competed in a fractured rock aquifer exhibiting a linear flow response.

The latter conclusion is supported by the data provided by Manera (1979), indicating well yields of 8, 10, 13, 35, 60 and 95 gpm from the six wells described in the report. As previously discussed, the well yields do not correlate strongly with either the geologic stratification or the well depths. The wide range of well

yields and lack of strong correlation between water-bearing zones indicate the wells most likely obtain groundwater from fractures intercepted by the well bores. The possibility that the water-bearing zones in the Schnebly Hill and upper Supai aquifer system may produce from fractures of such limited extent that they constrain aquifer flow to linear paths, as compared to production from a homogenously porous media or rock so densely fractured that radial flow to a well is possible through the fractures, has profound implications regarding the volume of groundwater stored in the aquifer as well as the potential for variability in groundwater flow and availability to wells across the area.

Fractures of limited distribution and extent offer far less groundwater storage capacity than a porous media such as sandstone. Likewise, the amount of groundwater flowing through the fractures may be highly variable from one location to the next, depending on the size and number of fracture openings and the degree of interconnection between fractures. The latter conditions may be the cause of the wide range of well yields obtained by the wells described in Manera (1979). If this is the case, the prediction of groundwater flow across the area, based on the tests of one well, may not be representative of the average conditions in the area. This factor may contribute considerably to the differences between historic technical quantifications of the groundwater resource and subsequent shortages experienced at levels of demand that were less than the predicted resource, inherent limitations in aquifer hydraulic properties notwithstanding.

The Manera (1979) report makes a valuable contribution to our understanding of the Schnebly Hill and upper Supai aquifer system. Recovery of the field data from Manera's 1979 tests, missing from the PSWID records, would be a worthwhile endeavor. Those data are bound to provide a better understanding of the aquifer when evaluated in the light of modern aquifer test interpretation techniques that were not universally known or available in 1979.

5.3. June 1987 Preliminary Report

During the late 1970's and early to mid-1980's, the Pine/Strawberry area experienced considerable growth in the form of residential subdivisions. The historic documents indicate growing concern about water supplies for the area. A September 9, 1987 letter from the Gila County Development Office Director, Mr. Bob Bigando, to Mr. Dale Jones and Concerned Residents of Pine/Strawberry touches on these issues as follows:

> "***Thank you for inviting our office to participate in your meeting regarding the future water supply for the Pine/Strawberry community.***
>
> ***For many years we have been aware that a water delivery problem existed in the Pine/Strawberry community and were***

concerned about the long term (sic) *capacity of the water supply to support the rate of development that the area experienced in the late 1970's and early 1980's.*

Since no hard data existed regarding the potential water capacity, we advised the Board of Supervisors of the desirability of contacting the Department of Water Resources and requesting that a study be done. In response, the Board submitted a request to the DWR, and, as you are aware, a preliminary report was issued in June.

Though our Department was not officially notified of the report, we were given a copy to review, by Supervisor Jones. Subsequently, we contacted the Department of Water Resources and were advised that a "final" report would be issued following a comment period. In response to our most recent inquiry, the DWR indicated that the response period could last up to three years. We concur with the residents of Pine/Strawberry that we need to begin to take some positive steps to address the issues raised i n the preliminary report pending issuance of the final report.

We are deeply concerned, but not alarmed, by the content of the preliminary report. Were there a number of proposed new developments in the Pine/Strawberry area, we would be even more concerned.

The phenomenal increase in subdivision development that was experienced in recent year, however, has virtually ground to a halt. At the present time there are no proposed subdivisions pending in the Pine/Strawberry area.

No final plat or development plans have been submitted for the proposed Solitude Pine Resort which was indicated as a concern to the residents in a recent newspaper article. As it now stands, the preliminary plat has expired, and any further development would be subject to a complete re-review and public hearing process. Further, we have had no communication from the developer in over a year.

Under these circumstances, we feel that [it] *is advisable to proceed very deliberately and to carefully explore all the options available to us in order to see that such future development as may occur does not jeopardize the welfare of the current residents and property owners of Pine and Strawberry. If the Pine-Strawberry* (sic) *is to continue to grow*

we share your concern that it grow at a rate and to an extent that water supplies will permit. . . ."

5.3.1. Groundwater Supply

The basis for the tentative conclusions and recommendations stated in the Gila County Development Office letter of September 9, 1987, is provided by the preliminary Arizona Department of Water Resources report. The preliminary report of June 1987 (ADWR, 1987) compares groundwater supply to water demand in the Pine/Strawberry area as of 1986. The ADWR (1987) report refers to annual groundwater flow into the area from the adjacent "lateral Sandstone aquifer", presumed to be the Coconino Aquifer, as "groundwater flux". Table 1 of the ADWR (1987) preliminary report summarizes the 1987 perception of the available groundwater resource.

Table 5-1: Reproduction of Table 1, ADWR (1987).

Table 1
Groundwater Available
Pine-Strawberry Area (1986)
(reproduced from (ADWR, 1987; Table 1)

Area	Groundwater In Storage *(AF/YR)	Groundwater Flux (AF/YR)	Total (AF/YR)
Pine Creek	22	237	259
Strawberry Hollow	14	38	52
Strawberry Canyon	57	79	136
Total	93	354	447

*Amount in storage distributed over 100 years.

The context of the ADWR (1987) report indicates the estimates of groundwater flux are based on the concept of a representative value of aquifer transmissivity applied across the entire width of the areas addressed, and do not take into consideration the possibility that groundwater flow is constrained to relatively narrow fracture systems, rather than flowing through widespread porous rock under the area. Likewise, the estimates of groundwater storage presented in Table 5-1 were based on application of a representative value of storativity (effective porosity) to the entire rock mass, not to a fracture system comprising a limited part of the overall rock mass. Recognizing that the wells in the area provide response to aquifer tests indicating linear flow of groundwater along fractures that constrain groundwater flow and storage to narrow zones, it is clear that the rough estimates in the ADWR (1987) report likely overestimate the availability of groundwater.

The ADWR (1987) estimates of the available groundwater resource as of the end of 1986 are for groundwater contained in the Schnebly Hill-Supai strata, characterized in the ADWR (1987) report as the "Mudstone/Shale/Limestone aquifer". The perception in 1986 and 1987 was that the Mudstone/Shale/Limestone aquifer contained considerable stored groundwater, at least as compared to the local water demand. However, it was also recognized that the groundwater levels at the time of the 1987 report were high due to a period of above normal recharge. These perceptions were described as follows:

> ***"A large increase in the groundwater elevation in the Mudstone/Shale/Limestone aquifer occurred between 1977 and 1987. This variation is probably associated with the "wet" period that occurred within those years. In spite of the abundance of precipitation within that period, water elevations in the lateral Sandstone aquifer (Coconino Sandstone) did not show any gains, but suffered severe declines (1.5-13.4 ft/yr). This probably caused by the limited vertical extent and the fractured nature of the aquifer, which lacks the storage capacity of the Mudstone/Shale/Limestone aquifer. A conservative estimate of the groundwater in storage in the Mudstone/Shale/Limestone aquifer yielded a value of about 2160 acre-feet*** (under Pine Creek, or about 22 ac-ft/yr for 100 years).
>
> ***The groundwater flux coming from the northeast paralleling Pine Creek was estimated to be about 11.0 AF/yr. The groundwater flux coming laterally from the sandstone formation was estimated to amount to about 226 AF/yr." (ADWR, 1987; pp. 1-2)***

The above statements are typical of much of the contradictory historical commentary about groundwater conditions in the PSWID area. It is clear from the above statements that groundwater levels in the nearby regional Coconino aquifer were declining at 1.5-13.4 feet per year. If correct, this meant that discharge from the Coconino was exceeding recharge, a condition inconsistent with the perception of a "wet" period. As far as the Coconino aquifer was concerned, this was a "dry" period and groundwater levels were falling accordingly. (In fact the period from 1977 to 1987 was a period of above average precipitation trends; therefore, falling groundwater levels in the Coconino aquifer during the same period of time simply indicate that nothing is simple as it first appears to be in regards to hydrology.)

5.3.2. Groundwater Fluctuations

If the 1977-1987 period was a time of declining groundwater levels in the Coconino aquifer, implying below normal recharge to the regional aquifers, why were the groundwater levels in the Schnebly Hill-Supai strata (Mudstone-/Shale/Limestone aquifer) reportedly rising? The 1987 ADWR report explains that this is the result of less groundwater storage in the Coconino aquifer than in the Supai strata. The contradiction in the latter statement is self-evident.

If the groundwater levels in the Coconino were declining due to inadequate recharge, the transfer of that same amount of water into the Schnebly Hill-Supai strata from the Coconino would not cause an increase in groundwater levels in the Schnebly Hill-Supai if the Schnebly Hill-Supai offered greater groundwater storage capacity than the Coconino. In order for groundwater levels to rise in the Schnebly Hill-Supai strata as the result of natural recharge plus drainage of water out of the Coconino and into the Schnebly Hill-Supai, the potential storage volume of the Schnebly Hill-Supai would necessarily be equal or less than that of the Coconino. In general, the groundwater storage properties (effective porosity) of un-cemented Coconino sandstone significantly exceed those of the relatively fine-grained Schnebly Hill-Supai strata, except where the Schnebly Hill-Supai strata are affected by localized fractures and/or solution cavities. Therefore, it is anticipated the Coconino materials potentially offer more groundwater storage than do the Schnebly Hill-Supai strata on a unit volume basis.

The fact that the ADWR observed declining groundwater levels in the Coconino aquifer from 1977 to 1987 while groundwater levels in the Schnebly Hill-Supai strata in the Pine/Strawberry area increased is not an unusual phenomenon in groundwater hydrology; i.e., it is not unusual for groundwater levels on one end of an aquifer system to rise while groundwater levels on the other end of the system decline. While it sounds trite to say that this happens because "water runs downhill", this is exactly what happens. During periods of drought or below average recharge, the groundwater stored in the recharge area of an aquifer continues to drain toward the lower end of the system, even though more recharge may not enter the aquifer. This causes the groundwater levels in the recharge area to decline because there is no groundwater storage up gradient from the recharge area to replace the natural flow of groundwater toward the low end of the system. This is why recharge areas experience relatively larger seasonal and long-term fluctuations, compared to down-gradient areas in an aquifer, in response to fluctuations in recharge.

By comparison, down-gradient areas receive the benefit of the groundwater flowing from recharge areas. Thus, while recharge areas may be in a period of declining groundwater levels, areas downstream may continue to exhibit rising groundwater levels while they receive the benefit of the groundwater flow draining out of the recharge areas. Taking this concept a step further, if the down-gradient part of a flow system offers less storage volume than the recharge

area per unit of material, the rise in groundwater levels in the downstream area due to the receipt of flow from the upstream area will thus be accentuated in both absolute rise and duration.

Considering the fact the Coconino sandstone generally offers considerably more effective porosity than the Schnebly Hill-Supai strata, it is not unreasonable to conclude that a transfer of groundwater from the Coconino strata into the underlying Schnebly Hill-Supai strata would result in rising groundwater levels in the Schnebly Hill-Supai while groundwater levels in the Coconino declined. The latter concept is also consistent with the idea that most of the groundwater storage and flow in the Schnebly Hill-Supai strata is controlled by fractures of limited extent, relative to the overall mass of rock, and therefore of limited groundwater storage capacity. Therefore, the most likely explanation of why groundwater levels were observed to rise in the Schnebly Hill-Supai strata while groundwater levels in the Coconino strata declined, is the small groundwater storage capacity of the Schnebly Hill-Supai strata, relative to the Coconino, and the fact that the Schnebly Hill-Supai strata tend to restrict the downward drainage of groundwater out of the Coconino.

5.3.3. 1986 Estimate of Water Demand

The 1987 ADWR report summarizes groundwater availability for Strawberry Canyon, Strawberry Hollow, and Pine Creek as 447 acre-feet per year. The demand for water in these same areas, calculated by ADWR for the end of 1986, is summarized as follows:

> ***"The water demand in the Pine-Strawberry area has increased enormously in the last 8 years. From a total water demand of about 163 AF/yr in 1979 to about 384 AF/yr in 1986, a 135% increase in water use for that period.***
>
> ***The drilling of new private domestic wells plus new irrigated areas account for a large part (~69%) of that increase. In 1979, there were about 96 private wells registered with the Department. In 1986, this number had increased to about 164. The irrigated area, for the same period, increased from 27 to about 119 acres. The water companies, on the other hand, have increased their water demands, at a more or less constant and slower pace (~9 AF/yr).*** (ADWR, 1987; pp.4-5.)

Comparison of the 1987 ADWR estimate of 447 ac-ft/yr of available resource to the estimated demand of 384 ac-ft/yr, indicates that by 1986, almost all of the available resource was needed to supply the demand. This fact was recognized by the ADWR who stated:

"Comparison of the total water demand with the total dependable water supply, in Figure 1, indicates that in 1986 the Pine-Strawberry area was using about 86% of its dependable supply. In spite of the large percentage of dependable supply used, the Mudstone/Shale/Limestone aquifer showed gains, not declines, in water levels.

Comparison of the water elevation data for 1974 and 1987 indicates that water levels in the Mudstone/Shale/Limestone aquifer have increased (1.4-8.4 ft/yr). As mentioned previously, these increases are a direct response of the aquifer to the natural replenishment from the excess precipitation that occurred between 1979 –1986 (sic).

If the water demand continues increasing at the present rate, in about 2 more years the Pine-Strawberry area will be using 100% of its dependable supply. After that, additional future demands will be accelerating the overdraft of the aquifer. If a "Dry" period were to occur severe declines might occur." (ADWR, 1987, p.4)

As previously discussed, an alternative interpretation of the observed rises in the groundwater levels in the Schnebly Hill-Supai strata (Mudstone/Shale/Limestone strata) from 1977 to 1987 is that they resulted from drainage of water out of the overlying Coconino strata, where declining water levels were observed during the same period. In the alternative interpretation, the declining water levels in the overlying Coconino therefore might be a harbinger of a future decrease in the availability of the resource in the Supai strata, particularly if what was perceived to be a wet period became a dry period. The potential for future shortages resulting from a change in the apparently above normal precipitation pattern was recognized by the ADWR (1987), who stated the following conclusions:

"(1) The Pine-Strawberry area is reaching its limit with regard to the amount of development that can be sustained with a dependable water supply over a long period of time (100 years).

(2) The available groundwater level data cover a "wet" period. Therefore, it is unknown how the Mudstone-/Shale/Limestone aquifer will respond to a "Dry" period. Continuous groundwater monitoring is essential.

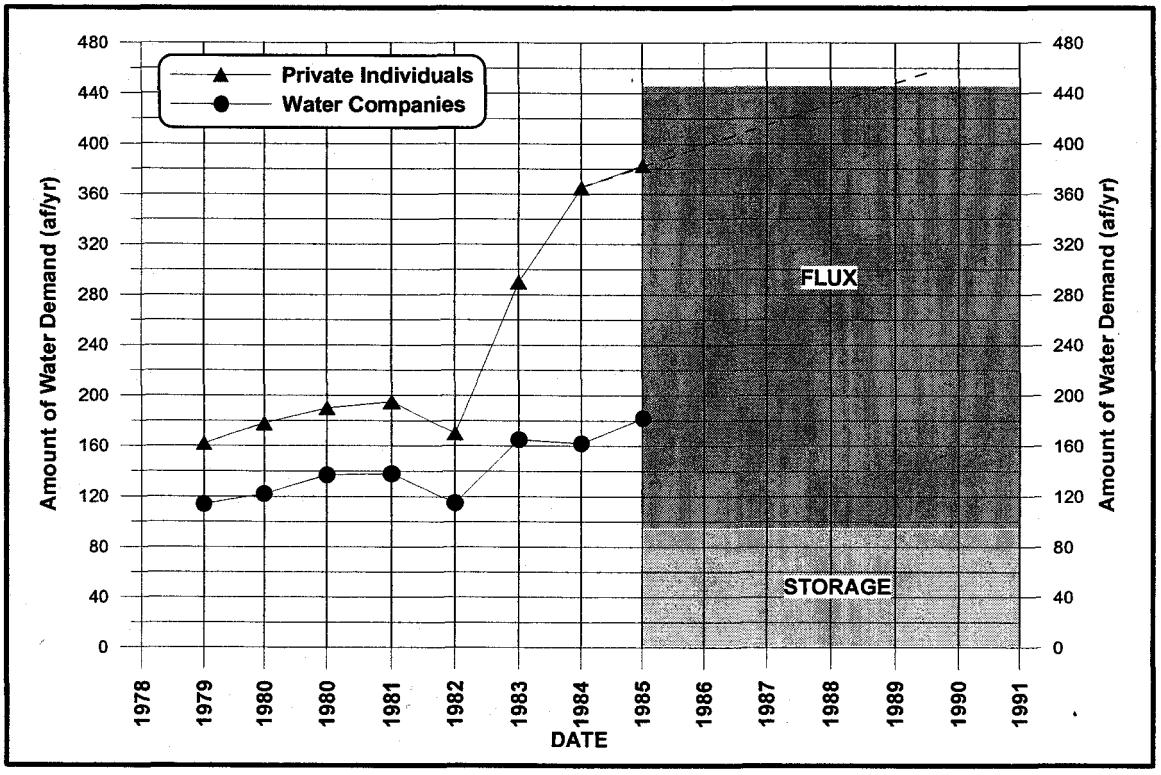
(3) The relationship between spring flow and groundwater level variations is unknown. Monitoring is needed to evaluate the amount of replenishment caused by the Pine Creek stream.

*(4) **The hydraulic parameters (T and Sy) used to estimate the groundwater in storage and the groundwater flux are uncertain, although they might be on the conservative side."*** (ADWR, 1987; p.5)

It is clear from the latter citation that the ADWR in 1987 not only recognized the potential for a period of drought to result in a shortage of groundwater, they also acknowledged the uncertainty in the values of aquifer transmissivity and aquifer storativity used to estimate the storage and flux values summarized in Table 5-1. They state that the values used "might be on the conservative side"; however, subsequent re-evaluation of test data, as discussed elsewhere in this report, indicates the values used were not only overly optimistic, they involved wholesale application to broad areas the relatively large transmissivity and storativity values that were appropriate only to fractures of limited distribution and extent.

Included in the preliminary report of June 1987 (ADWR, 1987) was a hand-drawn figure that compared water demand to the estimated flux and storage of groundwater in Strawberry Canyon, Strawberry Hollow, and Pine Creek. The hand-drawn figure is reproduced on Figure 5-2, projecting that the entire estimated groundwater resource for the latter areas would be developed in two to three years, if the 1985-1986 trends continued.

Figure 5-2: Reproduction of ADWR (1987) water demand figure.



5.3.4. 100-Year Supply Estimate

The Preliminary report of 1987 (ADWR, 1987) is an important document in that it recognized that the 1986 level of water demands might already exceed the dependable resource, when long-term fluctuations in recharge were considered. The conclusion that the 1986 level of development might exceed the resource without future growth, and without the onset of a drought, made it clear as early as 1986 that the aquifer system in the Schnebly Hill-Supai strata would not support any significant amount of continued growth and was very likely vulnerable to a period of below normal recharge, even without future growth.

The latter conclusions may not have been entirely clear due to the confusing language about the rising groundwater levels in the Schnebly Hill-Supai strata and about more groundwater storage available in the Schnebly Hill-Supai than in the Coconino. Additional confusion may have been generated by the estimates of 2160, 1400, and 5670 ac-ft, respectively, of groundwater stored under the Pine Creek, Strawberry Hollow, and Strawberry Canyon areas. The implication of those estimated groundwater storage volumes was that if annual flow (flux) ranged from 38 to 237 ac-ft/yr, the groundwater storage of up to 5670 ac-ft offered a comfortable margin of safety to support the 1986 level of demand, even if there were a few years of drought in succession.

For example, the ADWR (1987) estimated availability of 9230 ac-ft of storage under the three areas. If recharge and "flux" declined to zero for a few years, the estimated of volume of storage should have been adequate to support the 1986 level of demand, 384 ac-ft/yr, for 24 years. Accordingly, there may not have been a lot of concern about a few years of drought since subsequent periods of above normal recharge would make up any short-term deficit that might occur during a few dry years.

The basis for the estimate of groundwater storage is partly revealed by the ADWR (1987) description of the Strawberry Canyon area that states:

> ***"In this area the Mudstone/Shale/Limestone aquifer extends for about 840 acres. Using a conservative saturated thickness of 135 ft., the groundwater in storage underneath this area is about 5670 Acre-ft."***

Groundwater storage of 5670 ac-ft in a saturated thickness of 135 feet distributed throughout 840 acres is equivalent to an average porosity of 5 percent throughout the rock mass. This value falls at the low end of the range of porosity for sandstone that is indicated in a number of tables published in the technical literature, generally indicating a range of 5 to 30 percent porosity for sandstone.

However, such tables do not take into account compaction and cementing of sandstone that take place during the lithification process that converts relatively

consolidated rock into harder, more compact rock. Likewise, the assumption that the Schnebly Hill-Supai strata are comprised mainly of sandstone with an average porosity of 5 percent is not consistent with the outcrops observed in the PSWID which consist of limey and nodular very fine-grained structureless sandstone, silty fine-grained sandstone, cemented conglomerate, limey mudstone, and microcrystalline limestone, all of which appear to offer far less than 5 percent porosity.

As discussed elsewhere in this report, the sparse aquifer test data available from wells completed in Schnebly Hill and Supai strata in the PSWID area exhibit particular types of linear flow response. The response of the wells in the Schnebly Hill strata indicates the sedimentary rock hosting the fractures releases groundwater from storage in pores in the rock when the fractures are pumped. Similar tests conducted in Supai strata indicate the release of groundwater is entirely from storage in the fractures with no contribution from the rock hosting the fractures. These test data indicate the average porosity of unfractured Supai strata in the PSWID area is essentially insignificant to the release of groundwater to pumped wells and certainly not an average of 5 percent. As stated in Freeze and Cherry (1979; p. 154):

> ***"As sands become more cemented and compacted (i.e., more lithified) the contribution of fractures to the bulk permeability of the material increases. The tendency of large permeability values to occur in the horizontal direction is replaced by a preference for higher fracture permeability in the vertical direction. The nature of the anisotropy in the fractured medium can reflect a complex geological history involving many stress cycles."***

The above statement regarding the permeability of sandstone strata is equally applicable to the effective porosity of such strata and is consistent with the results of the aquifer tests which indicate linear flow to pumped wells controlled by discrete fracture zones of high conductivity surrounded by a host rock of low conductivity which does not release groundwater storage to the fractures.

Taking the foregoing factors into consideration, the assumption of a bulk porosity of 5 percent throughout a given saturated thickness of Supai strata is inconsistent with other evidence, particularly the aquifer response to pumping, and does not appear to be realistic. The aquifer response indicates there is essentially no storage of groundwater in bulk porosity in the Supai rocks and the storage of groundwater available to development by wells is limited to fracture systems of unknown, but limited extent. Accordingly, there is no basis to assume the groundwater storage estimated in the ADWR (1987) preliminary report as 9230 ac-ft for distribution over 100 years actually exists. The data suggest the actual groundwater storage available for distribution over a 100-year period is significantly less than a volume based on a presumptive value of 5 percent

porosity and that a safety margin may not exist for a period of little or no recharge to the aquifer.

Although the 1987 preliminary report may have overestimated the groundwater storage in the Pine/Strawberry area, the fact that demand was nearly equal to the estimated flow of groundwater through the area was not lost on the ADWR investigators. In a June 10, 1987 letter from ADWR Deputy Director of Engineering, transmitting the preliminary report to the Gila County Board of Supervisors, the ADWR cautions the Board of Supervisors as follows:

> ***"In response to your letter of December 23, 1986, and as a follow up on our letter of January 27, 1987, attached is a preliminary report on the water supply situation in the Pine/Strawberry area. This report indicates that your concerns regarding the rapid growth of the area were justified. The Department of Water Resources will continue to collect field data and periodically review the situation.***
>
> ***The presently available water level information correlates with the wet multi yearly cycle which started in about 1977. Therefore, it is of prime importance to continue collection of hydrologic information into the dry cycle which will follow. The Department of Water Resources will continue issuance of inadequacy statements for developments in the discussed area unless some hard hydrologic evidence indicates that conditions in portions of the area are more favorable than considered at this time."*** (Douglas Toy, Deputy Director – Engineering, ADWR, to Adolph B. Trujillo, Chairman, Gila County Board of Supervisors, June 10, 1987)

5.4. Report on Pine Area Water Shortage July 1989

Following presentation of the Preliminary Report of 1987 to Gila County, the water company serving the community of Pine experienced a severe water shortage in the summer of 1989. The shortage was partly offset by hauling about 40,000 gallons per day of water from Strawberry for use in the Pine water system operated at that time by the E&R Water Company. The need to haul water from Strawberry to Pine continued from time-to-time after 1987 to as recently as 1997.

The fact that the wells at Strawberry did not suffer the critical water shortage problems experienced in the wells operated by the E&R Water Company initially left questions as to whether the1989 shortage was the result of a lack of groundwater at Pine or was instead related to pump problems and distribution problems. Since 1989, it has become obvious that wells at Pine do not enjoy as reliable a source of groundwater as the wells at Strawberry. The results of this investigation suggest that is because the wells in Strawberry are completed in

the Schnebly Hill Formation whereas the wells in Pine are completed in the upper and lower Supai.

The present operators of the same E&R Water Company well field, now owned by Brooke Utilities, Inc., observe that their wells in the Strawberry area are more reliable than those in the Pine area. They have also attempted to develop additional wells in the Pine area with a low level of success. Consequently, Brooke Utilities, Inc. installed an 8-inch water line to connect their well field in the Strawberry area to the water system they operate in the Pine area so that water from Strawberry wells could be transferred to Pine without trucking the water as done in the past.

In the Environmental Assessment for the 8-inch water line, (Payson Ranger District, 1999), the need for the 8-inch water line was summarized as follows:

> ***"Previously, Pine residents that are customers of E&R Water Company have been under water use restrictions imposed by the water company – as allowed by the Arizona Corporation Commission (ACC), including a 40% reduction in indoor use, no outdoor use, and limited livestock watering. During the summer of 1997, Brooke Utilities hauled 4.5 million gallons of water from Strawberry to Pine to ease the water shortage. Five additional wells have since been drilled in Pine but only two have achieved a water standard necessary for economic development and there is uncertainty over a long-term reliable source of water in Pine. Well data collected by Brooke Utilities indicates surplus water production and storage in their Strawberry system."*** (Payson Ranger District, 1999; p.2)

The antecedents to the conditions described in 1999 to justify the 8-inch Strawberry-Pine pipeline have their roots in the Pine water shortage of 1989, described by ADWR (1989). Appendix A of ADWR (1989) shows E&R Water Company meter records for the summer of 1988 indicating production from the Pine Water System wells, as reproduced on Table 5-2.

The metered records shown in Table 5-2 are significant in that they record the demand for water from the wells in the Pine Water System prior to the shortage that began in early July, 1989. Implicit in the demand is the condition that the wells provided at least the metered volume of sales. Thus we know the minimum production from the Pine Water System wells, even though there is no record of well production and the metered sales do not include transmission losses or unmetered use. The report by ADWR (1989) indicates there were 11 wells in the system in 1989; however, it is not clear how many of the 11 wells were in operation:

Table 5-2: E&R Water Company metered water sales.

E&R Water Company Pine Water System Metered Water Sales	
Month	Gallons
June 1988	3,823,590
July 1988	3,775,330
August 1988	3,165,530
September 1988	2,694,720
October 1988	2,563,490
November 1988	2,191,310
December 1988	2,036,120
January 1989	2,064,240
February 1989	1,707,600
March 1989	1,795,140
April 1989	2,565,720
May 1989	3,762,900
June 1989	3,541,000

> ***"The results of field measurements of wells by the Department's Hydrology Division personnel found three wells with a combined reliable capacity of about 30 gallons per minute . . . Other wells were inoperative or not arranged for flow measurements."*** (ADWR 1989; p. 12)

The sale of 3,541,000 gallons in the month of June 1989, just prior to the onset of the water supply shortage, required a minimum average 24-hour-per-day pumping rate of 81.97 gpm from 11 wells, or 7.45 gpm per well. If only 8 wells were in production, each well would be required to produce 10.2 gpm; likewise five wells would be required to yield 16.4 gpm each, to satisfy the metered sales. Therefore, the record provides some indication of the minimum production requirement from individual wells; even though actual well production was not measured.

The most significant aspect of this record is that the wells produced more than 3.5 million gallons in June 1989, a rate of production not unlike the previous summer of 1988, but suddenly declined in yield in July 1989. The ADWR (1989) report states that well production in the Pine Water System had decreased to an average of 43,000 gallons per day (gpd) in July 1989 or about 36.4 percent of the June production. An additional 40,000 gpd was being hauled from Strawberry to Pine by trucks. In the absence of any identified change in the system or in the demand, the question is why the wells suddenly failed in 1989, shortly after a period of time in which the ADWR (1987) described a rise in groundwater levels over a 10-year period from 1977 to 1987.

The answer is provided in ADWR (1989) that states:

> ***"The Department of Water Resources' Hydrology Division performed field measurements on the water company's wells and determined total continuous production did not exceed 43,000 gallons per day and that groundwater levels were low and at some locations below pumping levels."*** (ADWR, 1989; p. 4)

The measured production of 43,000 gpd is equivalent to 1,290,000 gallons per month production in a 30-day month such as the preceding month of June when 3,541,000 gallons were produced. The observed production of 43,000 gpd is equivalent to a 24-hour-per-day pumping rate of 29.86 gpm. As previously cited, the ADWR staff found three wells producing a combined capacity of 30 gpm in July 1989, a fact indicating that only three of the 11 wells in the system were producing a significant yield of water at that time.

In view of the latter observations, there is no reason to seriously contemplate that the shortage experienced in Pine in 1989 and in subsequent years was the result of mechanical failures in the system, distribution system limitations, or bad management of the wells. The ADWR (1989) observations clearly document a rather abrupt decrease in the well yields in the Pine Water System due to a decline in the pumping water levels, and apparently in static water levels, at least at some of the wells.

The latter conclusion was evidently rejected by a part of Pine/Strawberry community, partly on the basis that a widespread loss of well yields did not occur throughout the area. For example, the wells in Strawberry provided the groundwater production that was trucked to the Pine system. Thus, the question arose that if the failure of the public water supply wells at Pine was due to a area-wide decline in groundwater levels, presumably linked to fluctuations in annual precipitation and recharge, why did not such "dry" conditions affect wells at Strawberry and the surrounding area.

Although such reasoning is logical, it overlooks another possibility, which is that long-term use of wells completed in a fractured rock aquifer had resulted in a progressive long-term decline in average annual groundwater levels that finally reached a threshold at which well yields were adversely and noticeably affected. As discussed in the following section of this report, a characteristic of fractured rock aquifers is initially high yield followed by a progressive decline in yield as the duration of pumping increases. This effect may be manifest in short-term pumping tests or may appear gradually over a period of years as groundwater is withdrawn from such a fractured aquifer. A gradual decline in average annual groundwater levels and ultimately in well yield in one area might therefore be a function of the pumping and use of the wells whereas other wells in nearby areas may be used in a different way and not experience the same loss of yield.

Likewise, small but significant differences in the hydraulic properties of the fractured rock from one area to another might cause wells in one area to be less reliable under long-term sustained pumping than wells in nearby areas, subject to the same hydrologic conditions and similar patterns of use.

As previously discussed, the most important factor appears to be that wells in the Strawberry area are completed in the Schnebly Hill strata whereas wells in the Pine area are completed in the Supai strata. The principal difference between the hydraulic properties of these two groups of strata, as shown by aquifer tests reported by Glotfelty (2002) in a subsequent part of this report, is that during pumping tests, the Schnebly Hill strata released groundwater storage from the rock mass as well as from fracture openings whereas the Supai strata only released water from the fracture openings and no water was released from storage in the rock mass between the pumped fractures.

Local differences in fractured rock aquifer characteristics and performance may be a "wild card" that makes it hard to distinguish between climatic effects, mechanical and hydraulic factors, management effects, and the effects of demand for water when comparing well performance at Strawberry to that at Pine. However, the effect of a loss of system capacity caused by the hydraulic limitations of the aquifer system is disastrous to the water users. During the Pine shortage in 1989, the ADWR (1989; p. 4) summarized the amount of water available to some 1,400 residences, if the water supply were to be limited to the 43,000 gpd provided by the wells in July 1989, as follows:

> ***"If all hauling of water terminates and only the well production is available, water usage will only be available at a rate of 30 gallons per home per day. The use of water without hauling must be limited to the minimum possible needs, estimated at about 5 gallons per capita daily, divided as follows: drinking, 3 pints; cooking 2 quarts; personal cleanliness, 1 gallon; laundry and dishwashing, 2 gallons. Exceeding this usage would deplete the water storage reserve. This low usage rate considers the wells maintaining their present production capacity."*** (ADWR, 1989; p.4)

Similar restrictions may potentially be imposed during water shortages at the time of this writing.

5.5. March 1994 Geohydrologic Evaluation – Portal IV Subdivision

Manera (1994) authored a report describing geohydrologic conditions in the Portal IV Subdivision, immediately west of and contiguous to the Portal II Subdivision of Manera (1979). Pumping test data provided in Manera (1994) are a definitive source of information about the hydraulic function of the upper Supai

Figure 5-3: Locations of wells from Manera (1979) and Manera (1994).

Qal = Modern Alluvium
Qc = Collumium
Tv = Volcanics, mostly basalt
Pk = Kaibab Formation
Pco = Coconino Sandstone
Pshu = Corduroy Member, Schnebly Hill Fm.
Psfa = Fort Apache Member, Schnebly Hill Fm.
Pshl = Bell Rock/Rancho Rojo Mbrs., Schnebly Hill Fm.
Psu = Upper Supai Formation
Psl = Lower Supai Formation
PPn = Naco Formation
Mr = Redwall Limestone
pCm = Mazatzal Quartzite

Private Land Boundary (Approx.)
PSWID Boundary (Approx.)
Geologic Contact (Approx.)
Well 3 Well from Manera (1979)
Well 1 Well from Manera (1994)

Well locations not field checked.

Myers-Portal III
Well 4
Well 3
Well 1
Well 2
Well 5
Jones Well

Geology modified from: Weir and Beard (1984)
Weisman and Weir (1990)

aquifer strata penetrated by the wells at locations shown on Figure 5-3. In addition to aquifer test data, Manera (1994) summarizes the perception of residential water demand used for planning purposes in the Pine/Strawberry area in the 1990's.

Reexamination of the pumping test data from Manera (1979) shows that the aquifer response to pumping was that of highly bounded linear flow in fractures. Moreover, the test response indicated the only release of groundwater from storage during the test was from the fractures with no contribution from the rock surrounding the fractures. Therefore, it must be concluded that groundwater flow and storage in upper Supai strata in the vicinity of this well are limited to narrow paths along fractures and that the rock surrounding the fractures does not store, release, or transmit significant amounts of groundwater. Accordingly, the interpretation of the aquifer test by Manera (1979), using the Cooper-Jacob method for radial flow, was inappropriate and did not provide a valid value of aquifer transmissivity. Similarly, application of a representative value of transmissivity to calculate the groundwater flow across the width of the entire area was not appropriate in view of the fact the test indicated groundwater flow is constrained to narrow fractures.

5.5.1. Water Use

As compared to Manera (1979), where seven years of recorded water use indicated an average monthly use of 3,010 gallons per month or about 100 gpd per residence, Manera (1994) uses a value of 110 gpd per unit for planning purposes. The basis for the 110 gpd per unit figure was cited in Manera (1994) as "***the fifteen (15) year daily average use of approximately three hundred (300) dwelling units in Portal 1, Portal 2, Portal 3, Strawberry Creek Hills and Canyon Shadows subdivisions***." These statistics reflect only a small increase in use per dwelling between the 1979 full time residences (Manera, 1979) and the 1994 residences. Manera (1994) does not distinguish between full time and part time residency demands, nor does either of the Manera reports provide information about summer water use versus winter water use.

5.5.2. Geology

In regards to the geology of the Pine area, Manera (1994) makes the following statements:

> ***"The records of Aero Drilling and Pumps, Inc. (Appendix A) show that 215 feet of the Supai formation and 165 feet of the underlying Redwall (Naco) limestone was*** (sic) ***penetrated while drilling Portal IV Well 1. At the site of Portal IV Well 2 the Supai formation was absent with only the limestone encountered during the drilling process."*** (Manera, 1994; p.5)

The Well Data Report in Appendix A of Manera (1994), as obtained from Aero Drilling and Pumps, Inc., shows Well 1 penetrating "Redwall Limestone" from essentially 215-380 feet, ignoring a 4-foot shale layer from 274-278. Figure 5-3 shows Well 1 starts in the lower Schnebly Hill Formation, approximately 140 feet above the base of the unit. This puts the first "Redwall Limestone" penetrated by the well an estimated 75 feet below the top of the upper Supai, as defined in this report. The total depth of the well ends approximately 90 feet above the bottom of the upper Supai.

Well 2 penetrates "Redwall Limestone" at 10-215 feet, shale from 215-230 feet, and "Redwall Limestone" from 230-360 feet. Well 2 is sited about 40 feet below the top of the upper Supai and, with a total depth of 360 feet, potentially penetrates 70 feet into the lower Supai.

Comparison of the locations of Portals IV Wells 1 and 2 to the structural map of the top of the Redwall Limestone, constructed for this investigation, indicates the depths to the top of the Redwall limestone are approximately 987 and 692 feet, respectively, at Wells 1 and 2. Likewise, the depths to the top of the Naco Formation, which includes considerable limestone, are approximately 732 and 437 feet, respectively, at the sites of Wells 1 and 2. Accordingly, the total well depths of 380 and 360 feet, for Wells 1 and 2 respectively, are not adequate to penetrate to either the Naco or the Redwall strata at those sites.

Description of the limestone cuttings from the two wells as "Redwall Limestone" is a logical interpretation of the data by the driller, based on the amount of limestone penetrated. However, the relationships shown on Figure 5-3 show the wells must be completed in the upper Supai, as defined herein. Although there are limestone layers ranging from 6 to 45 feet thick in this interval, as described by Weisman (1984), their presence does not explain the amount of limestone reported by Aero Drilling in either well.

A likely explanation for the amount of limestone logged in these two wells is the presence of the conglomerate lenses in the upper and middle Supai as described by Weisman (1984) and Blakey (1990). The conglomerate consists of a mixture of limestone pebbles and siltstone pebbles. Drill cuttings from the combination of carbonate layers, which according to Weisman (1984) are closely associated with conglomerates, and drill cuttings from the limestone pebbles in the conglomerates could easily give the impression that the boreholes were penetrating limestone strata with red silt, sand and clay infillings in fractures and cavities. Considering the position of the two wells on the geologic structure, penetration of the limestone layers and limestone pebble conglomerates in the upper Supai, as defined herein, is the most likely explanation for the carbonate drill cuttings logged as "Redwall Limestone" by Aero Drilling and Pump.

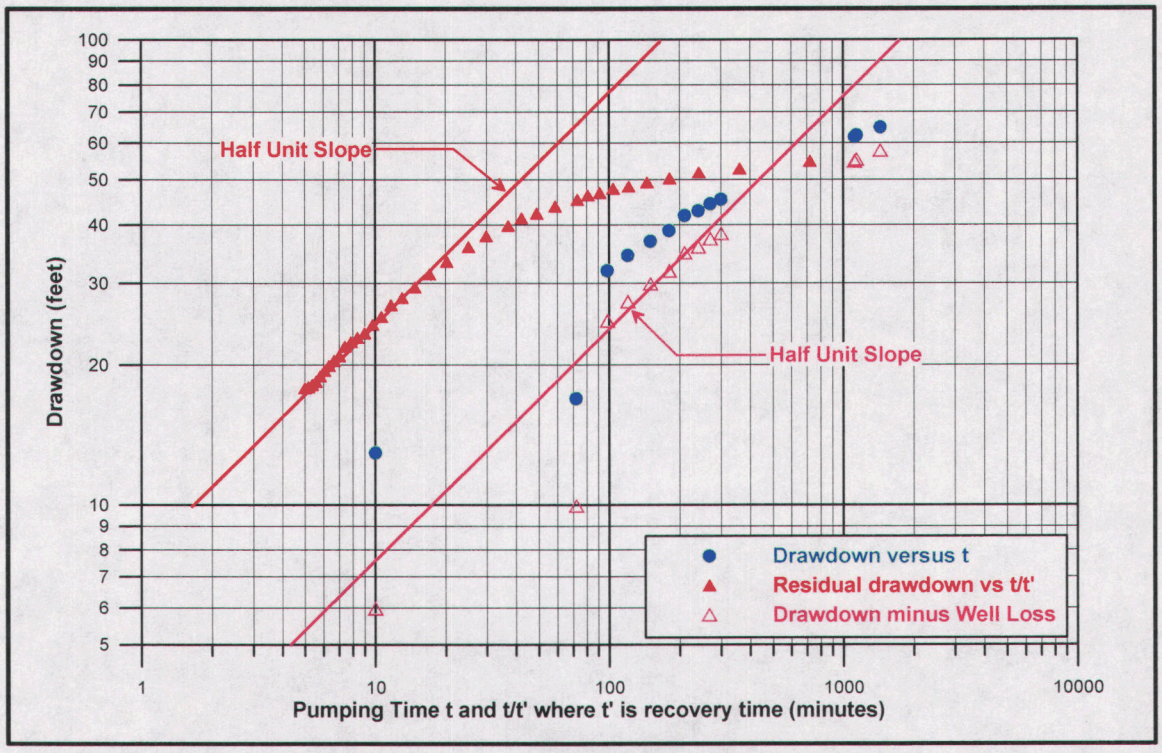
5.5.3. Pumping Test Analysis

Appendix C of Manera (1994) provides the time-drawdown measurements for a pumping test of Portal IV Well 1. The static water level of 232 feet prior to the test indicates the groundwater in the well is produced from the upper Supai as the base of the Schnebly Hill strata penetrated by the well is at about 140 feet. The pumping rate started at 138 gpm and declined to 123 gpm over 24 hours. The time-weighted average pumping rate was 129 gpm, indicating a maximum departure from the average pumping rate of less than 7 percent during the duration of the test.

Figure 5-4 shows a double log (log-log) plot of drawdown in feet versus elapsed pumping time in minutes. A log-log plot is the diagnostic plot used to evaluate the type of aquifer response obtained during any pumping test. Figure 5-4 also shows residual drawdown during recovery plotted versus t/t' where t is the time since pumping started and t' is the time since pumping stopped. Although the residual drawdown plot is normally shown only on a semilogarithmic plot, where time is logarithmic and drawdown is arithmetic, the residual drawdown is shown on the log-log plot on Figure 5-4 for the purpose of evaluating the type of aquifer response obtained.

The drawdown data in Figure 5-4 are subject to casing storage effects that reduce drawdown in the early part of the test. This is because water in the well

Figure 5-4: 1994 test of Portal IV Well 1 at 130 gpm average pumping rate.



casing provides part of the pumped water during the early pumping, thus slightly offsetting drawdown. The drawdown data are also subject to the effect of well loss drawdown throughout the pumping period. Well loss drawdown is the initial drawdown required to create a hydraulic gradient into the well to overcome entrance losses through the casing and formation near the well and to establish the differential pressure required to cause flow between the aquifer and the inside of the well at the given pumping rate. Well loss drawdown does not exist during recovery after pumping. Analysis of the data indicates well loss drawdown was about seven feet. A drawdown plot, corrected for seven feet of well loss, is shown on Figure 5-4 as "Drawdown minus Well Loss".

The time-drawdown plots on Figure 5-4 also reflect the progressive decrease of the pumping rate from an initial rate of 138 gpm at the start of the test to 123 gpm at the end of the test. The continuous decrease in the pumping rate caused a progressive reduction in the trend of the time-drawdown plot throughout the test. The residual drawdown, measured after pumping stops and the water level in the well is recovering, reflects the hydraulic response of the aquifer to pumping withdrawals absent the effects of casing storage and well loss that are associated with pumping. As shown on Figure 5-4, the initial recovery measurement, taken two minutes after pumping ceased, is about 10 feet less than the final drawdown during pumping. The 10 feet of drawdown offset along the drawdown axis in the first two minutes of recovery consists of 7 feet of well loss and 3 feet of recovery of the water level in the aquifer outside the well casing during the first two minutes of recovery.

For the first 75 minutes after pumping stopped, the water level in the well recovered relatively slowly, with the rate of recovery gradually increasing until, after 75 minutes of recovery, the rate of recovery stabilized at a half unit slope on the log-log plot. The initially slow rate of recovery exhibited by the Portals IV Well 1 during the first 75 minutes of recovery indicates the cone of depression around the pumped well was significantly constrained by boundaries consisting of materials that were not yielding groundwater.

The half unit slope response after 75 minutes of recovery is very significant. A half unit slope means that one log cycle of drawdown or recovery requires two log cycles of time. A half unit slope is a diagnostic response indicating linear flow of water to the pumped well, rather than converging radial flow. Linear flow is exhibited by gravel aquifers in narrow stream channels surrounded by less permeable materials, so-called "strip aquifer" response, and by fractured rock aquifers where the flow of groundwater to the pumped wells is controlled by discrete, essentially planar fractures. Underground mine workings and caverns in limestone penetrated by wells may also exhibit linear flow response.

The linear flow response exhibited by the Portals IV Well 1 is interpreted to indicate groundwater flow controlled by fractures. A half unit slope response

indicates not only that flow to the pumped well is linear, but that the rate of drawdown in the linear feature is controlled by the release of groundwater stored in the linear feature, not by the release of groundwater stored in the less permeable materials hosting the linear feature. In other words, the rock strata did not produce significant groundwater from porosity during this test and the well obtained its supply of water solely from storage in the fractures in the rock.

Because the geology at the Portals IV Well 1 indicates the water-bearing zones in the well are contained in the upper Supai strata, the results of this test indicate that the Supai strata at this location do not offer significant groundwater storage or capacity to transmit groundwater, except through fractures. The half unit response during the test indicates the pumped water was released from storage in the fractures and not from storage in porosity or interconnected micro-fractures in the sandstone, siltstone, and limestone hosting the fractures.

If a significant release of groundwater from micro-fractures or porous rock had occurred, the time-drawdown plot would have assumed a quarter unit slope, or in highly fractured rock, a radial flow response. A quarter unit slope consists of one log cycle of drawdown for four log cycles of time. A quarter unit slope on a log-log plot is a diagnostic aquifer response indicating the materials hosting the fractures are releasing water to the fractures such that the rate of drawdown is controlled by the release of storage from the rocks surrounding the fractures, not by the release of storage within the fractures. Therefore a quarter unit slope response implies the aquifer contains either primary rock porosity or widely distributed fractures as compared to the absence of such indicated by the half unit slope response. The quarter unit slope response did not occur in the test of the Portals IV Well 1.

Figure 5-4 shows that the drawdown response during pumping, as corrected for well loss, reasonably conforms to a half unit slope throughout the pumping test, if the effects of casing storage are ignored in the early part of the test and the effects of a continuously decreasing pumping rate are taken into account. The second data point during drawdown is anomalous, indicating the measurement was wrong or recorded incorrectly. Thus, both the drawdown and residual drawdown response obtained from the Portals IV Well 1 test are indicative of highly bounded groundwater flow through relatively planar fractures. An alternate interpretation would be linear flow through widespread solution cavities in a thin limestone layer or along solution-enlarged fractures or bedding planes.

5.6. March 2002 Water Resources Study

A second source of aquifer test data is provided in a letter report submitted by Clear Creek Associates (Glotfelty, 2002) to Mr. Thomas Wilmoth of Fennemore Craig, P.C., regarding a water resources study of the Strawberry/Pine area. Glotfelty (2002) provides test data from four wells operated by Brooke Utilities. Figure 5-5 shows the locations of the wells.

Figure 5-5: Locations of wells from Manera (1979), Manera (1994) and Glotfelty (2002).

Qal = Modern Alluvium
Qc = Collumium
Tv = Volcanics, mostly basalt
Pk = Kaibab Formation
Pco = Coconino Sandstone
Pshu = Corduroy Member, Schnebly Hill Fm.
Psfa = Fort Apache Member, Schnebly Hill Fm.
Pshl = Bell Rock/Rancho Rojo Mbrs., Schnebly Hill Fm.
Psu = Upper Supai Formation
Psl = Lower Supai Formation
PPn = Naco Formation
Mr = Redwall Limestone
pCm = Mazatzal Quartzite

Private Land Boundary (Approx.)
PSWID Boundary (Approx.)
Geologic Contact (Approx.)
Well 3 Well from Manera (1979)
Well 1 Well from Manera (1994)
Bloom Well from Glotfelty (2002)

Well locations not field checked.

Strawberry View III
Myers-Portal III
Johnson 1
Johnson 2
Bloom
Well 4
Well 3
Well 1
Well 2
Well 5
Jones Well

Geology modified from: Weir and Beard (1984)
Weisman and Weir (1990)

Similar to other historic analyses of pumping tests and groundwater flow in this area, the report by Glotfelty (2002) inappropriately applies radial flow analysis to linear flow conditions. Likewise, the report applies the erroneous aquifer transmissivity values, obtained by inappropriate application of the radial flow analysis, to represent groundwater flow across the width of the area, not recognizing that groundwater flow at the tested wells was limited to relatively narrow fractures. Therefore, the estimates of groundwater availability presented in the report are likely in error.

Reexamination of the test data provided in Glotfelty (2002) reveals another important factor in the performance of aquifers in the Schnebly Hill and Supai Group. Namely, the tests of wells completed in the Bell Rock Member of the Schnebly Hill Formation in Strawberry indicate that the rock surrounding the fractures penetrating the wells released groundwater from storage. Accordingly, the water pumped from those wells was not derived solely from storage in the fractures, but was instead derived primarily from storage in the rock surrounding the fractures. The test response obtained from the well completed in the upper Supai strata in Pine indicated that all of the pumped water from that well was obtained from storage in fractures with no contribution of water from storage in the rock surrounding the fractures. This indicates the amount of groundwater storage in the Schnebly Hill Formation is significantly greater on a unit volume basis than that in the Supai strata.

The Strawberry View III well is located on the north central edge of the Strawberry community and penetrates the top of the lower part of the Schnebly Hill strata near the land surface. The Johnson #1 and Johnson #2 wells are located at the east end of the Strawberry community just downstream from the crossing of Highway 87 over Strawberry Creek and also start near the top of the lower part of the Schnebly Hill Formation, as shown on Figure 5-5. The Bloom well is located on the east side of Pine Creek, nearly a mile upstream from Highway 87 and about a mile and a half from the crossing of Highway 87 over Pine Creek, and starts an estimated 180-200 feet below the top of the upper Supai. The static water levels in the wells indicate the groundwater is contained in the lower part of the Schnebly Hills strata at the Strawberry View III, Johnson #1 and Johnson #2 wells and in the upper Supai, probably subject to recharge from Pine Creek, at the Bloom Well.

5.6.1. Strawberry View III Well Test

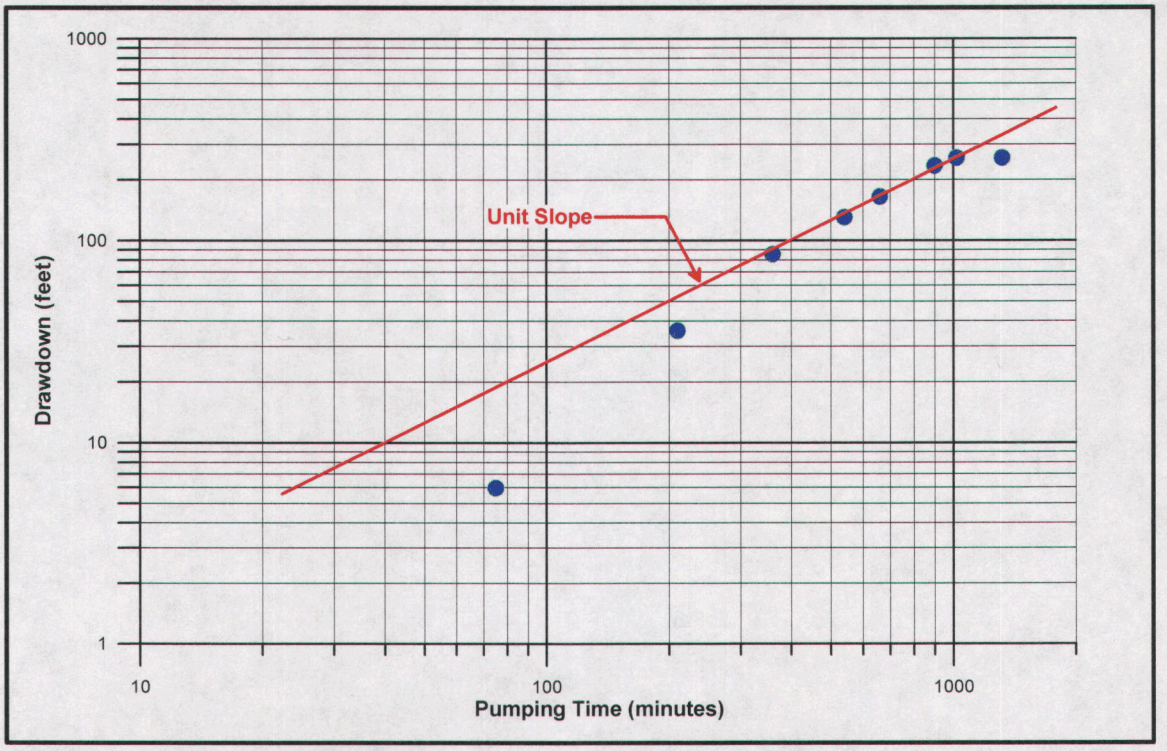
Figure 5-6 shows the diagnostic log-log time-drawdown curve for a "constant" rate test of the Strawberry View III well test. Data provided in Attachment B of Glotfelty (2002) indicates the test was started at a discharge rate of 29 gpm that gradually decreased to 25 gpm during the 1320-minute test. The time-weighted average rate during the test was 26.3 gpm. Recovery data were not provided

and the plot shown on Figure 5-6 is not corrected for well loss. The static water level in the well was 214 feet on 7/29/96 when the test was started.

After the first 200 minutes of pumping, the time-drawdown curve assumes a unit slope on the log-log plot. A unit slope consists of one log cycle of drawdown for each log cycle of time. A unit slope means that the change in head in the well was proportional to pumping duration; a condition generally interpreted to mean the rate of drawdown was controlled by well casing storage. However, the duration and pumped volume of the 1320-minute test indicates the casing storage was not adequate to influence the test past the first 100 minutes or less of pumping. In fact, the first two data points in the test fall below the unit slope line, probably due to the effects of casing storage superimposed over the aquifer response.

The unit slope response of the late data indicates the rate of drawdown was controlled by release of storage without a concomitant inflow of any significance. Since the well casing volume is not large enough to provide the volume of storage required to generate such a response, it is necessary to conclude the storage was provided by a void in the bedrock strata, penetrated by the well. The unit slope response does not provide any indication of the shape of the void; however, the absence of a departure from the unit flow indicates the size of the void was very large with respect to the rate of flow through the void, such that the

Figure 5-6: 1996 test of Strawberry View III Well at 26.3 gpm average rate.



walls of the void did not exert any resistance or head loss upon the flow of groundwater to the well. Thus, the rate of drawdown was essentially that which would be obtained if the water were pumped from a large tank. The abrupt departure of the last point on the test from the unit slope curve is interpreted to indicate the pumping water level had approached the pump inlet.

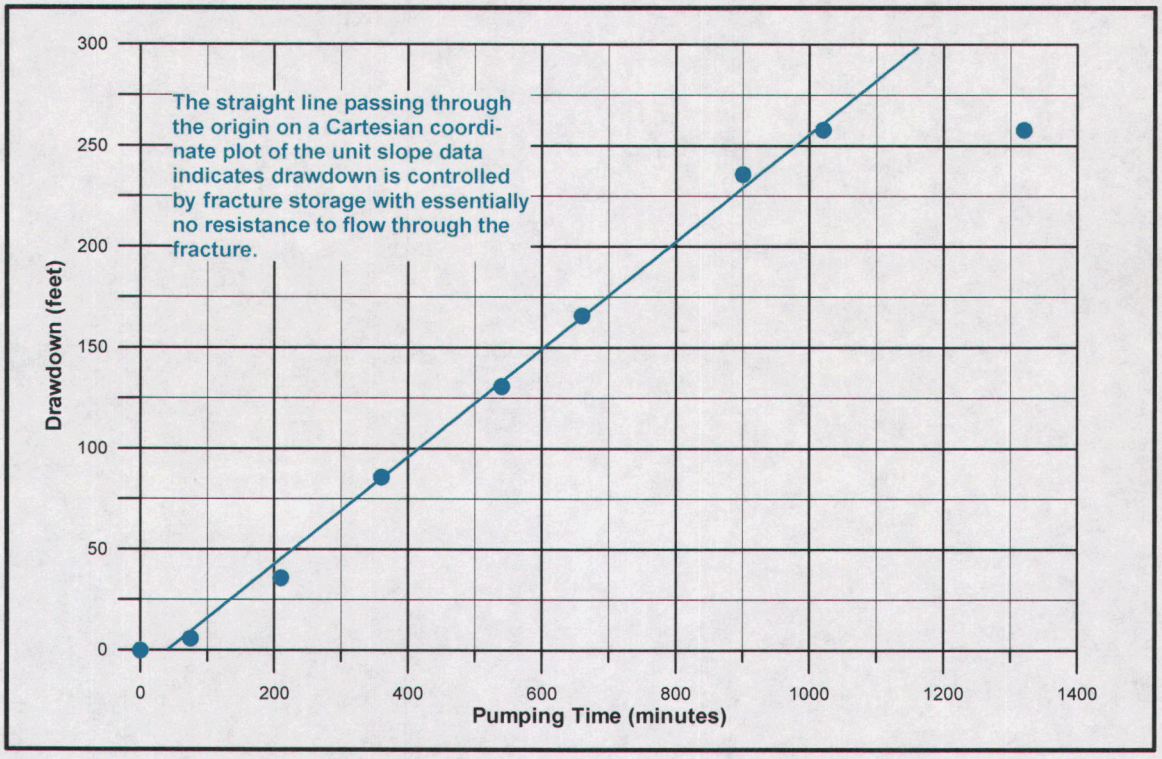
Thus, the response obtained during the test indicates the pumped water was obtained from a void in the rock, rather than from small fractures or porous strata. The void might be a large fracture or a zone of large solution cavities in a limestone layer. The volume of the void was small enough that the storage was being depleted during the test. Unfortunately recovery data were not provided with the test to show what happened when pumping stopped; however, it is manifest from the test response that the inflow (if any) to the void during pumping was negligible compared to the pumping rate.

A specialized plot for examination of storage effects on time-drawdown response is a Cartesian coordinate plot of drawdown versus the pumping time in which drawdown is proportional to time such that a straight line through the origin of the plot results. Figure 5-7shows a Cartesian plot of the Strawberry View III well test data. The data form a straight line, as expected for storage-controlled drawdown. The straight line is offset slightly from the origin, indicating less drawdown than expected in the first data point. The offset is likely the result of well casing storage superimposed over the later response to the aquifer storage. Accordingly, the intercept of the straight line with the time axis is a good approximation of the length of time during which casing storage affected the time-drawdown response.

Although the response obtained during the Strawberry View III well test is not strictly a fractured rock, linear flow response, it indicates the groundwater was stored in a large fracture or solution cavity of finite extent and which certainly cannot be considered representative of the hydraulic properties of the rock mass across the entire width of the aquifer. Therefore, the results of the test are applicable to an unknown but limited part of the aquifer mass and cannot be extrapolated to represent broad areas of groundwater flow through the aquifer. The diagnostic plot also indicates that the Cooper-Jacob straight-line solution is not an appropriate analytical method for interpretation of the pumping test and that, in fact, the test is not amenable to a solution for aquifer transmissivity.

The Strawberry View III well is completed in the Bell Rock Member of the Schnebly Hill Formation and may possibly penetrate into the upper Supai. The unit slope response requires a relatively large void to provide the water. These factors suggest the well penetrates a large, open fracture in the Bell Rock or, possibly, a cavernous zone in limestone in the upper Supai. This is consistent with the fact that many wells in the PSWID area are reported to intercept fractures and voids (Miller, 2003); however, the nature of the fracture or void is

Figure 5-7: Specialized plot of 1996 test of Strawberry View III Well.



unknown. The response of the water-bearing zone penetrated by the Strawberry View III well may be related to the question of what caused the Strawberry Valley, i.e., the well may be sited on a fracture zone.

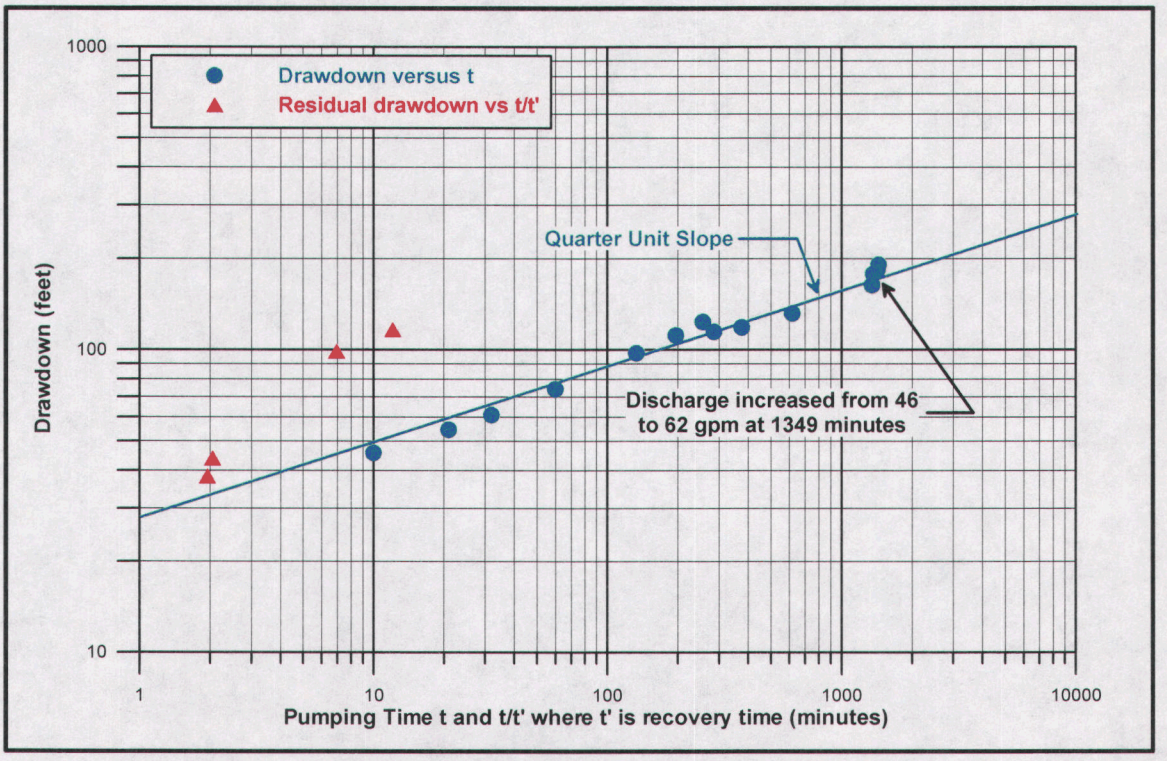
However, the geologic evidence in the Strawberry Valley does not support the concept of a fault or fracture zone aligned with the east-west axis of the valley. The surface upon which the basalt on Strawberry Mountain is deposited is thought to be the ancestral surface extending from the north, southward to the ancestral Mogollon Rim, preserved along the south end of Strawberry Mountain by the basalt cap. This being the case, the modern Strawberry Valley has been cut through the surface north of the ancestral rim and the Strawberry Mountain mass is a remnant of the old surface above the ancestral rim, bounded on the southeast by the Pine Creek valley, eroded through the ancestral rim, and on the southwest by the ancestral pediment between the rim and the basement fault to the south. The Strawberry Mountain mass has therefore been in a position over a considerable period of geologic time where it is potentially in tension due to gravity pulling the mass into the ancestral valley to the south. Therefore, it is reasonable to speculate that the void penetrated by the Strawberry View III well may be the manifestation of movement of the Strawberry Mountain mass southward under gravity and, in fact, the Strawberry Valley may be aligned with a zone of tensional fractures related to such movement.

This is not to imply that fractures or geologic structure were the primary causes of the alignment of the Strawberry Valley. Prior to creation of the Strawberry Valley, but following emplacement of basalt on the south-sloping erosion surface above the ancestral Mogollon Rim, surface water flowing down the south-sloping erosion surface was blocked by the basalt resting on the former erosion surface. This forced the surface drainage to flow east or west, around the basalt flow, to drain off the ancestral rim. As modification of the Mogollon Rim proceeded, the Strawberry Valley was likely cut by erosion into the ancestral slope above the rim, by water forced to flow westerly, along the northern edge of the basalt cap on Strawberry Mountain which blocked the former southward flow off the rim.

5.6.2. Johnson Well No. 1 Test

Figure 5-8 shows the time-drawdown response of the Johnson Well No. 1 to a "constant" rate test that averaged 52 gpm (based on a time-weighted average of the different rates during the test). The test response on the diagnostic log-log plot is that of a straight line with a quarter unit slope. The test data are not corrected for well loss, but the plot indicates such a correction would not change the slope of the curve. As explained previously, a quarter-unit slope response indicates linear flow to the well through a fractured-rock aquifer in which the fractures are functioning as a conveyance system and the rate of drawdown is

Figure 5-8: 2001 test of Johnson Well #1 at 52 gpm average rate.

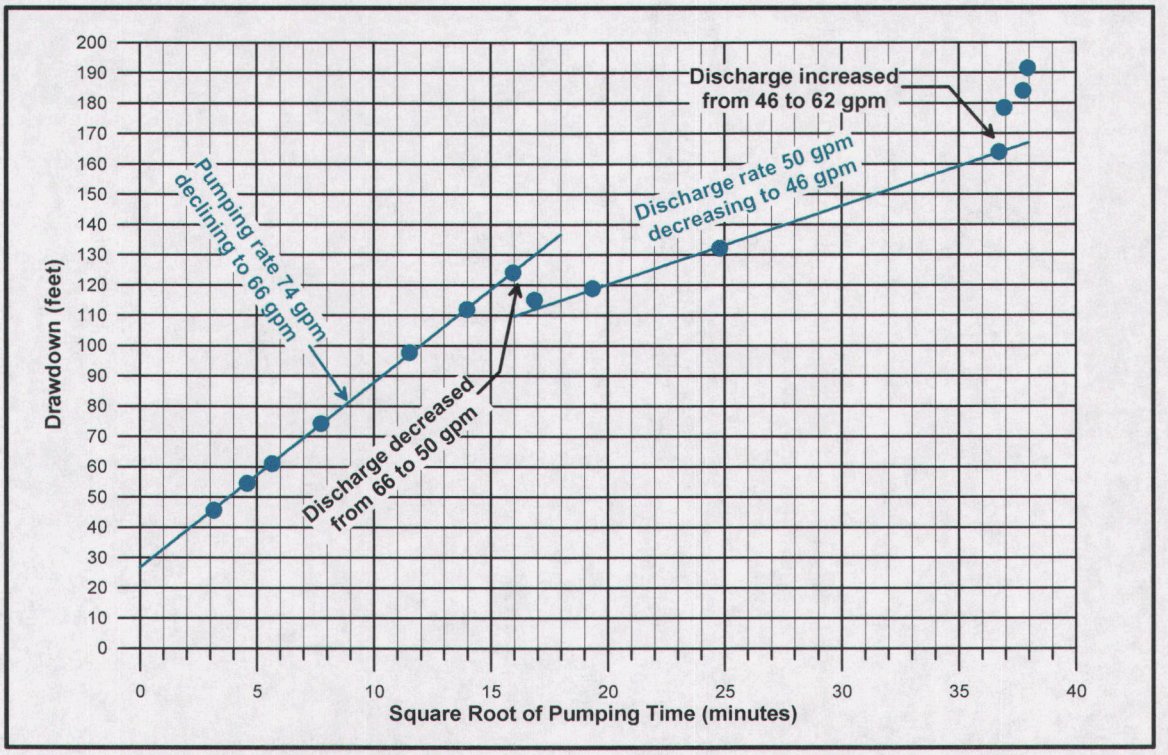


controlled by the release of groundwater from storage in porous rock hosting the fracture system. The porosity may be inherent primary porosity or secondary porosity due to interconnected fractures or micro-fissures.

The field data summarized in Attachment B of Glotfelty (2002) indicate the pumping rate was adjusted twice during the pumping test. One adjustment was at 285 minutes pumping time when the rate was throttled from 66 gpm to 50 gpm and the other was at 1349 minutes when the rate was increased from 46 gpm to 62 gpm (Attachment B includes a 60-minute error in the pumping time calculation, starting at 2100 hrs). Accordingly, it is necessary to examine how the changes in discharge rate affected the time-drawdown response summarized as a quarter unit slope on Figure 5-8.

This is accomplished with a specialized plot for linear flow in which linear flow makes a straight line through the origin of a plot of arithmetic drawdown versus the square root of time. Figure 5-9 shows the specialized plot for the Johnson Well No. 1 test.

Figure 5-9: Linear flow plot of 2001 test of Johnson Well #1.



The data from the Johnson Well No. 1 describe a good straight line on Figure 5-9; however, the straight line is displaced away from the origin along the drawdown axis. The amount of displacement is approximately 27 feet and may be considered to represent the well loss drawdown during the pumping test. When the discharge rate was decreased from 66 to 50 gpm, the slope of the data

changed; however, the data continue to provide a straight-line response indicative of linear flow and displaced away from the origin of the graph by drawdown related to the earlier pumping. After the pumping rate was increased to 62 gpm in the late part of the test, the data did not appear to regain a steady state rate of drawdown. The straight-line responses on Figure 5-9 indicate the aquifer penetrated by the Johnson Well No. 1 provided a linear flow response.

The Johnson Well No. 1 and the neighboring Johnson Well No. 2 are the only wells out of the five tests available to this report that exhibited a release of groundwater storage from the rock containing the fractures. These two wells and the Strawberry View III well which exhibited the response of pumping from a large void, are completed in the Bell Rock Member of the Schnebly Hill Formation whereas the other wells tested, which show the release of groundwater limited to the storage in the fractures with no contribution from the surrounding rock, are completed in upper Supai strata. The limited data therefore indicate the hydraulic properties of the Schnebly Hill Formation are much more favorable to groundwater production than those of the upper Supai strata. The quarter unit slope response indicates much more favorable aquifer conditions at the Schnebly Hill well sites than at the Supai test sites, not only because the quarter unit slope drawdown response is a less rapid rate of drawdown than the half unit slope response, but because the release of groundwater stored in the rock mass of the Schnebly Hill Formation indicates potential for more reliable long-term pumping rates than in the Supai Group.

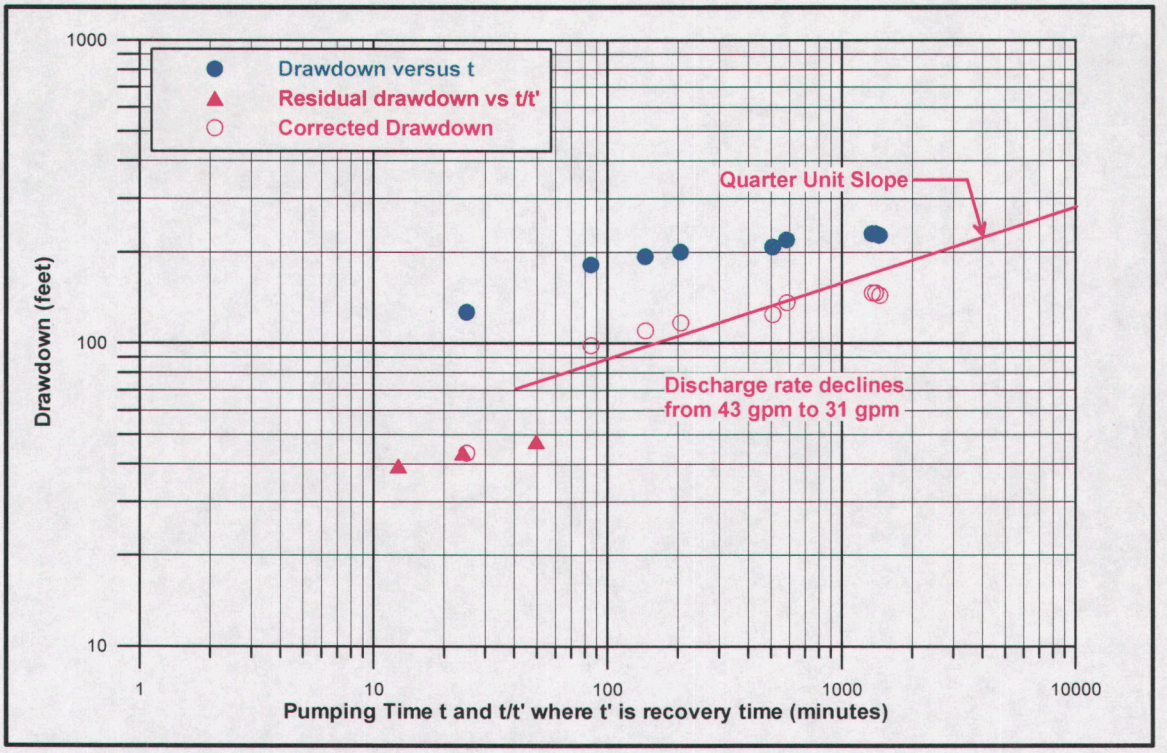
The release of groundwater from storage in the rock surrounding the fractures penetrated by the two Johnson wells implies that a "cone of depression" is developing around the fractures. Although the "cone of depression" may in fact be an elongate area of depressured aquifer extending out from a linear fracture system, the shape is not as important as the fact that drawdown in the rock around the fracture will eventually mimic the response of radial flow to a pumped well. When this happens, the pseudo-radial flow response will conform to a straight line on a semilogarithmic plot, i.e., the Cooper-Jacob solution. Although the tests conducted to date are not of sufficient duration for the Cooper-Jacob solution to be applicable to the available data, the presence of the quarter unit slope and the anticipation of pseudo-radial flow at some time in the future indicates there will be some constant rate yield that the well will support without any further significant loss of yield. This is a much better situation than the half unit slope responses in the Supai wells which dictate a foregone conclusion that drawdown at some duration of pumping will result in a decrease in well yield and that well yield will continue to decrease with increased pumping duration after the onset of decreased yield.

5.6.3. Johnson Well No. 2 Test

Figure 5-10 shows the time-drawdown response of the Johnson Well No. 2 to a "constant" rate test that averaged 32 gpm (based on a time-weighted average of

the different rates during the test). The test response on the diagnostic log-log plot is that of a straight line with a quarter unit slope. The sparse recovery data were used to make an estimated correction for well loss and the corrected drawdown curve is shown on Figure 5-10. When the decline in discharge rate from 43 gpm at the beginning of the test to 31 gpm after 1453 minutes of pumping is taken into consideration, the diagnostic log-log plot of the data conforms reasonably well to a quarter unit slope response. The discussion of the quarter unit slope response provided for the Johnson Well No. 1 is equally applicable to this well.

Figure 5-10: 2001 test of Johnson Well #2 at 32 gpm average rate.



5.6.4. Bloom Well Test

Figure 5-11 shows the time-drawdown response of the Bloom well, on the east side of Pine Creek, to three separate constant rate tests that averaged 30.5, 30.4 and 30.5 gpm, respectively, based on time-weighted averages of the rates recorded during the tests. The durations of the tests were 740 minutes the first day, 720 minutes the second day, and 525 minutes the third day. Figure 5-11 shows the time-drawdown curve flattened after about 500 minutes of pumping during each of the three tests, presumably because the pumping water level had declined to near the pump inlet.

Figure 5-11: 1999 tests of Bloom Well.

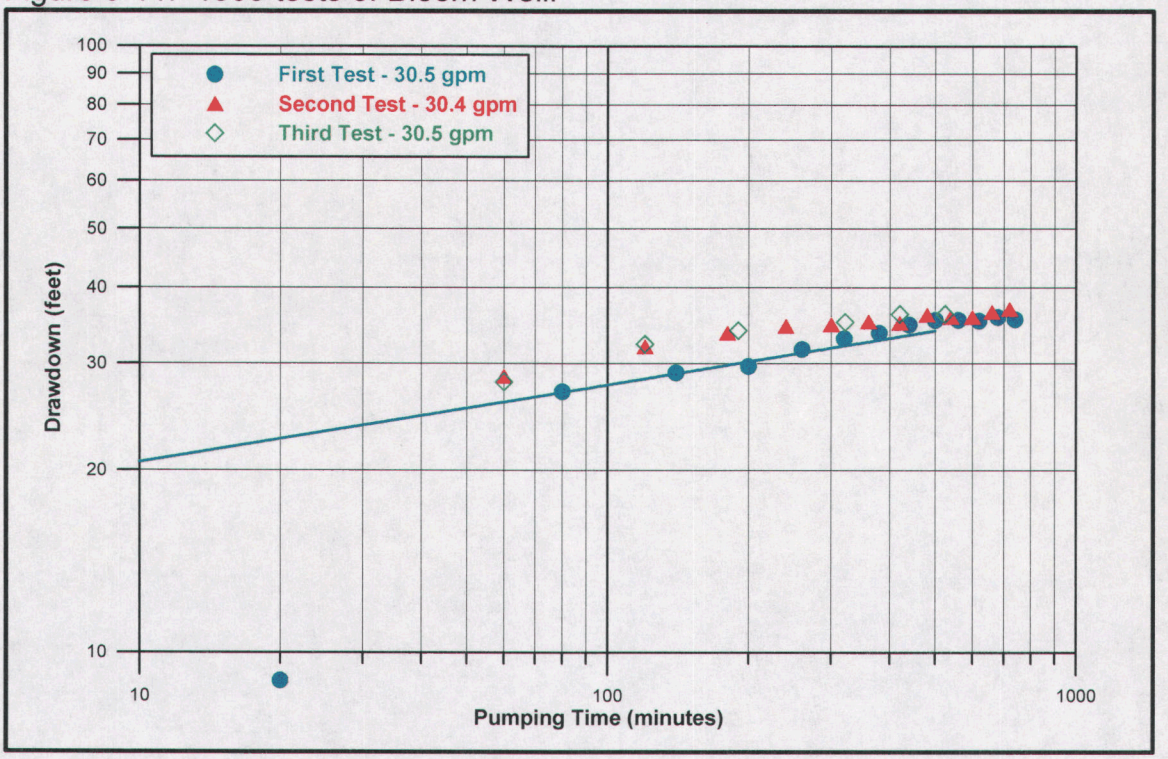
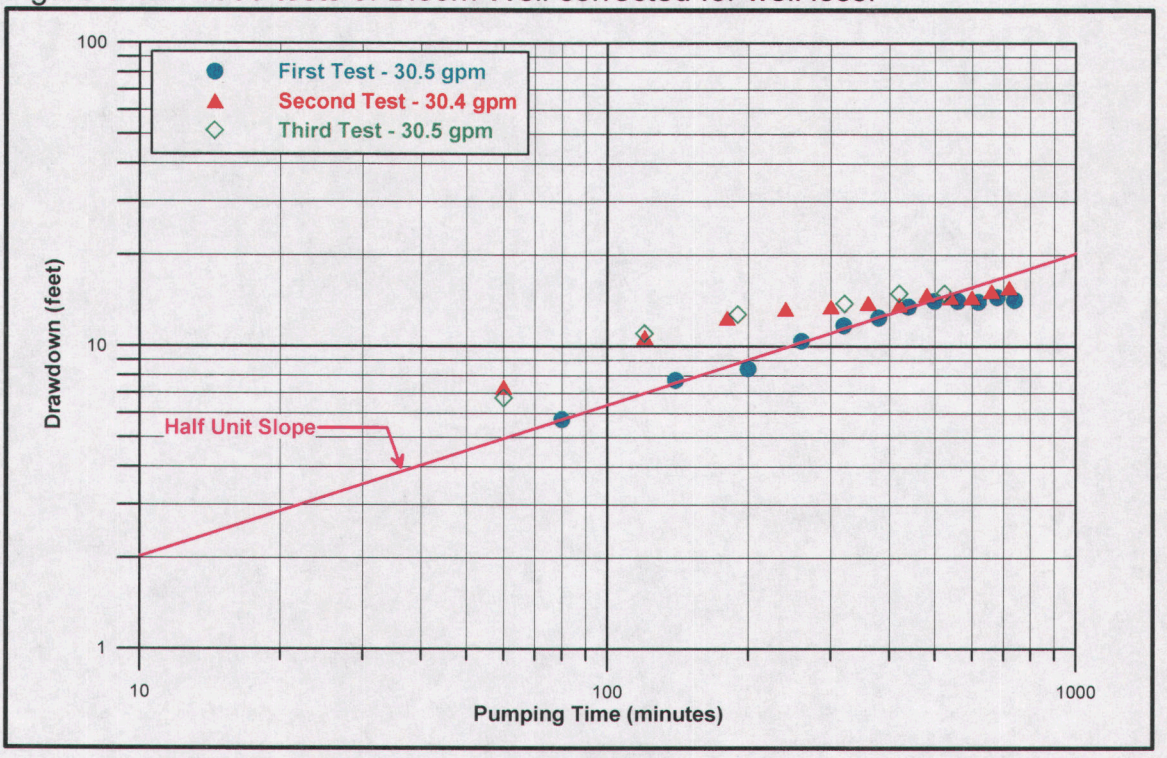


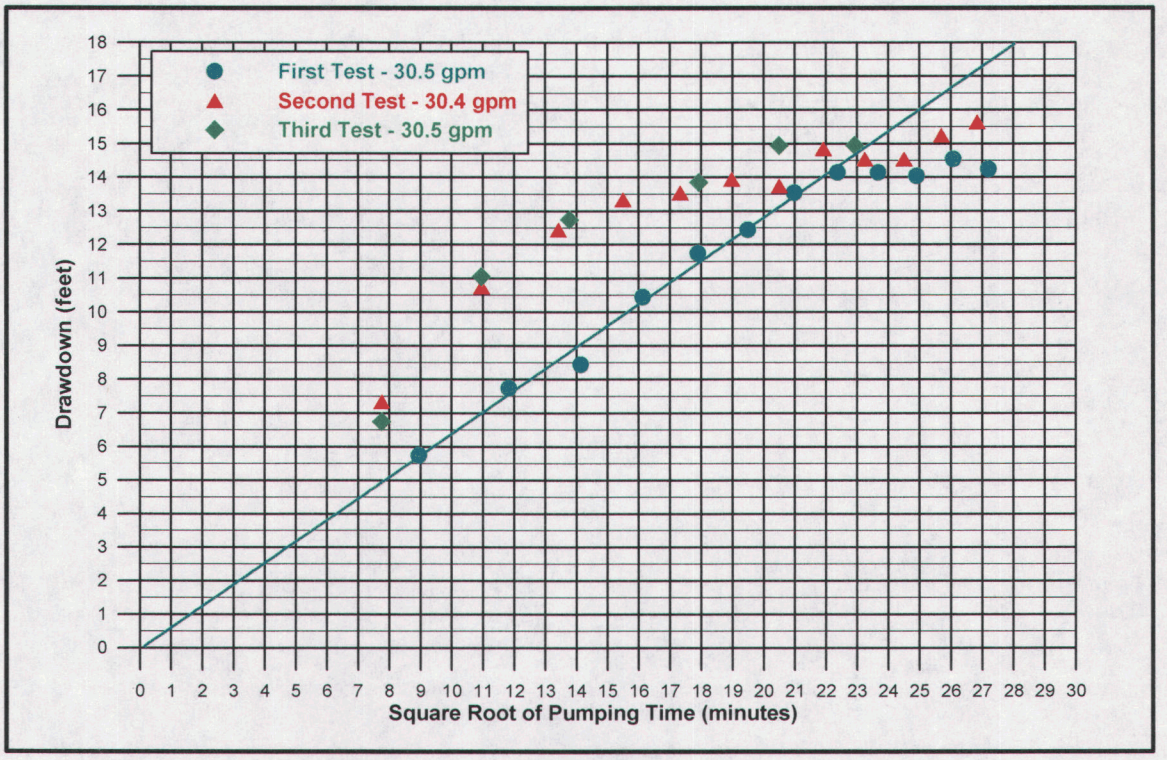
Figure 5-12: 1999 tests of Bloom Well corrected for well loss.



A projection of the test data from the first day of pumping intercepts the drawdown axis of Figure 5-11 at about 21 feet, providing a rough approximation of well loss drawdown. Figure 5-10 shows the time-drawdown data for the three tests as corrected for 21.25 feet of well loss. The basis for 21.25 feet of well loss is that it corrects the specialized plot of drawdown versus the square root of pumping time, as shown on Figure 5-13, to pass through the origin of the time and drawdown axes. The time-drawdown responses of the diagnostic log-log plots of the corrected drawdowns shown on Figure 5-12 follow a half unit slope until the pumping water level essentially stabilizes. This may indicate the water level has approached the pump inlet; however, the records show the pumping rate was consistent throughout each of the three tests and did not decline significantly during the period of stabilized drawdown. This indicates the stabilized drawdown was likely due to recharge from Pine Creek, rather than due to the pumping water level reaching the pump inlet. There is an increase in drawdown between the initial test and the last two tests. The increased drawdown on the second and third day of pumping might indicate the well did not fully recover from the initial day of pumping, or it may simply indicate slight differences in the pumping rates between the three tests due to an imprecise method of observing and measuring the discharge rate.

Figure 5-13 is used to verify the conclusion from the diagnostic plot on Figure 5-12 that the aquifer provided a linear flow response, with the drawdown data

Figure 5-13: Linear plot of 1999 tests of Bloom Well corrected for well loss.



plotting as a straight line versus the square root of pumping time. The plot of drawdown versus the square root of time provides an enhanced view of the difference between the first test response and that of the second and third tests. The slight curvature in the slope of the data in the last two tests indicate they were likely subject to the effect of residual drawdown remaining from the first test. If this interpretation is correct, it indicates the groundwater levels in the aquifer did not fully recover from pumping between tests. The recovery time between the first and second test was 11.5 hours and 12 hours between the second and third tests. It is not unusual for aquifers with linear flow response to require recovery times longer than the pumping durations to fully recover to static levels, a factor that contributes to loss of well yield when such wells are subjected to sustained pumping over long periods. As suggested by Figure 5-13, this results in progressively increasing cumulative drawdown (and associated decrease in well yield) each time a new pumping cycle is started before the well is fully recovered from the previous pumping cycle. Over the course of a season of summer pumping to meet high water demands, the cumulative drawdown may have a significant effect in reducing the yield of the well.

The fact the Bloom well test shows linear groundwater flow to the well as controlled by fractures, and no significant release of groundwater storage from the rock mass bounding the fractures, indicates the aquifer performance cannot be considered representative of the hydraulic properties of the rock mass across the entire width of the aquifer. Therefore, the results of the test are applicable to an unknown but limited part of the aquifer mass and cannot be extrapolated to represent broad areas of groundwater flow through the aquifer. The diagnostic plot also indicates that the Cooper-Jacob straight-line solution is not an appropriate analytical method to determine the hydraulic properties of the aquifer from the pumping test.

5.7. Radial vs. Linear Flow Implications

The verification by this analysis that groundwater flow in the Schnebly Hill and Supai Group takes place along linear flow paths controlled by fractures rather than as a "flux" across the cross-sectional width of flow through porous strata results in several conclusions regarding estimation of the volume of groundwater flow through any given area:

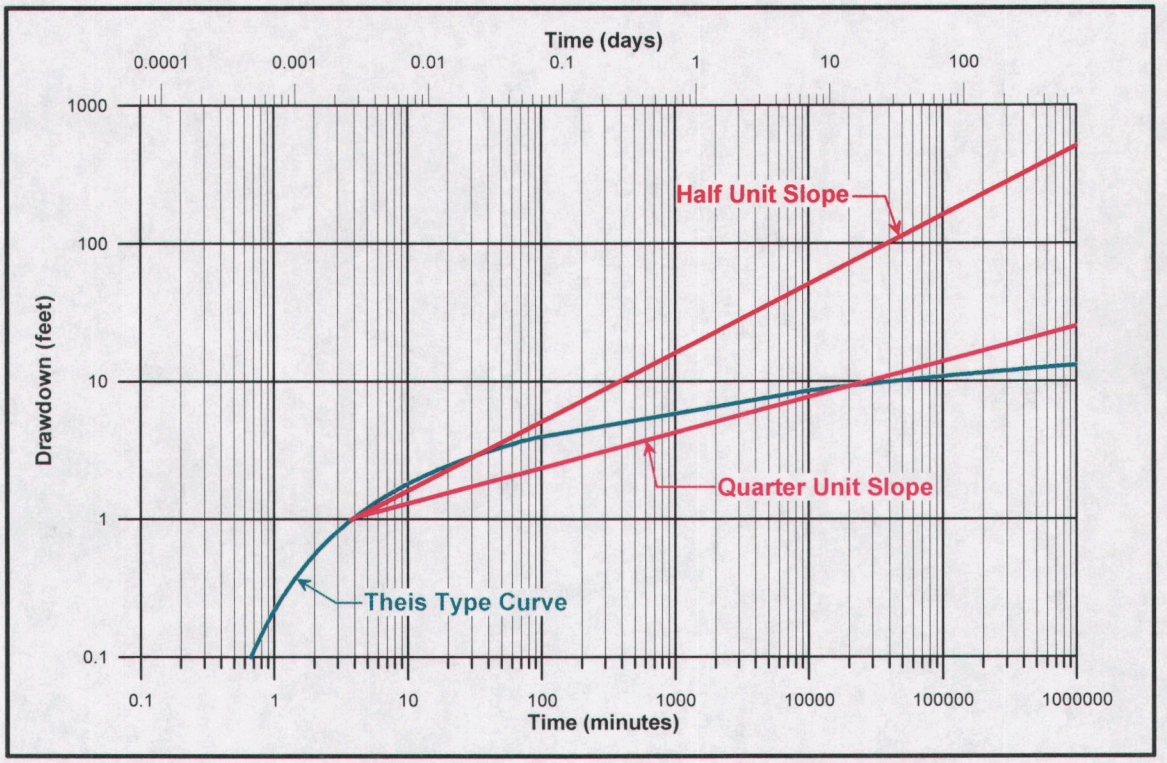
1. The presence of linear flow changes how aquifer transmissivity is determined from the test data. Transmissivity must be calculated from the appropriate linear flow analysis, not from the Cooper-Jacob solution for confined radial flow at late pumping times. The historic calculations of aquifer transmissivity erroneously applied the Cooper-Jacob radial flow solution to aquifer systems exhibiting linear flow.

2. The presence of linear flow changes how the transmissivity applies to the rock mass underneath an area where calculations of an Adequate Water Supply are attempted. The application of the term "transmissivity" to flow through linear fractures is a matter of convenience; however, it must be recognized that linear flow fracture transmissivity is not physically the same as radial flow transmissivity. Whereas radial flow transmissivity, if considered representative, is applied to the entire width of an aquifer system, linear flow transmissivity applies only to the fracture tested and cannot be applied to the remainder of the rock mass under an area of investigation. Moreover, linear flow transmissivity in various fractures across the width of an area may differ greatly from fracture to fracture, a fact demonstrated in the PSWID by the significant differences in well yields from one location to another and from one depth to another. Therefore, fracture flow transmissivity cannot be applied wholesale to estimate the groundwater flow through an area without some consideration of how the width of the fracture flow path is constrained by the fracture boundaries. This step was not taken in the historic calculations of groundwater flow and availability.

3. Control of groundwater movement through the aquifer by linear flow in fractures changes how the sustainability of well yields is assessed. Assuming adequate recharge is available, the sustainable yields of individual wells are constrained by the local hydraulic characteristics of the fractures penetrated. The constraints imposed by the local hydraulic characteristics are described by the response of the aquifer to pumping tests. Therefore, time-drawdown curves from pumping tests provide the fundamental tool to assess the long-term sustainable pumping rates of wells. Simplistically, projection of the time-drawdown response into the future shows how long it will take the water level in a well to decline to the pump inlet. When the water level declines to the pump inlet during pumping, the yield of the well will decrease. Historic evaluations of well yields have been based on application of the Cooper-Jacob method for radial flow, applied incorrectly to linear flow conditions.

Figure 5-14 compares the Theis type curve for radial flow to the half unit and quarter unit responses for linear flow, without and with release of stored water from the host rocks, respectively. Recalling that the Cooper-Jacob solution is simply a modification of the Theis type curve, for that part of the Theis type curve that is changing slowly (after 100 minutes or more on the conceptual example on Figure 5-14), it is clear from Figure 5-14 that the half unit and quarter unit slope drawdown responses obtained by the various historic tests of wells in the PSWID will cause water levels in the wells to reach the pump inlets much sooner than predicted by erroneous application of the Cooper-Jacob or Theis type curve.

Figure 5-14: Conceptual comparison of radial and linear flow response.



It is also apparent in the simplistic conceptual example on Figure 5-14 that the greatest disparity in the predicted pumping water levels is between the half unit slope and the radial flow curve (Theis type curve). Accordingly, erroneous application of radial flow equations to predict drawdown at wells exhibiting a half unit slope, such as the wells completed and tested in the Supai Group in the PSWID, will result in a much greater error than incorrect application of the radial flow equations to wells exhibiting a quarter unit slope, such as the wells completed and tested in the Bell Rock Member of the Schnebly Hill Formation in the PSWID. The conceptual example on Figure 5-14 is consistent with the experience in the PSWID wherein the wells completed in the Supai strata, primarily in the area of Pine, have experienced a greater incidence of lost yield problems than the wells completed in the Schnebly Hill strata in the Strawberry area.

5.8. Precipitation and Groundwater Level Trends

Based on the foregoing considerations, there is little doubt that the most significant factor affecting the reliability of well yields in Pine and Strawberry is the inherent nature of the fractured rock aquifer. Wells abstracting groundwater from fractures with linear flow response typically provide initially good yields that later decrease with increased pumping time. During times of relatively low water demand, when there are ample periods of recovery between pumping cycles, the limitations on the well yields are not obvious. During times of high water

demand, when the periods of recovery between pumping the wells are small, the limitations imposed on well yields by the linear fracture flow conditions become obvious and pronounced with initially high well yields decreasing significantly.

The limitations imposed on well yields by the fracture flow hydraulics take place independently of long-term or short-term fluctuations in groundwater levels. As previously stated, the failure of a well operating under fracture flow limitations to recover fully between pumping cycles becomes cumulative during periods of high demand, causing progressively lower groundwater levels in the well during the passage of time. The progressive decline in the water level in such a well is a function of the pumping rate and duration and is caused because the non-pumping periods are not sufficiently long to allow the groundwater level in the fractures to recover between periods of pumping. However, such a decline is often mistakenly interpreted to be the result of "drought" conditions or a "dry summer"; i.e., it is assumed to result from inadequate recharge.

It is important to recognize that the hydraulic conditions controlling drawdown of water levels and recovery of water levels during pumping and non-pumping cycles in wells subject to linear flow in fractured rock are the cause of the seasonal decreases in well yields and manage the wells accordingly. Stated another way, water systems depending on such wells for water supply will experience seasonal decreases in well yields due to the nature of the aquifer. The seasonal decreases in well yields do not happen because of dry years or inadequate recharge, but occur due to the nature of hydraulic factors controlling the flow to pumped wells in the aquifer.

However, a decline in groundwater levels in the aquifer due to natural recession of groundwater levels during a time of below average recharge is simply added to the decline caused by pumping wells in the fractured rock aquifer, and therefore makes the problems caused by the aquifer hydraulic conditions just that much worse. Accordingly, water users dependent on water wells in such a fractured rock system cannot depend on periods of above average precipitation and recharge to cure the problems caused by the nature of the fractured rock hydraulics. On the other hand, the problems caused by the fractured rock hydraulics will be amplified by groundwater level declines caused by below average precipitation and recharge conditions. Drought conditions exacerbate the limitations imposed on well yields by unfavorable fractured rock hydraulics.

5.8.1. Precipitation Trends

Figure 5-15 shows plots of monthly precipitation values from stations at Childs, Payson, and Heber Ranger Station. The Childs record begins September 1915, Payson, August 1948 and Heber in August 1950. The monthly precipitation values shown on Figure 5-15 exclude any month in which more than five daily precipitation values were missing from the records. Figure 5-15 demonstrates

Figure 5-15: Monthly precipitation.

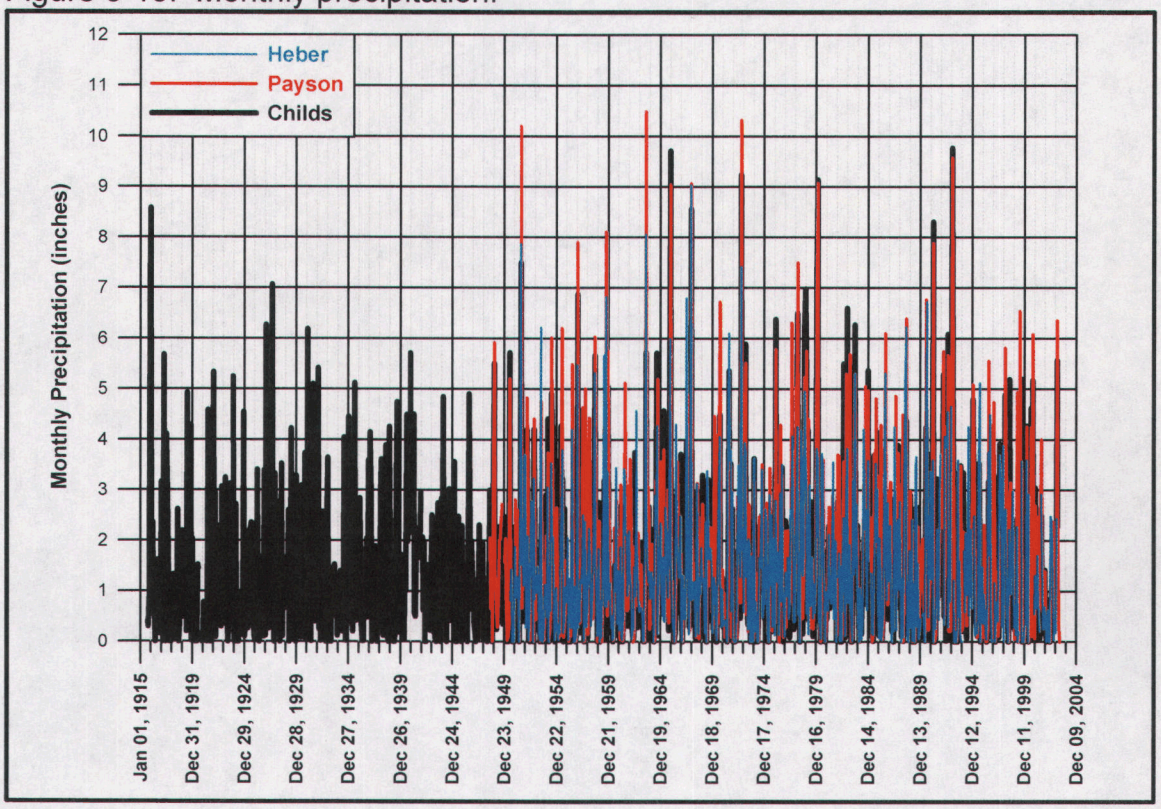
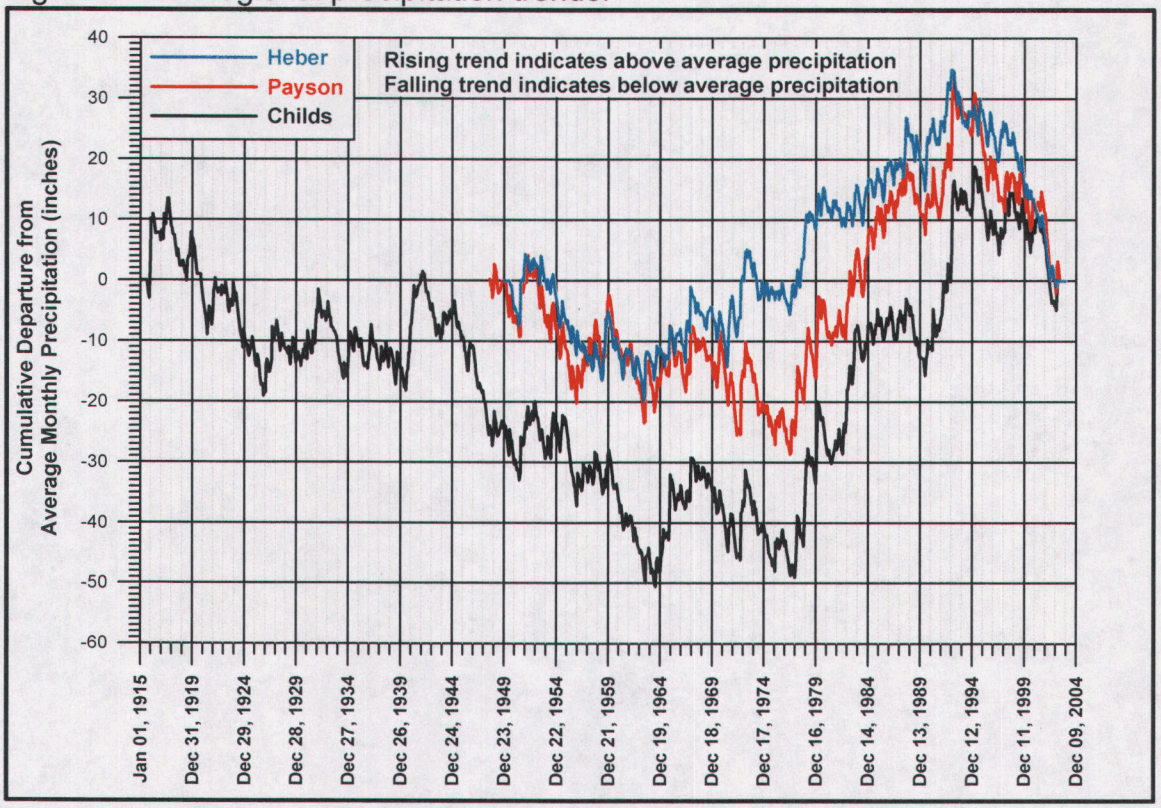


Figure 5-16: Regional precipitation trends.



the difficulty of perceiving trends from monthly or annual values of precipitation or any type of time-series plot.

One tool commonly used to evaluate trends of precipitation, stream flow, and other time-series data is the cumulative departure from an average or mean plotted versus time. Figure 5-16 shows a plot of cumulative departure of monthly precipitation from the average monthly precipitation for the period of record at each of the three precipitation stations. The value of zero cumulative departure corresponds to the average monthly value for the period of record. The fact that cumulative departure values are greater or less than the average value at zero has no particular significance. However, the trend of the cumulative departure is significant in that increasing trends indicate periods of above average precipitation and decreasing trends indicate periods of below average precipitation.

Each of the three precipitation stations shown on Figures 5-15 and 5-16 are located at different elevations and subject to the influence of somewhat different factors. The station at the Heber Ranger station is on the north side of the Mogollon Rim at an elevation of 6,590 feet and perhaps more influenced by winter precipitation than the other two stations. The Payson and Childs stations are on the south side of the Mogollon Rim; however, the Childs station is at an elevation of 2,650 feet whereas the Payson station is at 4,910 feet elevation. Accordingly, the data from the Childs station exhibit more variability than Payson and are more reflective of the desert climate and the influence of summer thundershowers. Considered collectively, the Payson station may most closely represent precipitation trends at Pine and Strawberry; even though the PSWID area probably exhibits its own local characteristics, differing somewhat from the Payson station. However; the precipitation trends at all three stations are essentially the same, with minor variations, and it is anticipated that precipitation trends in the PSWID are likewise similar.

The long-term record from the Childs station shows below average precipitation from 1915 through the end of 1963. The shorter records from Payson and Heber follow the same trend; however, in mid-1962 both the Payson and Heber stations exhibit a change to above average precipitation trends. The above average trend continued at Heber through 1992; however, the Payson record reflects a period of below average precipitation from 1967 through early 1977 before resuming the above average trend through 1992. The lower elevation Childs station shows a similar pattern but with no strong trend developing between 1963 and 1977.

All three stations exhibit a marked increase in above average precipitation between 1977 and 1987 followed by a short period of below average precipitation from mid 1987 through early 1990. The above average precipitation trend resumed from early 1990 through 1992. The overall trend at all three stations, following a long period of below average precipitation ending in 1962 or 1963,

was a period of average or above average precipitation from 1962 or 1963 through 1992, about 30 years, including less than three years of below average conditions from mid 1987 through early 1990, followed by below average precipitation from 1992 to the present (June 2003).

Starting at the end of 1992, all three stations show the onset of a period of below average precipitation that continues to the present. The below average trend accelerates at Heber and Payson beginning in 1998. The trends at Childs are the same, but with more variability. The information on Figure 5-16 supports the ADWR (1987) conclusion that the period from 1977 through 1987 was a period of above average precipitation, thus indicating that the experiences with water shortages, water rationing, and hauling of water starting in 1989 occurred after 10 years of above average precipitation. Therefore, the decreases in well yields and the historic water shortages occurred despite availability of above average precipitation. Hence, it follows that decreases in well yields and water shortages may be worse during below average precipitation and recharge conditions.

5.8.2. Groundwater Trends

Figure 5-17 shows the locations of four wells in the PSWID where the ADWR collects groundwater level data on a reasonably frequent basis. Figure 5-18 compares the precipitation trends to the hydrographs from the two wells at Strawberry, based on the ADWR data. Figure 5-19 compares the precipitation trends to the hydrographs from the two wells at Pine.

The wells at Strawberry are completed in the Bell Rock Member of the Schnebly Hill Formation in the eastern part of Strawberry and therefore enjoy the benefit of groundwater released into fracture flow from the rock containing the fractures. The wells at Pine are completed in the upper Supai, one near the bottom of Strawberry Hollow and the other just east of Pine Creek in the north central part of Pine, and therefore may be assumed to obtain groundwater storage solely from the fractures with no contribution from the rocks containing the fractures.

Regression analysis of the groundwater levels for the two wells in Strawberry (Figure 5-18), limited to that part of the data collected from December 1992 and later during below average precipitation conditions, shows a rate of groundwater level decline ranging from 8.985 feet per year (ft/yr) at Well 1 to 14.416 ft/yr at Well 2. Regression analysis of the data for the wells in Pine (Figure 5-19) indicates a rate of groundwater level decline of 2.176 ft/yr at Well 3 and no rising or declining trend at Well 4. Thus, declining groundwater level trends in both wells at Strawberry and at one well in Pine show correspond to the period of below average precipitation conditions. The fact that Well 4 in Pine does not show an upward or downward trend in water levels is probably due to recharge of the fractures penetrated by the well by infiltration of local surface water into the upper Supai strata out of Pine Creek.

Figure 5-17: Locations of wells measured by ADWR for hydrographs.

Qal = Modern Alluvium
Qc = Collumium
Tv = Volcanics, mostly basalt
Pk = Kaibab Formation
Pco = Coconino Sandstone
Pshu = Corduroy Member, Schnebly Hill Fm.
Psfa = Fort Apache Member, Schnebly Hill Fm.
Pshl = Bell Rock/Rancho Rojo Mbrs., Schnebly Hill Fm.
Psu = Upper Supai Formation
Psl = Lower Supai Formation
PPn = Naco Formation
Mr = Redwall Limestone

Private Land Boundary
PSWID Boundary (Approx.)
Geologic Contact (Approx.)
Well 3 Well from Manera (1979)
Well 1 Well from Manera (1994)
Bloom Well from Glotfelty (2002)
ADWR Hydrograph

Well locations not field checked.

Strawberry View III
Johnson 1
Johnson 2
Myers-Portal III
Bloom
Well 1
Well 2
Well 3
Well 4
Well 5
Jones Well

Geology modified from: Weir and Beard (1984)
Weisman and Weir (1990)

Figure 5-18: Well hydrographs compared to precipitation trends at Strawberry.

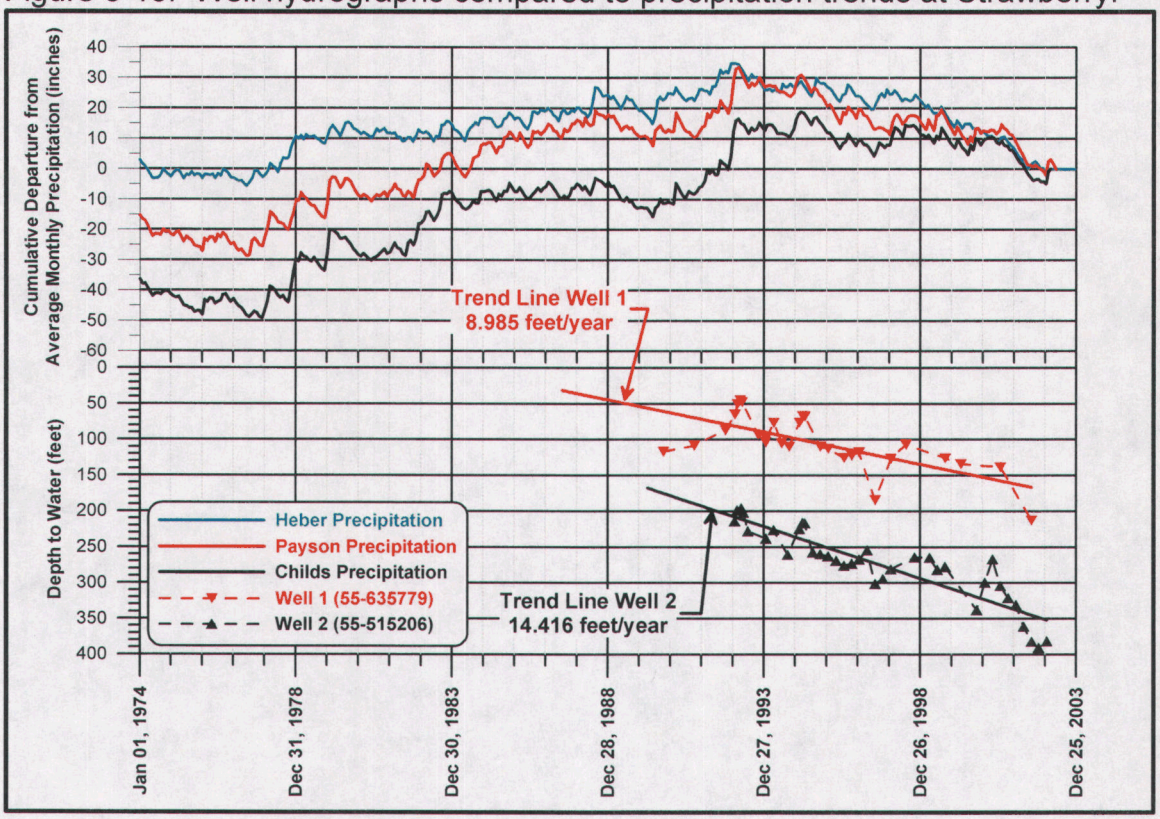
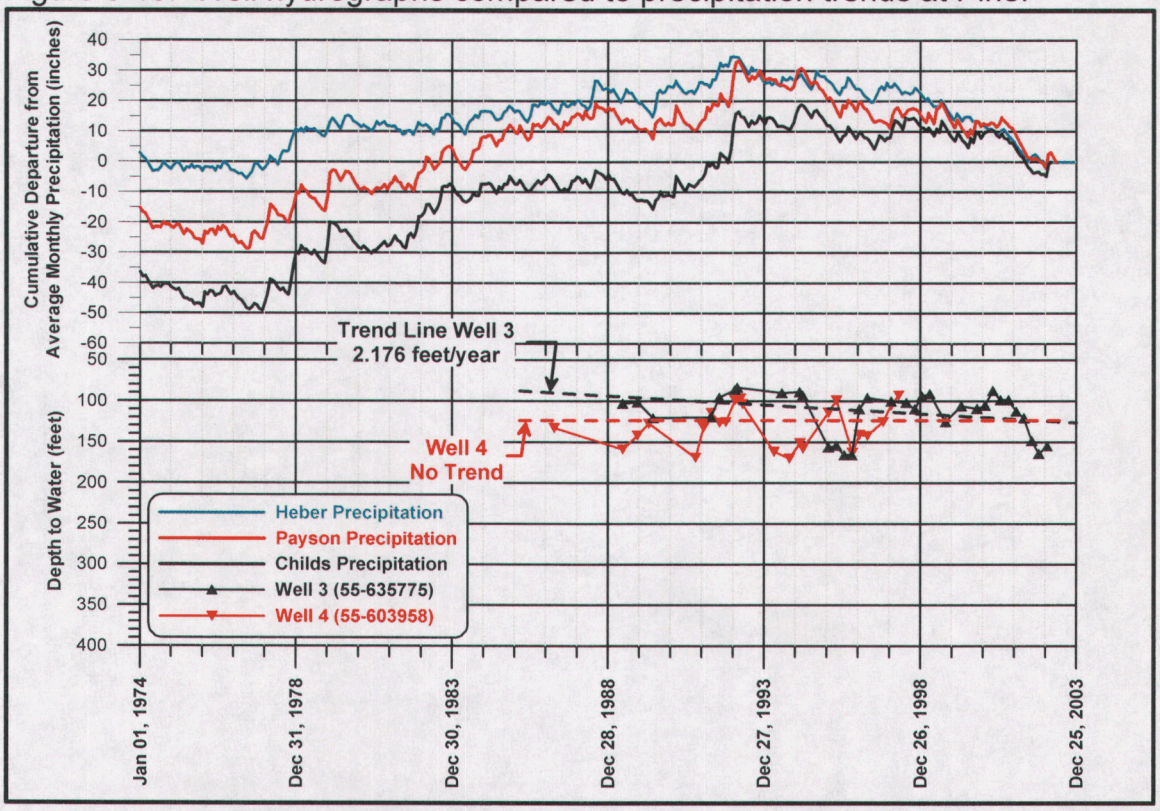


Figure 5-19: Well hydrographs compared to precipitation trends at Pine.



The relationships shown on Figures 5-18 and 5-19 do not support a distinction between the long-term decline of groundwater levels caused by pumping versus the natural recession rate of groundwater levels caused by below average precipitation and recharge. This is because each of the wells monitored for groundwater levels is a pumped well used for community or domestic water supply. Each hydrograph therefore potentially includes an element of long-term drawdown caused by the pumping.

The groundwater hydrographs (with the exception of Well 4 which is suspected to be subject to localized recharge) exhibit long-term trends indicating declining groundwater levels since the end of 1992. The hydrographs also show short-term or seasonal fluctuations superimposed over the long-term trends. In nearly all instances, the short-term seasonal pumping induced fluctuations recover fully back to the trend lines, suggesting that below average precipitation conditions are a significant factor in the long-term declining trends. However, the differences in the rates of recession between the trend lines imply that pumping rates and durations also play a role in creating the long-term trend. The other variable that likely affects the long-term trends is differences in local fractured rock aquifer hydraulics between the three well sites and differences in pumping rates and/or durations at the three wells. Data have not been sought in this investigation regarding the latter factors.

Well 1 (ADWR 55-635779) - Although it is not possible to separate the long-term declining groundwater level trends into components for pumping versus precipitation causes, the significance of the trends cannot be lost on anyone examining the data. At an average annual recession rate of 8.985 ft/yr, the 11-year average decline in the groundwater level at Well 1 in Strawberry, since the onset of below average recharge conditions began at the end of 1992, is 98.8 feet. The highest groundwater level depth at Well 1 was 44.8 feet on April 21, 1993 and the lowest level, subject to seasonal pumping effects superimposed over the long-term trend on August 16, 2002, was 212.35 feet or a total decline of 167.55 feet for long-term recession combined with seasonal pumping effect in about 10 years.

Well 2 (ADWR 55-515206) – At an average annual recession rate of 14.416 ft/yr, the 11-year average decline in the groundwater level at Well 2 in Strawberry is 158.6 feet. The highest groundwater level depth at Well 2 was 195.8 feet on April 21, 1993 and the lowest level, subject to seasonal pumping effects superimposed over the long-term trend on November 5, 2002, was 390.6 feet or a total decline of 194.8 feet in about 10 years.

Well 3 (ADWR 55-635775) – At an average annual recession rate of 2.176 ft/yr, the 11-year average decline in the groundwater level at Well 3 in Pine is 23.9 feet. The highest groundwater level depth at Well 3 was 83.3 feet on March 18, 1993 and the lowest level, subject to seasonal pumping effects superimposed

over the long-term trend August 16 through November 14, 1996, was 165.6 feet or a total decline of 82.3 feet in about 3.5 years. The long-term trend of declining static levels has continued at this well; however, the pumping pattern reflects decreased use until early 2002 when combined long-term decline and short-term pumping cause a depth of water of 164.1 feet by November 5, 2002.

Well 4 (ADWR 55-603958) – Data collected from Well 4 do not exhibit a trend. Seasonal fluctuations caused by seasonal pumping are about 75 feet. As previously stated, it is likely the fracture system from which this well abstracts groundwater is locally recharged by infiltration of surface water from Pine Creek or infiltration of groundwater from the alluvial deposits along Pine Creek. The available recharge must exceed the capacity of the fracture system to accept recharge, thus causing the groundwater level in the well to return to essentially the same level every year. Likewise, operation of the pump causes the pumping water level to decline to essentially the same level every year, during the period of high demands for water.

5.8.3. 2001 to 2002 Season

The long-term recession rates exhibited by the wells monitored by the ADWR, particularly those at Strawberry, are alarming. It does not matter if the cause of the declining groundwater levels is pumping or drought conditions or a combination thereof; however, the recession rates correspond to below average precipitation conditions, showing that the droughty conditions are a contributing factor to the loss of well yield associated with declining groundwater levels. Wells 1, 2 and 3 all exhibit a pronounced decline in groundwater levels starting in early to mid-2001 that continues until late 2002. Data are not available from Well 4 for the same period of time. The data show a small recovery in February 2003 but more current data are not available to see if the recovery continued past February 2003. Well 3 exhibits a similar fluctuation in 1993-1994, but the other wells do not exhibit a similar fluctuation of drawdown-induced pumping spanning more than one season.

The groundwater decline in response to pumping during 2001-2002 appears to be greater than in previous years in the period of record. This is particularly true at the domestic well, Well 2 (ADWR 55-515206) in Strawberry. Pumping caused the depth to water in this well to decline from a depth of 266.9 feet on May 17, 2001 to 390.6 feet on November 5, 2002. The depth of 390.6 feet to water was the lowest water level recorded in this well since the record started February 17, 1993 by 52.7 feet.

The relatively anomalous declines in groundwater levels in the monitored wells during pumping in the 2001-2002 period correspond to the period of accelerated departure of monthly precipitation below the average value, as can be seen on Figures 5-18 and 5-19. The record is presently too short to make conclusions about the slight recovery of groundwater levels in February 2003; however, that

recovery corresponds to a trend in cumulative departure from average precipitation of three months of above average precipitation, including the February 2003 value. The foregoing relationships suggest the unusually dry conditions in 2001-2002 caused the anomalously large decline in associated groundwater levels either directly or indirectly. The decline may have been caused directly by the effects of inadequate recharge or it may have resulted indirectly from increased pumping durations during the dry period.

5.8.4. Summary

The historical documentation reveals that production of groundwater from the Schnebly Hill and upper Supai strata is inherently limited by the hydraulic characteristics of groundwater flow through fractures to the pumped wells. The fractures highly constrain the flow to pumped wells such that initially good yields progressively decrease as pumping duration increases and associated non-pumping times for recovery of groundwater levels decrease. Moreover, the potential for competition and interference between wells completed in this type of aquifer system is high, suggesting that the ability to overcome the problem of constrained well yields by simply drilling more wells into the system is limited due to the potential for mutual interference between wells.

Comparison of groundwater level hydrograph data collected by the ADWR from pumped wells in the PSWID area to long-term precipitation trends indicates that the seasonal declines in well yields caused by the inherent hydraulic properties of the aquifer system are amplified by below average precipitation conditions. However, historic shortages of water occurred during extended periods of above average precipitation trends; therefore, the historic water shortages were not the product of drought conditions but resulted from the demand for water exceeding the production capacity of the wells, as limited by the aquifer hydraulic characteristics, particularly in the Pine area which offers less favorable aquifer characteristics than the Strawberry area.

It is concluded, based on the foregoing considerations, that the adequacy of the groundwater resource in the Schnebly Hill and upper Supai aquifer system in the PSWID has been demonstrably inadequate to support the historic and currently existing levels of demand for residential water supply in the Pine area and marginal in the Strawberry area and therefore does not offer any reasonable potential to support continued population growth in the PSWID area with the concomitant need for increased production of water supply. Accordingly, it is necessary to seek alternative sources of water for the PSWID communities.

6. ALTERNATIVE WATER SOURCE

Preliminary steps to identify an alternative source of water were taken in Strawberry in May and June, 2000, through a cooperative effort of the Northern Gila County Water Plan Alliance, the PSWID, Gila County, the U.S. Forest

Service, the U.S. Bureau of Reclamation, the U.S. Geological Survey, the Arizona Department of Water Resources, the Salt River Project, and the City of Payson. The collective effort of these entities resulted in the funding and accomplishment of an exploratory drilling program to gather information about the deep subsurface geology of the area, culminating in construction of an 1,872-feet deep well at Strawberry in 2000, referred to herein as the "Strawberry Borehole".

The Strawberry Borehole was successful in determining that groundwater is present in the Redwall and deeper strata; however, funding limitations and construction difficulties prevented the well from being completed in a manner in which it could be subjected to pumping tests. Accordingly, the well can presently be used to monitor the groundwater level in the Limestone Aquifer at this location, but has not provided information about the potential yield from the Limestone Aquifer.

In July 2002, the PSWID released a Request for Proposals (RFP), seeking a consultant to help build on the previously collected information to identify new sources of water supply for future development. The introduction to the RFP summarized the objectives of the study as follows:

> "***The Pine/Strawberry Water Improvement District is seeking a qualified firm, or firms, to provide Geohydrologic/Engineering Services for the development of a District Water Resource and Action Plan directed at development and the well siting of deep production wells in the Pine/Strawberry area of Gila County, Arizona.***
>
> ***The Pine/Strawberry Water Improvement District is seeking new sources of potable water that would be less sensitive to drought and climatic changes than the currently used water sources.***
>
> ***HISTORICAL PERSPECTIVE: The Pine & Strawberry area of Gila County is a Community of historical significance in Arizona. The Community's domestic water needs are largely obtained from ground water and served by a mix of private wells, regulated water utilities, and domestic water improvement districts. The Pine/Strawberry Water Improvement District (District) boundaries encompass the general extent of the area, including the entities listed above, but the District itself does not provide domestic water service to the Community. The map showing the approved boundaries of the***

District is shown in Appendix A. The Arizona Department of Water Resources has deemed this area to have an "inadequate water supply."

Efforts have been under way for several years to collect data and begin the process of identifying potential sources. The Northern Gila County Water Plan Alliance (of which the P/SWID is a partner) in cooperation with the Arizona Department of Water Resources is in the third year of a five-year geologic-hydrologic study of the Mogollon Highlands (which includes the Pine-Strawberry area). This five-year study is being conducted by the U.S. Geologic Survey and is described in more detail on the USGS website. In June of 2000, the Northern Gila County Water Plan Alliance, in partnership with the Pine/Strawberry Water Improvement District, Gila County, the Arizona Department of Water Resources and the U.S. Forest Service completed the drilling of an exploratory borehole, approximately 1870 feet deep, in the community of Strawberry. Geological samples gathered during the drilling process have been documented and used to correlate with previously obtained geologic information to formulate an opinion of the sub-surface geology of the immediate area. Groundwater was encountered during the drilling process and water in the borehole presently stands at approximately 1380 feet below the surface. A detailed report of findings, prepared by the Arizona Department of Water Resources, is also available for this project.

The Pine/Strawberry Water Improvement District would like to build on the available data and proceed in identifying potential sites for future production wells capable of accessing a more reliable groundwater source." (P/S 2002 DOCUMENT Dated 07/23/02)

The investigation of alternate sources of water reported herein has been conducted pursuant to the objectives stated in the above RFP.

The hydrogeologic conditions in the region around and including the PSWID offer three potential sources of groundwater for development consisting of the perched aquifer in the volcanics, where present; the Regional Aquifer system consisting of the Kaibab, Coconino, Schnebly Hill, and Supai strata; and the deep Limestone Aquifer.

Only the Schnebly Hill and Supai strata are present within the PSWID as a known aquifer system. Basalt layers (volcanic rock) are present as caps on Strawberry Mountain and the Mogollon Rim, including Milk Ranch Point;

however, their topographic positions indicate they offer little potential for storage of groundwater and are largely drained out to the adjacent lower terrain, thus offering little or no potential as sources of water supply.

Kaibab and Coconino strata are present north of the Mogollon Rim but offer two potential disadvantages. One disadvantage is that topographic features such as Pine Canyon, Strawberry Canyon, Weber Creek, Calf Pen Canyon, and Fossil Creek Canyon are all incised through the Kaibab and Coconino strata and therefore drain groundwater out of the formations throughout the area reasonably near to the PSWID. Accordingly, wells drilled into the Kaibab-Coconino part of the Regional Aquifer immediately north of the PSWID will penetrate a significantly drained part of the aquifer. A related condition is the fact that the portions of the Kaibab-Coconino aquifer immediately north of the PSWID area is at the uppermost end of that aquifer system and therefore offers limited groundwater storage, even where not drained out to lower terrain. It is probable that groundwater abstraction rates required to satisfy present and future demands for water in the PSWID will result in mining of groundwater in the Kaibab-Coconino system along the northern edge of the PSWID area with resultant depletion of the available groundwater storage that is already affected by drainage to lower terrain. The second potential disadvantage of the Kaibab-Coconino system is that a long pipeline will be required to convey water to the PSWID from potential well sites in this system.

The strata of the Limestone Aquifer are present in the subsurface of the PSWID and outcrop at the southern edge of Pine. However, they have not been historically regarded as a potential source of groundwater, partly because of the history of certain wells in the Pine area penetrating dry voids in the Redwall strata into which drained the production from the overlying Supai strata, leaving the wells with no water for production. Hix (1978; p. 23) dismissed the Limestone Aquifer as a potential source of groundwater, stating:

> "***There have been reports of water wells within the Pine area that have been lost when dynamite was used to loosen the rock. This is what would be expected of a formation in which the water was controlled by solution channels rather than a consistent permeability. Aquifers of this type are generally unreliable producers and are subject to contamination and seasonal variations in rainfall. Drilling water wells with targets of this nature is risky and could be considered a hit or miss proposition.***"

In addition to the foregoing unfavorable description of the Redwall Limestone as a potential aquifer, it has been recognized that the surface flow of Pine Creek historically submerged into the alluvial gravel along its channel and did not resurface downstream where the gravel is dammed by the Mazatzal quartzite. It was correctly perceived that the historic loss of surface flow occurred along the

surface channel of Pine Creek near where the alluvium rests on the Naco Formation and Redwall Limestone, and that the water was lost to the Redwall. The loss of surface flow into the Redwall Limestone was taken as another indication of the fact that the unit was above the water table and dry.

Completion of the Strawberry Borehole project, demonstrating that groundwater is present in the Limestone Aquifer in the subsurface of the PSWID, changed the perception of the problem from one of concluding that no groundwater was available in the Redwall/Martin strata to one of recognizing that the strata might be dry under only part of the PSWID and wondering where to drill to develop water from a part of the Limestone Aquifer that is not dry. A preliminary review of the existing information, including the ADWR (1987) and ADWR (1989) reports about the area and the declaration by ADWR that the PSWID is an area of "inadequate water supply", focused the attention of this investigation away from the Supai strata, and away from what is now recognized as Schnebly Hill strata. Likewise, review of the available data focused attention away from the Kaibab-Coconino strata as the first priority for identifying a new source of water. Instead, the primary focus of this investigation was the Limestone Aquifer consisting of the Redwall Limestone and Martin Formations.

6.1. Fossil Springs

One of the factors that focused the attention of this investigation on the Redwall/Martin strata early in planning the work is the discharge from Fossil Springs in the canyon of Fossil Creek. Fossil Spring discharges from the Redwall Limestone near the contact with the Naco. The spring has been variously described as from the Naco or the Redwall due to the juxtaposition of the several hundred yard long spring zone along the contact between the two formations, but there is no doubt the main source of the flow is groundwater discharged from the Redwall Limestone.

Figure 6-1 is a hydrograph of the flow diverted from the channel of Fossil Creek below Fossil Springs into a flume conveying the water to the Irving Power Plant some 4.5 miles downstream. The measured flow is water diverted to the power plant and does not include small flows that bypass the diversion and continue down the streambed of Fossil Creek. Likewise, the measurements of the diversion do not distinguish between water discharged from Fossil Springs and flow in Fossil Creek from the watershed upstream from Fossil Springs. However, most of the time the flow is essentially all from Fossil Springs and most of the time nearly all of the flow is diverted into the flume. The few times in the record when the measured flow is less than 38 to 40 cubic feet per second (cfs), it is because not all the water is being diverted, i.e., the fluctuations that show relatively low flows are related to changes in the diversion into the flume, not to changes in the discharge rate from Fossil Springs.

Figure 6-1: Monthly average flow at USGS gage on Fossil Creek.

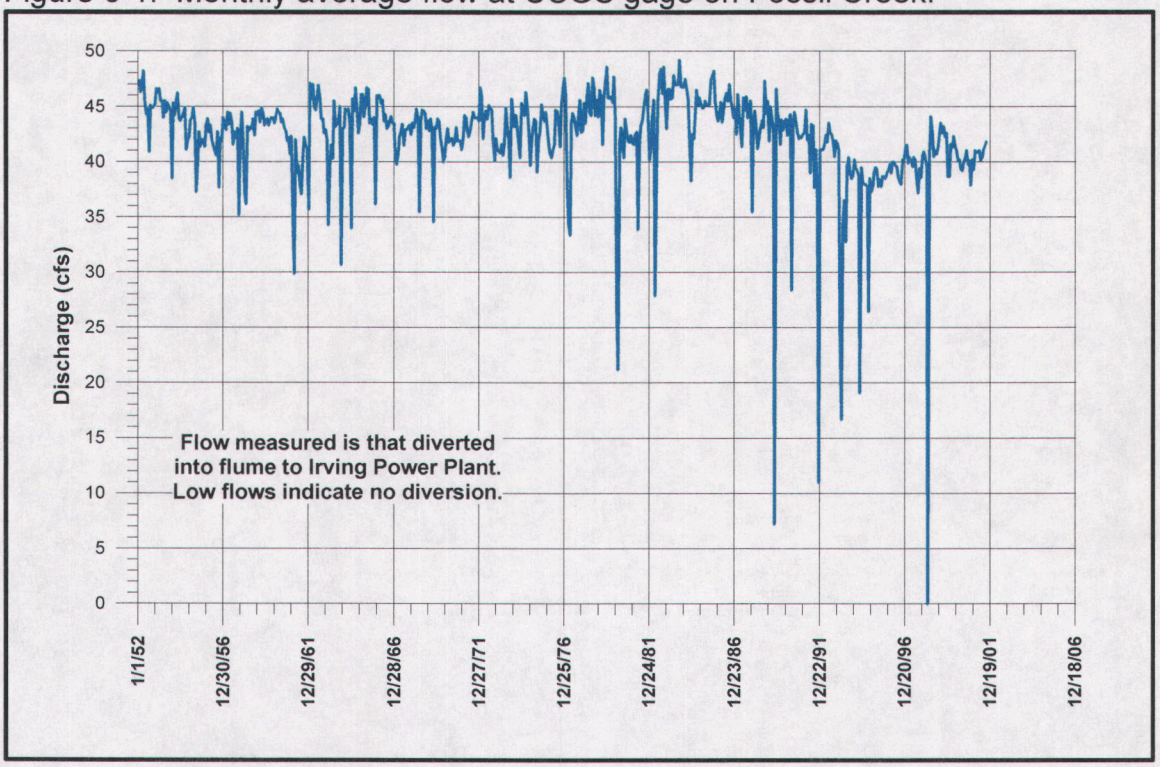


Figure 6-2: Cumulative departure from monthly average flow to Irving Plant.

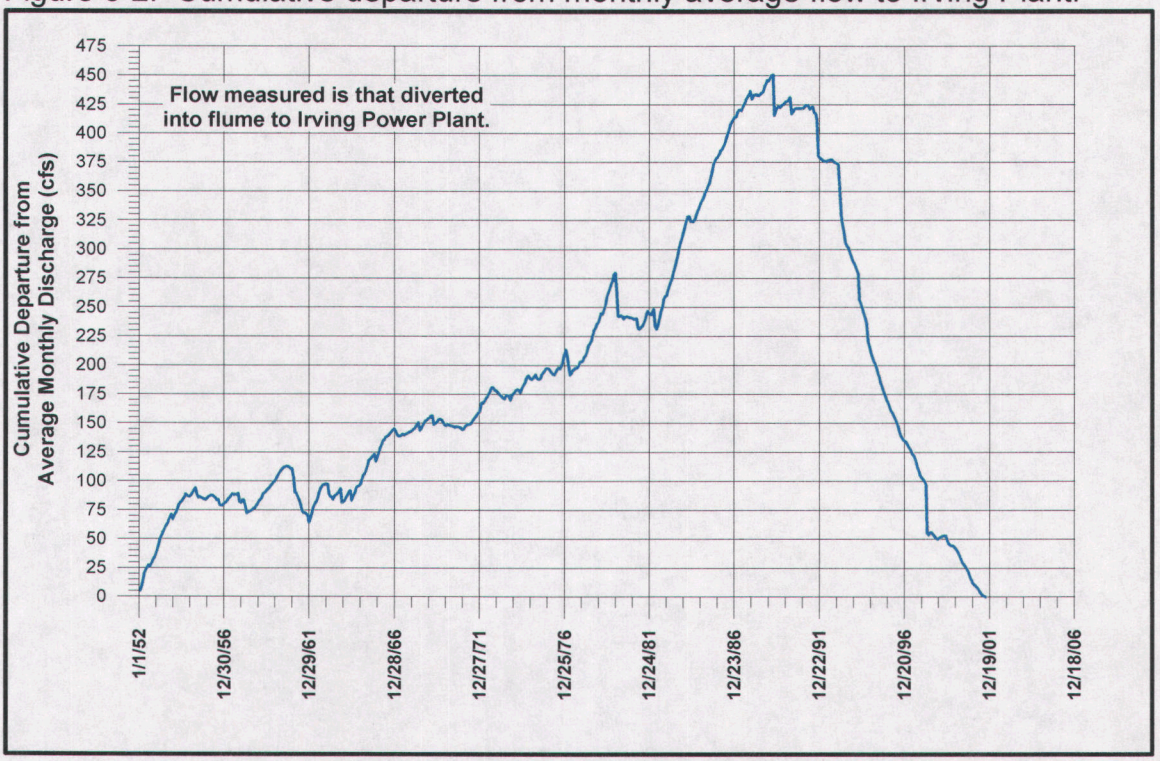
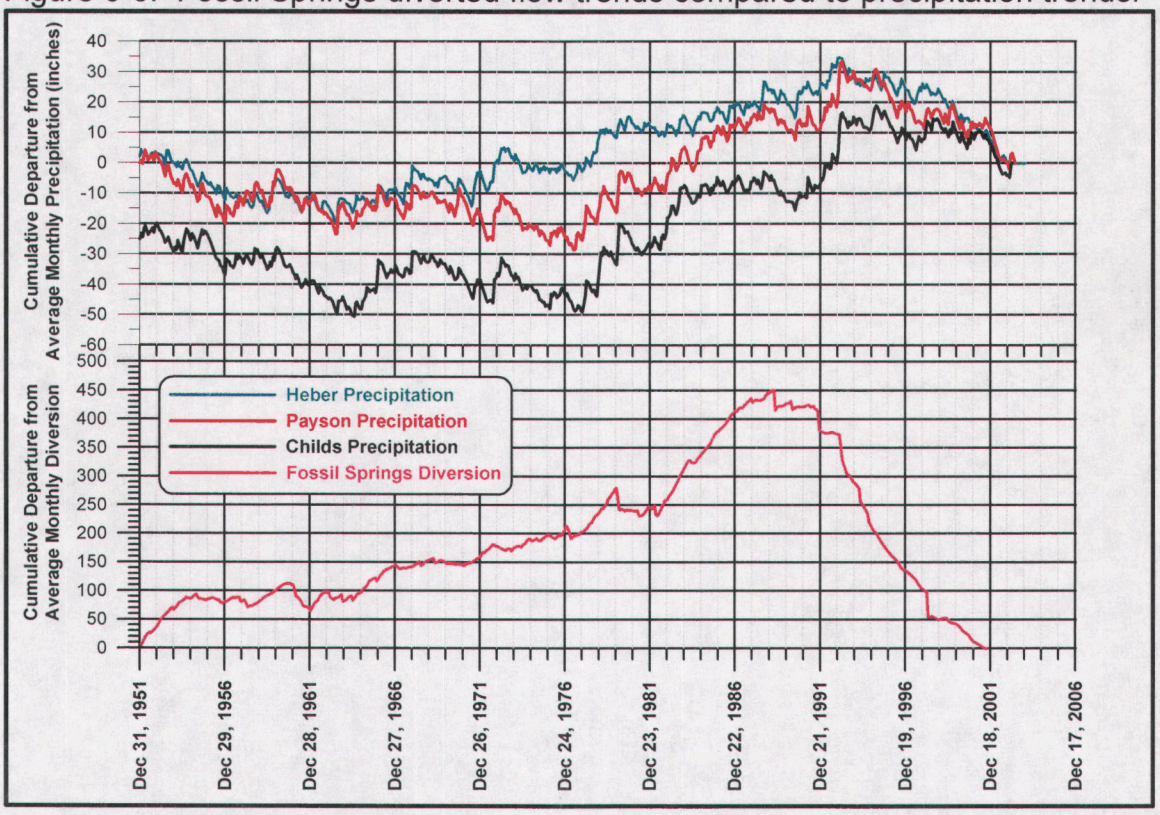


Figure 6-3: Fossil Springs diverted flow trends compared to precipitation trends.



The flow of diverted water averages 42.3 cfs for the period of record shown on Figure 6-1. A cubic foot per second (cfs) is equal to 448.86 gallons per minute so an average flow of 42.3 cfs is equivalent to an average flow of 18,987 gpm.

Figure 6-2 shows cumulative departure from the average flow for the period of record. The hydrograph on Figure 6-1 shows seasonal fluctuations of 3.5 to 5.0 cfs (depending on what period of time in the record is examined) superimposed over the long-term trends of the hydrograph. The seasonal fluctuations are likely the measure of the range of surface water flow contributed from the Fossil Creek watershed upstream from Fossil Springs. Since they are small (3.5 to 5.0 cfs) with respect to the average flow of 42.3 cfs, it may be concluded the long-term trends reflect trends in the discharge from Fossil Springs. This being the case, the trends of the cumulative departure plot on Figure 6-2 indicate the trends of the discharge from Fossil Springs and therefore, reflect the trends of the groundwater elevations in the Redwall Limestone or Limestone Aquifer at this location.

Figure 6-3 provides a comparison of trends in the diverted flows to regional precipitation trends. As described previously, the relationship to zero cumulative departure is not significant; however, rising, constant, or falling trends indicate above average, average, or below average conditions, respectively. The trends of the diversion flows are, of course, potentially modified to an unknown extent by

how the diversion was operated. Taking into account potential modification by diversion operations, there is a reasonably good correlation between the regional precipitation trends and trends in the amount of water diverted, thus showing there is a correlation between the flow of groundwater from Fossil Springs and regional precipitation trends.

The long-term range of flow from Fossil Springs, as shown on Figure 6-1, is therefore from a maximum of approximately 47 cfs, in the above average precipitation period between 1977 and 1987, to a minimum of about 37.5 cfs, in 1993, during a period of below average precipitation, all ± 5.0 cfs or less of surface water flow. This is equivalent to a range in flow from 18,852 to 14,588 gpm when a surface water flow contribution of 5.0 cfs is subtracted from the total diverted flow.

The long-term flow from Fossil springs, ranging from an estimated 14,588 to 18,852 gpm over a 50-year period, indicates the flow from the springs discharges from a relatively large body of stored groundwater that is sensitive only to long-term trends in precipitation and recharge and relatively insensitive to seasonal and other short-term trends. This degree of reliability satisfies one of the principal tenants of the PSWID RFP, namely, identification of "***sources of potable water that would be less sensitive to drought and climatic changes than the currently used water sources.***" Accordingly, the work plan for this investigation was focused on determining where to drill to develop a water supply from the large body of groundwater storage in the Redwall Limestone and associated strata.

6.2. Redwall Limestone Structure

Once the Redwall Limestone was identified as a primary target for drilling, selection of a favorable location was a matter of geometry between the land surface elevations, the elevations on the top of the Redwall, and the elevation of the potentiometric surface (water table). In order to determine the structure of the Redwall and its relationship to the potentiometric surface of the groundwater as well as to the land surface, a precision survey was made to control points on the geologic structure, utilizing precision GPS surveying methods.

The control points were surveyed on the basal contact of the Fort Apache Member of the Schnebly Hill Formation. The Fort Apache Member, referred to colloquially as the Fort Apache limestone, is a geologic horizon that provides a marker bed of regional extent on the southernmost end of the Colorado Plateau. Locations of the control points were selected carefully to provide an adequate and appropriate distribution of data to support construction of a structural elevation map of the unit by standard statistical methods. A major consideration in selecting the control points was consideration of the various faults mapped by Weisman (1984) and Weisman and Weir (1990). The control point locations were selected to minimize or eliminate the influence of faults on statistical

projection of a surface between the points. It was easy to minimize the effect of the faults due to their localized extent and due to their relatively small offsets. The influence of faults with large offsets, extending into the area from the north (Weisman and Weir, 1990) was avoided by locating the control points so as not to straddle such faults. The statistical method used to project the structural surface between the data points was first-order Kriging applied with Golden Software Surfer™ 8.0. Appendix A contains the coordinates for the surveyed control points used to construct the structural contour maps in this report.

After control elevations were established on the base of the Fort Apache Member, it was necessary to adjust those elevations to the top of the Redwall Limestone. This was accomplished by subtracting a constant thickness of 1,279 feet from the Fort Apache Member elevations. The basis for the 1,279 feet between the base of the Fort Apache Member and the top of the Redwall Limestone is as follows:

Schnebly Hill Fm. Below Fort Apache Mbr.	479 feet
upper Supai	330 feet
lower Supai	215 feet
Naco Formation	255 feet
Total Thickness	1,279 feet

Figure 6-4 depicts the structural elevation contours projected to represent the top surface of the Redwall Limestone in the PSWID area and shows the locations of the control points, including the Strawberry Borehole, used for statistical construction of the map. The Schnebly Hill Formation includes 40 feet of Fort Apache Member, 390 feet of Corduroy Member referred to as upper Shcnebly Hill above the Fort Apache Member, and 479 feet of combined Bell Rock and Rancho Rojo Members referred to as lower Schnebly Hill on Figure 6-4. The geologic formation contact lines on all figures represent the lines of zero depth from the land surface to the projected structural surfaces.

The structural elevation contours on the upper surface of the Redwall Limestone, shown on Figure 6-4, are valid only within the area circumscribed by the control points and are not valid if projected across major faults such as the north-south aligned fault between Tin Can Draw and Sandrock Canyon that cuts across Nash Point. It is not clear if the latter fault extends through the subsurface southward across the west end of the Strawberry Valley, obscured by basalt and residuum, or if it ends on Nash Point; however, the structural contours suggest the fault extends across the west end of the Strawberry Valley.

The Redwall structure, assuming it is congruent to that of the Fort Apache Member, dips gently to the northwest. An anomalous low in the structure occurs under Strawberry Mountain and extends under the eastern end of Strawberry Valley. The low area in the structure is well defined by data points, including

Figure 6-4: Map of projected structure on surface of Redwall Limestone.

Qal = Modern Alluvium
Qc = Collumium
Tv = Volcanics, mostly basalt
Pk = Kaibab Formation
Pco = Coconino Sandstone
Pshu = Corduroy Member, Schnebly Hill Fm.
Psfa = Fort Apache Member, Schnebly Hill Fm.
Pshl = Bell Rock/Rancho Rojo Mbrs., Schnebly Hill Fm.
Psu = Upper Supai Formation
Psl = Lower Supai Formation
PPn = Naco Formation
Mr = Redwall Limestone
pCm = Mazatzal Quartzite

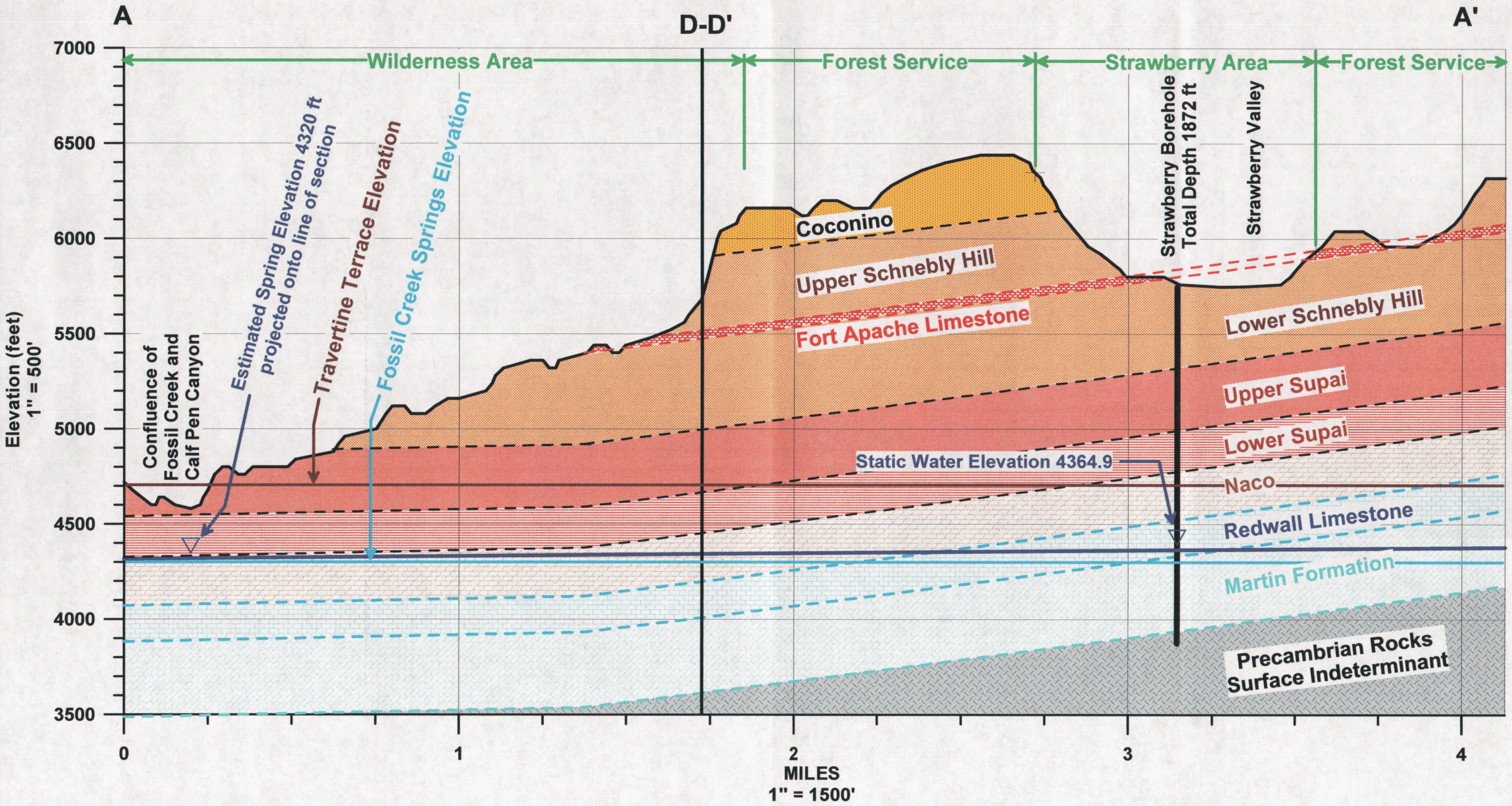
Private Land Boundary (Approx.)
PSWID Boundary (Approx.)
Geologic Contact (Approx.)
4400 Elevation Contour Top of Redwall
Surveyed Control Point

Geology modified from: Weir and Beard (1984)
Weisman and Weir (1990)

OVERSIZED DOCUMENT

FIGURE 6-5: LOCATIONS OF GEOLOGIC CROSS SECTION

Figure 6-6: Cross Section A to A' - Groundwater elevations projected to line of section.



OVERSIZED DOCUMENT

FIGURE 6-7:

CROSS SECTION B TO B' TO B" GROUNDWATER ELEVATIONS PROJECTED TO LINE OF SECTION

OVERSIZED DOCUMENT

FIGURE 6-8:

CROSS SECTION C TO C' GROUNDWATER ELEVATIONS PROJECTED TO LINE OF SECTION

OVERSIZED DOCUMENT

FIGURE 6-9:

CROSS SECTION D TO D' WATER LEVEL AT STRAWBERRY BOREHOLE PROJECTED TO LINE OF SECTION

94), and 395 feet for the Martin Formation, based on the general description and several measured sections in Huddle and Dobrovolny (1952).

The parts of the Redwall/Martin strata where the groundwater head is confined by overlying strata are the most desirable locations for production wells. As shown by Cross Sections A-A', B-B", and C-C' (Figures 6-6, 6-7, and 6-8), the estimated groundwater head in the Redwall/Martin strata is too low in elevation to present confined conditions under private land or under most of the Forest Service land in most of the areas potentially accessible to drilling, i.e., on private land or Forest Service land outside of Wilderness areas. This is particularly true considering that the Naco Formation, overlying the Redwall Limestone, may not be a good confining bed and may instead be hydraulically connected with the Redwall and Martin. If the latter situation is the case, the estimated thickness of about 255 feet of Naco Formation will cause the top of the combined Naco-Redwall-Martin sequence to be above the water table essentially throughout any area potentially accessible for well drilling, outside the Wilderness Area.

Unfortunately, the elevation of the groundwater surface in the Redwall/Martin strata is known at only one location within the PSWID area and that is at the Strawberry Borehole where the depth to water was measured at 1,382 feet on January 17, 2003, using a downhole TV camera as well as several types of geophysical logging tools. A precision survey of the elevation on the top of the well casing provided an elevation of 5749.65 feet based on the 1983 NAVD vertical datum currently in use. Conversion of this elevation to the vertical datum for the Strawberry 7.5-minute topographic quadrangle, 1929 NVGD, provides an elevation of 5746.91 feet for use with the U.S. Geologic Survey 7.5-minute topographic map. The January 17, 2003 depth to water subtracted from the top of casing elevation of 5746.9 ft provides a water table elevation of 4364.9 feet. An earlier measurement of the static water level conducted by ADWR personnel on June 16, 2000 provided a depth to water of 1,377 feet. The difference of 5 feet between the two measurements probably reflects some differences in how the measurements were made; however, the difference is large enough to indicate the groundwater level in the Redwall/Martin strata has probably declined at this location by about 5 feet between 2000 and 2003. This is consistent with the other data provided in this report showing below average precipitation conditions and associated groundwater level recession in other wells in the PSWID area.

The only other elevation data used to evaluate the groundwater head in the Redwall/Martin strata is Fossil Springs. The elevation of Fossil Springs is estimated to be 4320 feet, based on interpolation between 40-foot contours. The flow from the spring indicates that the unknown potentiometric surface at the springs is more than the estimated elevation 4320 feet. The difference between the groundwater elevation of 4364.9 feet in the Strawberry Borehole and the estimated land surface elevation of 4320 feet at the springs indicates the potentiometric surface elevation at the springs cannot be much higher than the

land surface and the pressure driving the springs cannot exceed the approximately 45 foot difference between the surveyed borehole elevations and the estimated elevation at Fossil Springs.

Based on the foregoing considerations, the groundwater level in the Redwall/Martin strata is depicted on each of the geologic cross sections as a line through the land surface elevation of 4320 feet at Fossil Springs and through the groundwater elevation of 4364.9 feet at the Strawberry Borehole, projected onto the line of section for each cross section. Thus, the estimated water table in the Redwall/Martin is depicted with a generally east-southeast to west-northwest gradient, at the same elevations on each cross section.

The cross sections show that the saturated thickness of the Redwall/Martin strata increases north and northwest from the PSWID area. The saturated thickness of the Redwall/Martin strata decreases to the south. The Strawberry Borehole was drilled near the southernmost limit of groundwater in the Redwall Limestone, as shown by Cross Section A-A' (Figure 6-6). Up gradient from the Strawberry Borehole, the Redwall strata rise above the estimated groundwater level. Similarly, the Redwall and Martin are both above the estimated groundwater elevation in the southern part of Pine, as shown by Cross Section B-B" (Figure 6-7). These relationships are consistent with the historic experience at Pine where wells penetrating the Redwall Limestone have encountered drained fractures and voids.

6.4. Potential Redwall/Martin Drilling Sites

Based on the foregoing considerations, it is desirable to drill into the lowest elevation of Redwall/Martin strata available in the PSWID area, in order to seek the maximum saturated thickness of potential aquifer material. Figure 6-10 shows the structural contours on the top of the Redwall Limestone superimposed on the geologic map from Figure 4-2. Figure 6-10 shows that the lowest structural elevation on the top of the Redwall, within the PSWID boundaries and on private land, is along the northern boundary of the private land in the Strawberry Valley where the elevation on the top of the Redwall is 4350 feet or lower just east of the northwest corner of the private property.

Accordingly, that portion of the north half of the north half of the southwest quarter of Section 20, T12N, R8E where the structural elevation of the Redwall is 4350 feet or less, as shown on Figure 6-10, offers the most favorable conditions within the boundaries of private lands in the PSWID area for completion of a well or wells into the Redwall/Martin strata. The northern boundary of the private land, from the quarter corner on the mid-point of the western boundary of Section 20 to about 0.75 miles east along the northern boundary of the private property, is all aligned on favorable conditions for drilling a Redwall/Martin well. The

Figure 6-10: Favorable area for drilling to Redwall Limestone.

Qal = Modern Alluvium
Qc = Collumium
Tv = Volcanics, mostly basalt
Pk = Kaibab Formation
Pco = Coconino Sandstone
Pshu = Corduroy Member, Schnebly Hill Fm.
Psfa = Fort Apache Member, Schnebly Hill Fm.
Pshl = Bell Rock/Rancho Rojo Mbrs., Schnebly Hill Fm.
Psu = Upper Supai Formation
Psl = Lower Supai Formation
PPn = Naco Formation
Mr = Redwall Limestone
pCm = Mazatzal Quartzite

Private Land Boundary (Approx.)
PSWID Boundary (Approx.)
Geologic Contact (Approx.)
4400 Elevation Contour Top of Redwall
Surveyed Control Point
Most Favorable Area

Most Favorable Area

Geology modified from: Weir and Beard (1984)
Weisman and Weir (1990)

foregoing line is fairly high on the slope below the Mogollon Rim and practical considerations might dictate wells sited somewhat lower on the slope, south of the private property boundary.

6.4.1. Drilling Depth

Figure 6-11 shows contours of the depth from the land surface to the top of the Redwall Limestone. The depth contours on Figure 6-11 were obtained by subtracting the structural elevations on the top of the Redwall from topographic elevations in the form of a Digital Elevation Model (DEM) file obtained from the Arizona Regional Image Archive (ARIA). The original DEM data, obtained at a 30-meter grid spacing, was processed by first order Kriging to provide a 25-meter grid spacing of topographic elevations to match a 25-meter grid spacing of structural elevations on the top of the Redwall Limestone, all within the boundaries of Figure 6-11. The structural grid data were then subtracted from the topographic grid data to provide a third grid file containing depths to the top of the Redwall at 25-meter intervals. The depth values were then contoured to provide the depth map shown on Figure 6-11.

It must be recognized that the depths shown on Figure 6-11 are only to the estimated top of the Redwall Limestone. Use of Figure 6-11 to estimate the total depth required to drill a well into the Limestone Aquifer must include addition of the desired depth of penetration into the Limestone Aquifer to the depth to the top of the Redwall. For example, if it is assumed that the Redwall Limestone is 265 feet thick and a well is to fully penetrate the unit, then 265 feet must be added to the depth to the top of the Redwall to estimate the total drilling depth required at a given location.

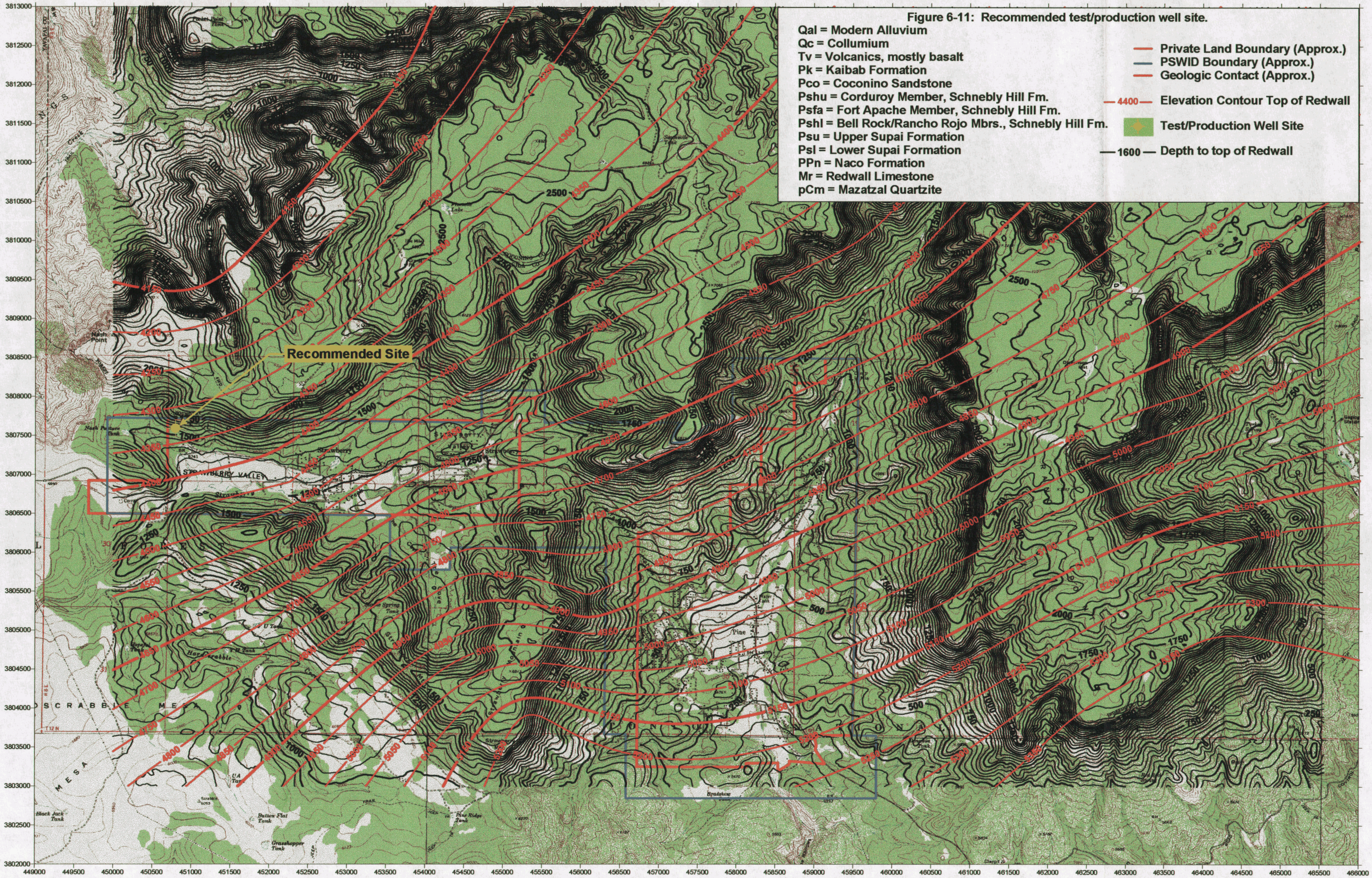
Assuming a potential thickness of 190 feet for the Redwall Limestone and 360 feet for the Martin Formation, 550 feet must be added to the depth to the top of the Redwall to estimate the drilling depth necessary to penetrate fully through the Limestone Aquifer strata in the PSWID area. Figure 6-11 shows the structural elevation contours on the top of the Redwall in addition to the depth contours. The area bounded by the 4350-foot elevation contour and the northwestern property boundary of the PSWID area exhibits depths to the top of the Redwall ranging from 1,420 feet in the southwest corner to 2,000 feet in the northeast corner where the 4350-foot contour crosses the property line. Accordingly, maximum potential drilling depths range from 1,970 to 2,550 feet. The top of the Redwall offers less than 50 feet of structural relief within the described area; accordingly, most of the range of drilling depth is due to topographic relief.

It is desirable to drill as far north as possible, in order to obtain the greatest saturated thickness in the Redwall. However, drilling depth increases rapidly to the north and the terrain becomes very steep, requiring extensive site preparation to establish a work platform for a drill rig and accessory equipment.

Figure 6-11: Recommended test/production well site.

Qal = Modern Alluvium
Qc = Collumium
Tv = Volcanics, mostly basalt
Pk = Kaibab Formation
Pco = Coconino Sandstone
Pshu = Corduroy Member, Schnebly Hill Fm.
Psfa = Fort Apache Member, Schnebly Hill Fm.
Pshl = Bell Rock/Rancho Rojo Mbrs., Schnebly Hill Fm.
Psu = Upper Supai Formation
Psl = Lower Supai Formation
PPn = Naco Formation
Mr = Redwall Limestone
pCm = Mazatzal Quartzite

Private Land Boundary (Approx.)
PSWID Boundary (Approx.)
Geologic Contact (Approx.)
4400 Elevation Contour Top of Redwall
Test/Production Well Site
1600 Depth to top of Redwall



Therefore, an initial test well site will probably be a compromise between drilling as far north as possible while staying on reasonable terrain. A good compromise appears to be at a land surface elevation of 5,870 feet and a depth to the top of the Redwall of 1,560 feet, shown on Figure 6-11 as the recommended site for a test well. The potential drilling depth at the site, including penetration of 550 feet of Redwall and Martin strata, is 2,110 feet.

The recommended site potentially offers 125 feet more of saturated thickness in the Redwall Limestone than did the Strawberry Borehole. The estimated elevation at the top of the Redwall at the recommended drilling site is 4,325 feet or about 40 feet below the groundwater elevation measured in the Strawberry Borehole, suggesting 40 feet of confined head in the Limestone Aquifer at this location. However, the possibility that the 255-feet thick Naco may contain solution openings in hydraulic communication with those in the Redwall makes it impossible to conclude whether or not the Redwall Limestone (and Limestone Aquifer strata) is confined at the recommended drilling location.

It is important to note that the structural elevation contour on the statistically projected Redwall surface at the recommended drilling site is elevation 4325 whereas subtraction of the depth contour of 1,560 feet from the published topographic map land surface elevation of 5,870 feet provides an estimated Redwall elevation of 4310 feet. The 15-foot difference between the structural contour elevation and the Redwall elevation estimated from the depth map appears to be the difference between statistical reproduction of the land surface elevation from the DEM data and the land surface elevation on the published U.S. Geological Survey 7.5-minute topographic map. Therefore, the potential vertical error from the statistical treatment of the DEM data is at least plus or minus 15 feet, relative to the published topographic map and relative to the precision survey.

6.4.2. Well Design Considerations

The static water level depth in the Redwall/Martin strata at the recommended test well drilling site is estimated to be 1,505 feet, based on the elevation of the static water level in the Strawberry Borehole. Assuming pumping of a well in this formation might result in as much as 200 feet of drawdown, the pumping lift is potentially 1,500 to 1,700 feet, depending on the amount of drawdown generated at a given pumping rate. Judicious selection of a pump column diameter to reduce pump column friction loss should keep pump column losses to less than 50 feet. For example, 4-inch pump column at 150 gpm would provide a friction loss of 34 feet and 5-inch pump column at 300 gpm would provide a friction loss of 41 feet. Smaller diameter pump column at the latter pumping rates would result in a significant increase in pump column friction loss with 1,700 feet of pump column. Based on the foregoing considerations, total pumping lift out of a

well at the recommended test well site, based on 150 to 300 gpm production, is potentially in the range of 1,550 to 1,750 feet Total Dynamic Head (TDH).

A range of 1,550 to 1,750 feet of TDH will require a minimum of 75 horsepower at 150 gpm. Accordingly, the smallest diameter submersible pump motor available for conventional water well pumping equipment that will provide 75 horsepower is an 8-inch motor. Thus, the smallest diameter well casing required for a test well or production well must accommodate an 8-inch submersible motor.

Due to the relatively low head above the Redwall Limestone, it may be necessary to set the pump inlet and motor below the production zone in the well. In this case, there will not be a flow of water past the pump motor, which hangs below the pump inlet, and the motor will not receive sufficient cooling. In order to provide sufficient cooling of the pump motor, it is necessary to direct the flow of water to the pump inlet past the pump motor with a pump shroud. An 8-inch pump motor will require a minimum diameter 10-inch pump shroud.

Taking these factors into consideration, the minimum diameter casing for a well completed into the Redwall/Martin strata, with the anticipation of producing at least 150 gpm, is a 12-inch nominal diameter casing to accommodate an 8-inch pump motor with a 10-inch pump shroud.

A 12-inch casing offers a great deal of flexibility in selecting a pumping system for a deep well into the Redwall/Martin strata. For example, 12-inch casing will allow installation of up to an 8-inch diameter pump and 8-inch motors up to 200 horsepower. Although conventional water well pump manufacturers do not make 8-inch pumps that will operate under more than about 1,200 feet of TDH, specialty oil-field and mine dewatering pump manufacturers such as Reda and Centriflow Pumps manufacture 8-inch pumps that will deliver more than 1,000 gpm at TDH in the range of 1,550 to 1,750 feet when equipped with adequate horsepower. Accordingly, installation of 12-inch casing in a test/production well will allow the full potential of the potentially cavernous, high-capacity Redwall strata to be developed by not imposing a limitation on the pumping equipment that can be installed.

An additional consideration is protection of the pump motor wire during installation of the pump. The pump motor wire is clamped to the pump column as the pump and motor are lowered into the well therefore is installed between the pump column and the inside of the well casing. The pump motor wire must pass between the pump housing and the inside of the well casing because submersible pump motors are attached to the bottom of submersible pumps. It is therefore necessary that the space between the pump housing and the inside of the well casing be sufficiently large for installation of the pump wire.

Since deep wells are seldom perfectly straight or plumb, it is almost certain the pump will rub against the inside of the well casing during installation. This creates the opportunity for the pump motor wire to be caught between the pump and casing where friction during deep-set installations may rub a hole through the insulation on the motor cable. This also may be a problem higher up on the pump column, if a section of the well casing offers too much deviation from a straight alignment, resulting in the pump column rubbing on a part of the well casing during pump installation.

Typical submersible pump cable is a flat cable with the conductor wires laid flat and encapsulated side-by-side in insulation and a protective jacket. This type of cable is adequate for most types of pump installation; however, it is vulnerable to damage by rubbing and friction on deep-set pumps. Where damage to the pump motor cable by rubbing is likely, it is necessary to use an armored cable. Armored cable is typically a round cable with the four conductor wires encapsulated in insulation and fillers which are in turn armored with aluminum or galvanized steel interlocked armor which is in turn covered with a PVC jacket.

Assuming availability of 460-volt, three-phase power, a 75-horsepower motor (for 150 gpm) hanging at about 1,700 feet will require 4/0 AWG copper wire. A pump capable of delivering 300 gpm with 1,750 feet of TDH will require a 175-horsepower motor (at 76 percent efficiency). A 175-horsepower motor hanging at about 1,700 feet will require 350 MCM copper wire. The dimensions of 4/0 AWG submersible pump flat cable are 2.82 inches wide by 0.80 inches thick. The dimensions of 350 MCM flat cable are 3.550 inches wide by 1.20 inches thick. The 4/0 AWG and 350 MCM flat cables are not armored. The diameter of 4/0 AWG armored round cable is approximately 1.93 inches and the diameter of 350 MCM armored round cable is approximately 2.380 inches. High horsepower applications for as much as 1000 gpm will require pump motor cables up to 750 MCM copper wire size which in a round, armored cable has an approximate diameter of 3.260 inches.

Considering the diameters of the various pump motor cables, it is evident that a 12-inch casing offers the opportunity to install armored cable past 7-inch and 8-inch diameter pumps for up to 175 horsepower or 350 MCM copper wire size without unduly pushing the pump off-center in the 12-inch casing. In other words, the annulus around an 8-inch pump in a 12-inch casing is a 2-inch annulus. Installation of an electrical motor cable larger than 2-inches in diameter will therefore push the pump to one side in the casing and result in constant rubbing of the wire against the casing as the pump is installed. Thus, 350 MCM armored cable for a 300 gpm pump and 175 horsepower motor slightly exceeds the 2-inch annulus for an 8-inch pump; however, a pump capable of 300 gpm can probably be obtained with a diameter of 7.0 to 7.5 inches.

Based on all the foregoing considerations, the minimum diameter required for a test/production well into the Redwall/Martin strata in the PSWID is 12-inches; two

nominal casing diameters larger than an 8-inch pump motor, as required to provide room for a pump shroud for motor cooling and to allow armored electrical cable to pass between the pump and the casing.

If the results of the test/production well indicate yields of more than 300 gpm are possible from the Redwall/Martin strata and it is desirable to produce larger yields, an appropriate well casing diameter must be selected for future wells to accommodate the necessary pumping equipment. However, preliminary indications are that a 12-inch casing will allow installation of pumping equipment capable of more than 300 gpm, with appropriate design of a fabricated flat conduit attached to the side of the pump, for passage of the larger electrical cable sizes past the pump by removal of the armor and side-by-side installation of the four conductor wires through the flat conduit along the side of the pump.

The requirement for a pump shroud can be satisfied by selection of specialty electrical motors, manufactured by Reda and Centriflow Pumps, that will fit inside the shroud. These motors can be less than 6-inches in diameter for more than 250 horsepower and therefore can be shrouded. Individual motors are accordingly quite large in length to provide the motor windings lost to reduced diameter. The additional length of such motors, sometimes over 100 feet in length, must be taken into consideration in designing the final well depth. A drawback to these types of motors is that the electrical power to such motors must exceed 480 volts to compensate for the longer wire windings in the long-bodied motors. In oilfield applications, the power company may supply 5,600-volt power to a well field using these types of motors. However, this would be an additional cost consideration at a PSWID well field using specialty motors.

Based on the foregoing considerations, installation of a 12-inch casing is not only necessary for smaller pumping equipment beginning at a minimum of 75 horsepower and 150 gpm, but it is adequate for installation of a wide range of larger pumping equipment, with proper design measures.

6.4.3. Structural Considerations

Figure 6-10 shows the structural contours on the top of the Redwall Limestone superimposed on the geologic map from Figure 4-2. Geologic information transferred from the Weir and Beard (1984) map includes two large faults extending into the northern side of Figure 6-10.

The west fault is aligned between Tin Can Draw and Sandrock Canyons, crosses the confluence of Fossil Creek and Calf Pen Canyon, and ends on Nash Point. The fault is referred to herein as the "Nash Point" fault (Figure 6-10). The Nash Point fault displaces Tertiary volcanics and older rocks with the block on the east side of the fault offset downward. The displacement of the admittedly poorly exposed fault on the north face of Fossil Creek canyon at Nash Point is about 160 feet.

The east fault extends from north of Sandrock Canyon, across that canyon, and generally north to south across the middle of a bench called "The Pocket" before crossing Calf Pen Canyon. The fault disappears into the south side of Calf Pen Canyon in an unnamed tributary draw slightly less than a mile northwest of Five Mile Lake. This fault is referred to herein as the Calf Pen Canyon Fault (Figure 6-10). The block on the west side of the Calf Pen Canyon fault is displaced downward an estimated 200 feet, as observed on the north wall of Calf Pen Canyon. The fault offsets the Coconino Sandstone at least 200 feet on The Pocket, resulting in a topographic change of 200 feet between the eastern and western benches. A photograph on Figure 6-12 shows the Calf Pen Canyon fault exposed in the north wall of Calf Pen Canyon.

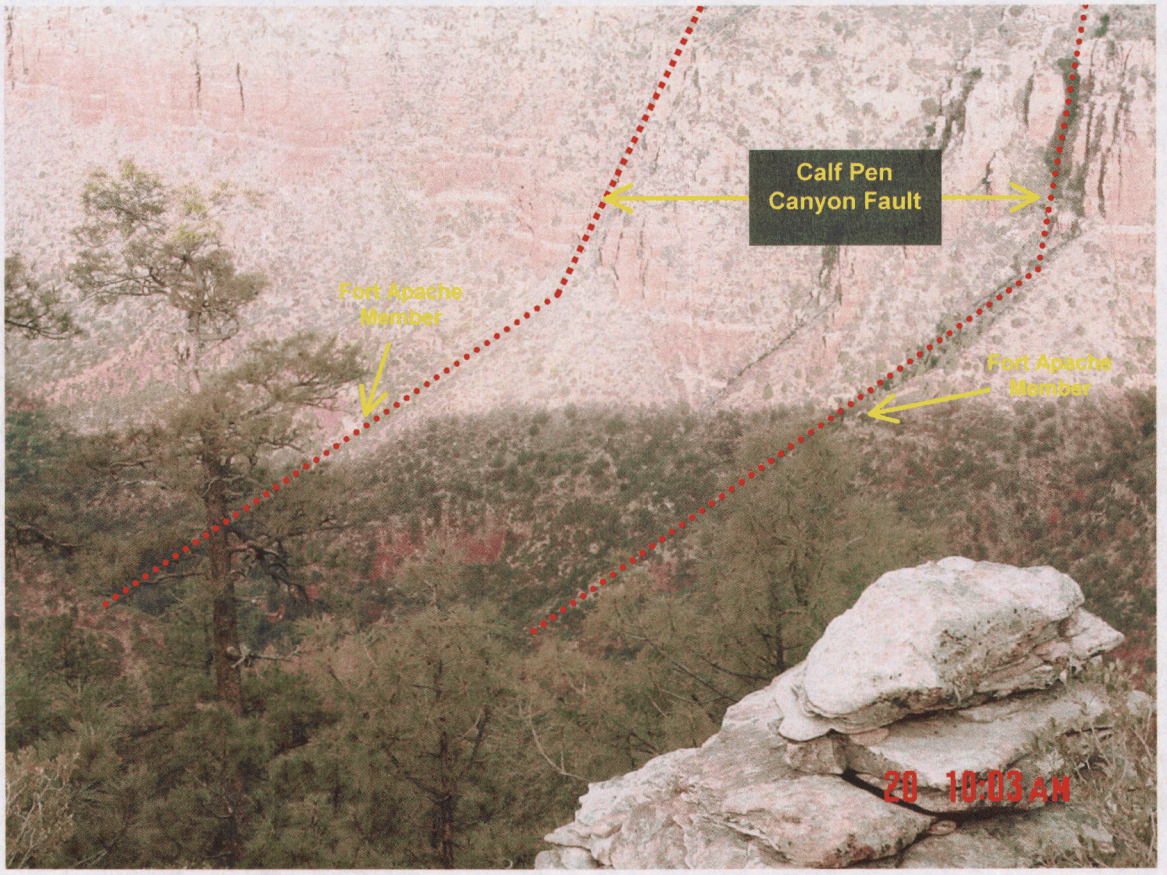


Figure 6-12: View of bifurcated Calf Pen Canyon fault on north face of canyon. Offset of Fort Apache Member shows fault displacement of 200 ft.

The Nash Point and Calf Pen Canyon faults bound the west and east sides of a down-faulted block. Geologists refer to an elongate down-faulted block, such as that bounded by the Nash Point and Calf Pen Canyon faults, as a "graben" and this particular graben is referred to herein as the Calf Pen Canyon graben.

The Calf Pen Canyon graben has a significant effect on interpretation of both the structural geology and how that geology affects movement and availability of groundwater in the PSWID and nearby area. The Calf Pen Canyon graben is structurally aligned with the anomalous low in the Redwall structure under Strawberry Mountain. The Calf Pen Canyon fault is in reasonable alignment with the sudden northwesterly bend in the structural contours along the east side of Strawberry Mountain (Figure 6-10). The alignment of the Calf Pen Canyon fault and the change in structural elevations does not coincide with the alignment of the fault shown on the Weisman and Weir (1990) map; however, as previously discussed, the surveyed structural control point south of the highway through Strawberry Hollow shows the Weisman and Weir (1990) alignment to be faulty.

In addition to the alignment of the Calf Pen Canyon fault with the east side of the structural low under Strawberry Mountain, the ridge of Coconino Sandstone between Calf Pen Canyon and Strawberry Canyon exhibits a 200-foot step in elevation, similar to that along the fault on The Pocket. The topographic step on the ridge between Calf Pen and Strawberry Canyons is not as obvious as the step on The Pocket because it is partly obscured by overlying basalt. An additional noteworthy terrain feature is the hill at the west end of Strawberry Valley in the southeast quarter of Section 19, T12N, R8E. Although this hill is capped with basalt, it is supported mostly by Schnebly Hill Formation and might be interpreted as another topographic expression of a "step" in the terrain with the hill on the west side of the Nash Point fault.

The foregoing considerations strongly suggest that the Strawberry Mountain structural low is a southern extension of the Calf Pen Canyon graben and might well be called the Strawberry graben. Recognition of the Strawberry area as part of a graben is consistent with the presence of the Schnebly Hill Formation in this area, on the down-dropped fault block, as compared to the absence of the Schnebly Hill Formation in Pine on the structurally higher area. It is also consistent with the fact that groundwater is present in the Redwall beneath Strawberry whereas the Redwall at Pine, outside the down-dropped fault block, is above the water table.

If this interpretation is correct, it is significant to how the surveyed structural control points must be used to construct the structural contour map. This is because three of the precision surveyed elevations on the structure, plus the Strawberry Borehole, are included in the hypothesized graben, and are therefore offset downward with respect to the surveyed control points on the structure east of the graben.

Figure 6-13 shows an alternate interpretation of the structural contours on the surface of the Redwall Limestone, using a fault offset of 160 feet for the Nash Point fault and 200 feet for the Calf Pen Canyon fault and projecting the faults

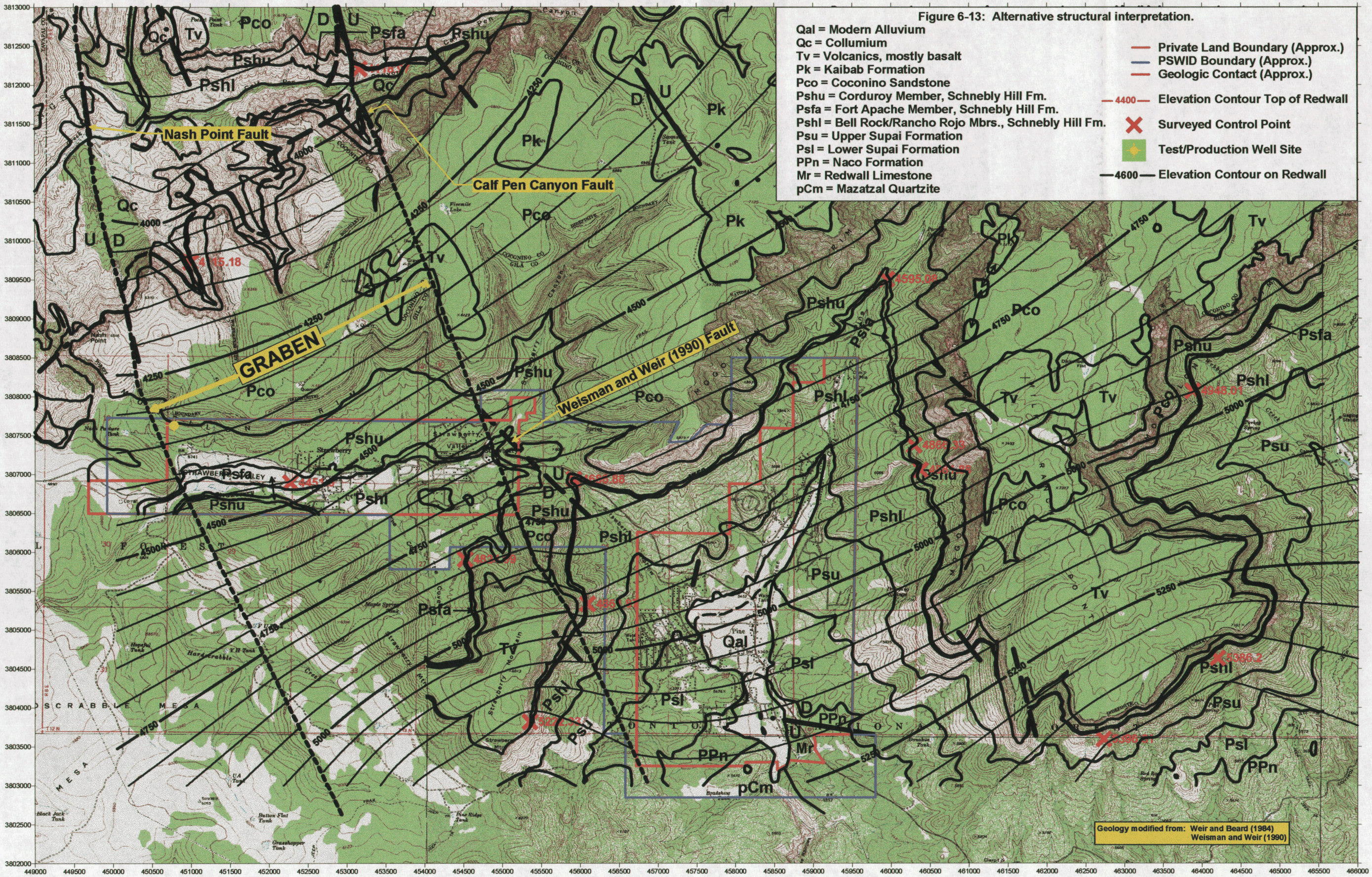


Figure 6-13: Alternative structural interpretation.

through the entire PSWID area. The structural contours within the graben are based on Kriging of the data points within the graben, independently of the other data points. The analysis shows little to no difference in the structural elevations across the Nash Point fault on the southwest side of the graben because there are no surveyed data points on the west side of the fault. Therefore, the statistically Kriged projection of the contours is the same whether the entire data set is analyzed or only the data in the graben are analyzed, because the only data in the Strawberry area are all in the graben.

6.4.4. Hydrogeologic Considerations

The structural contours in the hypothesized graben show the greatest offset from those outside the graben near surveyed data points. Where few surveyed data points are available, the statistical projections of contours inside and outside the graben become similar in elevation. This suggests the absence of large offsets near the north to south center of the graben, as shown on Figure 6-13, is the result of an absence of data rather than an absence of actual offset. In other words, the approximately 160 feet of offset on the Nash Point fault and the 200 feet of offset on the Calf Pen Canyon fault may persist along the entire graben, contrary to the lesser amounts of offset shown by statistical projection of structural elevations on Figure 6-13. This is suggested by the fact the offsets are relatively large where they can be observed and where surveyed data are available.

Considering the thickness of the Redwall Limestone is only 189 feet at the measured section south of Pine and is known to be less in some areas, depending on the nature of basement rock topography, potential fault offsets of 160 to 200 feet along the boundaries of the fault block comprising the graben raise the question of how the fault block and the faults affect the movement of groundwater through the Redwall/Martin strata, presumably towards Fossil Springs. Do the faults block groundwater flow or do they transmit groundwater? How much groundwater does the Martin Formation transmit? Does the Naco Formation transmit groundwater? These questions bear upon whether or not groundwater flows across the graben structure and whether or not groundwater penetrated in the graben by a well at the recommended drilling area in Strawberry is flowing to Fossil Springs.

Cross Section D-D' (Figure 6-9) shows the structure of the Redwall Limestone and associated units is higher in elevation at the East Verde River than at Pine and Strawberry or at Fossil Springs. The distance along the cross section from the East Verde River to Fossil Springs is about 18 miles. The other cross sections show the Redwall Limestone and associated strata dip north or northwest back under the Mogollon Rim from outcrops in the vicinity of the Control Road. The structural dip indicates recharge water entering the outcrops along Control Road, south of the Mogollon Rim, can potentially follow the dip of the strata back under the rim, and contribute to the flow through the Redwall and

associated strata towards Fossil Springs. Feth and Hem (1963) described the recharge as follows:

> "***During most of the year, the flow in Webber Canyon, Bray Creek, Chase Creek, and the East Verde River decreases to zero along a line roughly parallel to and about 3 miles south of the Mogollon Rim. This line is believed to coincide with a fault zone that brings the Redwall limestone to or near the surface. The cavernous nature of the Redwall has already been described . . .***" (Feth and Hem, 1963; p. H33)

We know now that the line parallel the Mogollon Rim where the various streams flowing off the rim lose water to the Redwall is the outcrop of the Redwall exposed on an erosion surface eroded back from the Little Diamond Rim fault as the Mogollon Rim retreated northward to its present location. Thus, the loss of water into the Redwall does not occur along a fault line, but simply where the limestone outcrops at the land surface. However, the recharge of water into the Redwall Limestone at these locations is significant, in view of the structural relationships indicating much of the flow should be back towards the north, under the Mogollon Rim, into the flow system to Fossil Springs, although some of the recharge discharges south through springs such as Indian Garden Spring on Tonto Creek near Kohls Ranch.

Accordingly, the likely presence of the structural graben hypothesized from this analysis raises questions about how recharge and groundwater flow in the Redwall Limestone and/or in the Limestone Aquifer strata collectively are affected by the graben. The extensive travertine deposits at Fossil Springs may provide an answer to these questions.

Figures 6-14 and 6-15 show the travertine deposits at Fossil Springs viewed from the road to the Irving Power Plant. The photographs show that the upper level of the travertine deposits is at an elevation much higher than the present outlet elevation for Fossil Springs. The U.S. Geological Survey 7.5-minute topographic map with 40-foot contour intervals indicates the elevation at the top of the travertine deposits is more than 4700 feet. This shows that in order for discharge from the spring to deposit travertine at this elevation, the groundwater level in the aquifer had to be at least at this elevation in the geologic past.

The estimated top of the travertine deposit is projected through the geologic cross sections on Figures 6-6 through 6-9 at an elevation of 4700 feet to show the minimum level of groundwater in the geologic past, necessary to support groundwater discharge to the top of the travertine deposits. Cross Section A-A' shows the ancestral groundwater level would have been well above the top of the Redwall Limestone and nearly to the top of the Naco Formation at the location of the Strawberry Borehole. Cross Section D-D' (Figure 6-9) shows the Redwall

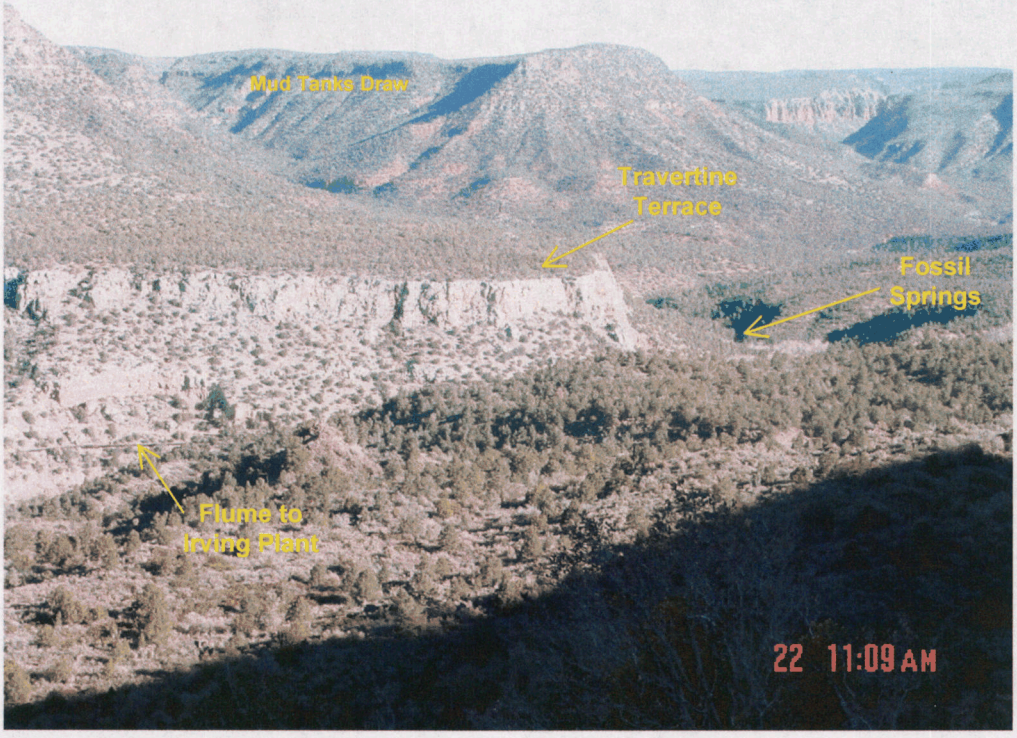


Figure 6-14: View of travertine terrace at Fossil Springs.

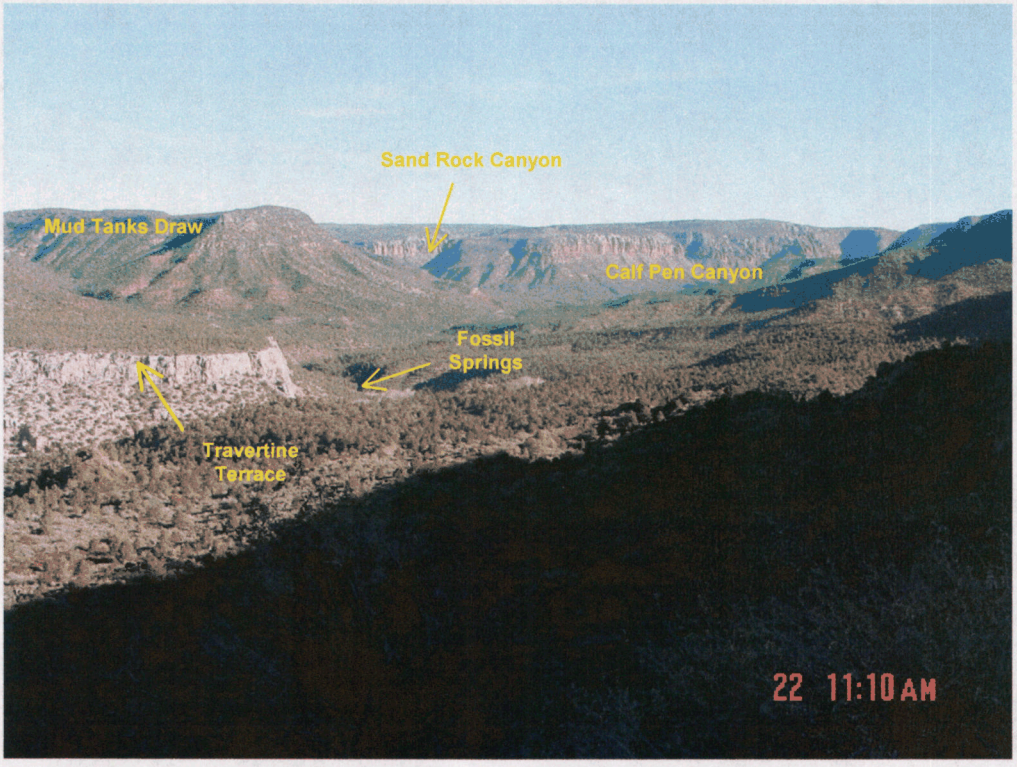


Figure 6-15: Fossil Springs with mouth of Calf Pen Canyon in background.

Limestone would have been fully saturated at the ancestral groundwater level as far east of Fossil Springs as the west side of Milk Ranch Point.

The travertine terrace deposits above the modern outlet to Fossil Springs therefore document the fact that the Redwall Limestone and/or the collective strata comprising the Limestone Aquifer system have been significantly drained over a period of geologic time, resulting in modern groundwater levels more than 335 feet lower in the PSWID than at some time in the geologic past. The volume of the travertine terrace deposits, including a large amount of travertine that has likely been removed by erosion, represents the volume of limestone dissolved from the Naco, Redwall, and Martin strata over geologic time and deposited as travertine downstream from the ancestral Fossil Springs. This process continues today, as evidenced by the deposits of calcium carbonate around the flume and penstock where the water from Fossil Springs is diverted to the Irving Power Plant.

The evidence of removal of limestone from the strata of the Limestone Aquifer by solution and transport in the groundwater system, combined with observations of solution caverns and solution enlarged fractures in the Redwall Limestone, is a strong argument that the voids penetrated in the Naco Formation by the Strawberry Borehole are solution-enlarged openings. If the Naco Formation contains solution conduits, it follows that it is in hydraulic communication with the Redwall Limestone and must be considered part of the Limestone Aquifer system. Including the Naco in the Limestone Aquifer system has the effect of greatly increasing the thickness of the aquifer system and reducing the possibility that fault offsets of 160 to 200 feet along the margins of the hypothesized graben could block the flow of groundwater through the system.

Taking all of the foregoing considerations into account, it is necessary to conclude that if the faults bounding the graben are blocking the flow of groundwater to Fossil Springs significantly, the groundwater level in the Redwall in the graben, as measured at the Strawberry Borehole, should be at some elevation considerably higher than the modern groundwater elevation, potentially up to 335 feet higher. The fact that the groundwater level measured in the Redwall in the graben is only slightly higher than the elevation of Fossil Springs and is essentially 335 feet lower than the ancestral groundwater level indicates the graben and its boundary faults do not block or restrict groundwater flow through the Limestone Aquifer across the graben. The modern groundwater level at the Strawberry Borehole indicates the groundwater level in the graben was drained by the same geologic processes that drained the Limestone Aquifer to its current groundwater level, well below the top of the travertine terrace, both in and out of the hypothesized graben.

All of these factors indicate the groundwater in the Redwall Limestone, penetrated by the Strawberry Borehole and underlying the recommended drilling sites along the northwestern boundary of the PSWID area, is hydraulically

connected to the same large body of groundwater storage necessary to support the long-term groundwater discharge rates observed at Fossil Springs. Therefore, a water well penetrating these strata at Strawberry, and operated within its long-term hydraulic capacity, should enjoy the benefit of a reliable source of groundwater by virtue of the available groundwater storage.

6.4.5. Source of Recharge

Planning of the investigation reported herein was based partly on the perception that the loss of water into the Redwall outcrop east of Milk Ranch point from Weber Creek, Bray Creek and the East Verde River was the principal source of recharge to the body of groundwater discharging through Fossil Springs. This perception was based in part on the fact that springs discharging from the Redwall Limestone east of the PSWID, along the Salt River, are highly mineralized with total dissolved solids concentrations ranging from 2,200 to more than 6,000 mg/l. The source of the mineral content is apparently dissolution of gypsum and anhydrite by recharge water percolating into the Redwall north of the Salt River through the Supai beds. The absence of strong mineral concentration in the water from Fossil Springs therefore argued that it had a different source of recharge than the Redwall springs to the east and, apparently, that the recharge could not have percolated through the overlying Supai beds as interformational leakage. Therefore, the loss of fresh water into the formation from surface flows east of Milk Ranch point seemed to be a good explanation for the absence of strong mineral concentrations in the Fossil Springs water.

The latter notion was abandoned in view of geologic Cross Sections A-A' through D-D' that show the PSWID area is on the very southernmost fringe of the saturated Redwall/Martin strata with the groundwater level under the PSWID area barely above the level of the outlet at Fossil Springs. These relationships suggest the groundwater storage required to support the long-term discharge rate at Fossil Springs is not explained by the volume above the springs on the four cross sections. Likewise, the cross sections suggest that, in the absence of adequate storage volume, the long-term discharge rate from Fossil Springs cannot be explained solely by leakage from the surface water streams east of Milk Ranch Point.

In view of the conclusion that recharge in the area east of Milk Ranch Point does not fully explain the volume and reliability of discharge from the Redwall Limestone at Fossil Springs, it was clear that the other possibilities all required infiltration of recharge water through the Supai beds for recharge to enter the Redwall. This meant that contrary to the experience with groundwater percolating through the Supai into the Redwall east of the PSWID, where highly mineralized water in the Redwall resulted, groundwater percolating through the Supai in the PSWID area and in the area north of Fossil Springs, must not become highly mineralized.

The latter realization is verified by the investigations of the Regional Aquifer (Bills et al., 2000) underlying the Colorado Plateau north of the PSWID area, including part of the area between Flagstaff and the PSWID. Water chemistry data collected from the Lake Mary group of wells, reported in Bills et al. (2000), show the major cation-anion chemistry of groundwater in the Regional Aquifer to be essentially the same as that in the Redwall Limestone in the PSWID as well as that in the wells completed in the Schnebly Hill and Supai strata in the PSWID area. The data from the Regional Aquifer north of the PSWID show the evaporite beds present in the Supai between Holbrook and the Salt River are not present in the Supai south of Flagstaff.

The conclusion drawn from comparison of the Regional Aquifer water chemistry to that of the water discharged through Fossil Springs is that one major source of groundwater storage supporting the flow at Fossil Springs is probably groundwater stored in the Regional Aquifer system that is draining into the Limestone Aquifer through interformational leakage and ultimately discharging through the Redwall Limestone at Fossil Springs.

The latter interpretation appears to be supported by the trends of the potentiometric surface in the Regional Aquifer as shown by Bills et al. (2000; Plate 2). The Regional Aquifer potentiometric surface exhibits a groundwater mound in the vicinity of the Mormon Mountain Anticline. Although the data are not extended south into area on the Mogollon Rim immediately north of the PSWID area, the implication of groundwater elevations as high as 6,800 feet at the Mormon Mountain Anticline is that groundwater flows south from the mound toward Fossil Creek and the PSWID. These relationships suggest a major source of groundwater storage supporting the discharge of water from Fossil Springs is the southerly flow of groundwater out of the Regional Aquifer.

The method used to compare the water chemistry of the Regional Aquifer to that of Fossil Springs and of the Schnebly Hill and Supai strata supporting wells in the PSWID is the Durov diagram (Figure 6-16). The Durov diagram provides a better display of hydrochemical types than the conventional Piper trilinear plot and is related to a greater extent to hydrochemical processes. The example Durov diagram on Figure 6-16 is expanded to separate the cation and anion triangles along the 25 percent axes so that the main field is divided accordingly. A field for a seventh parameter is added to the right side of the diagram. Figure 6-16 provides an explanation of the significance of the nine fields on the expanded Durov diagram; however, it must be recognized that other processes may also result in the cation-anion species defined in the nine Durov diagram fields.

Figure 6-17 shows water chemistry data for the Lake Mary group of wells in the Regional Aquifer (Bills et al., 2000; Table 2 and Figure 47) compared to water chemistry from the Strawberry Borehole, water chemistry from Fossil Springs at

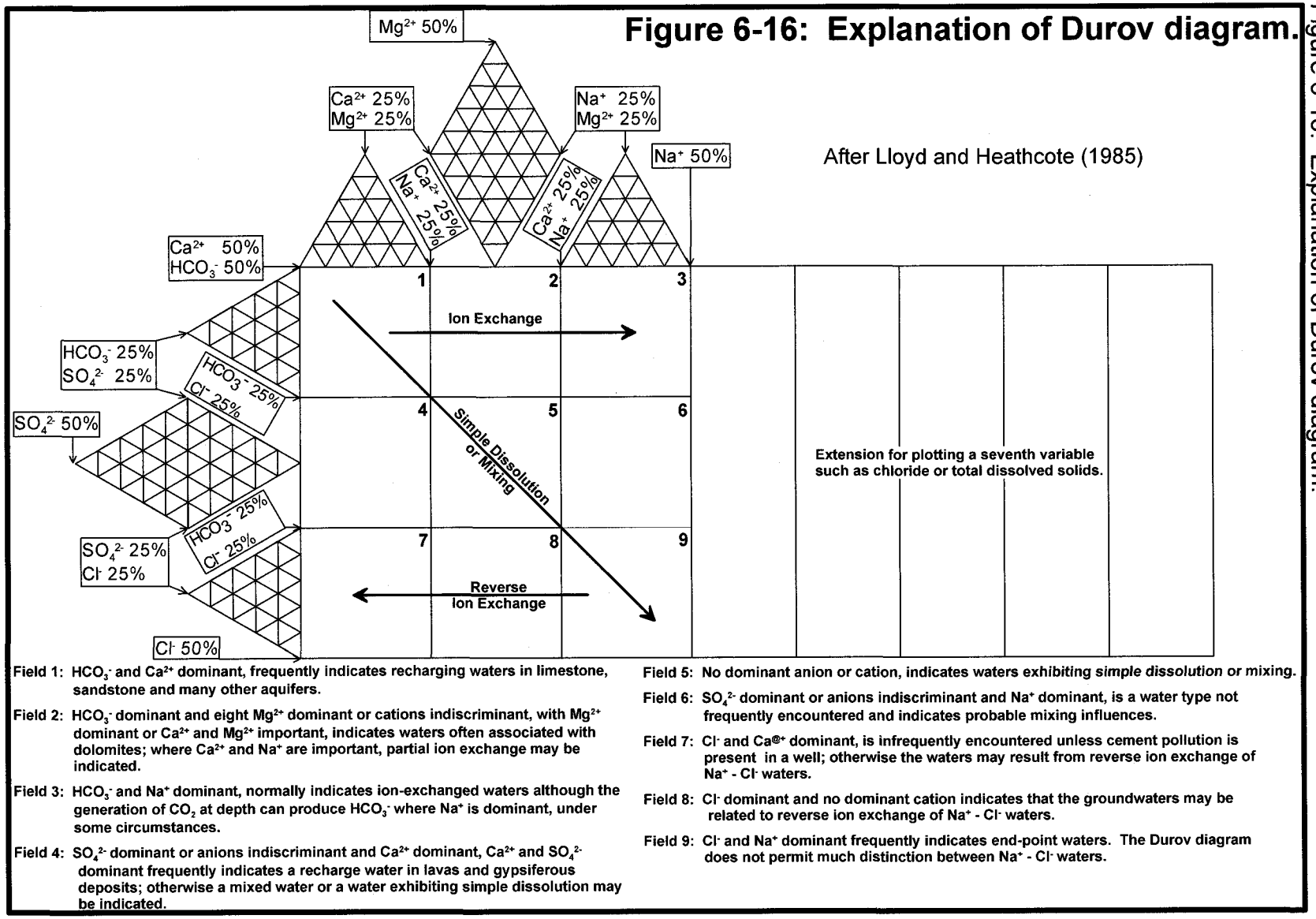


Figure 6-16: Explanation of Durov diagram.

Figure 6-17: Regional aquifer data, including other Redwall springs with TDS.

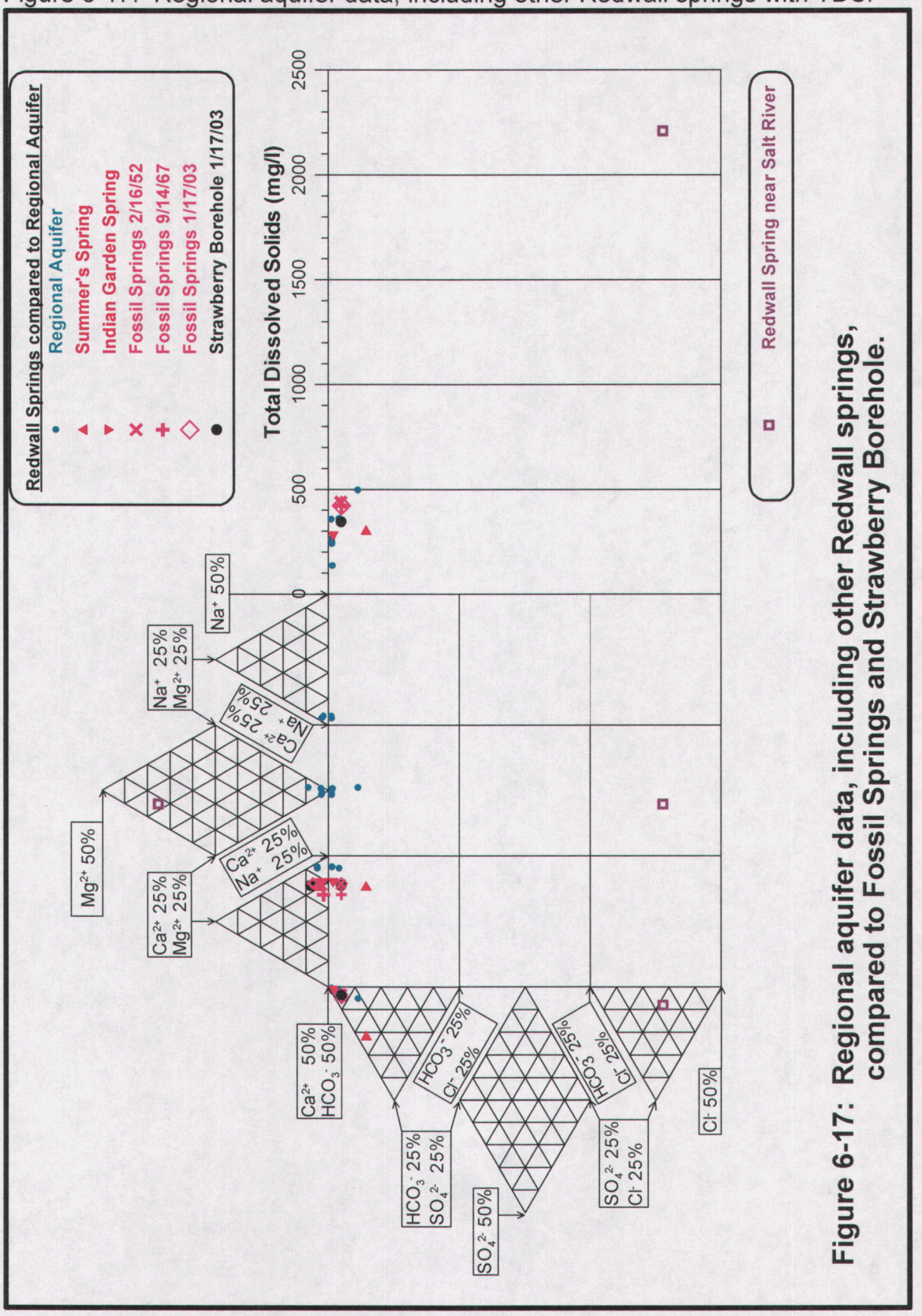


Figure 6-17: Regional aquifer data, including other Redwall springs, compared to Fossil Springs and Strawberry Borehole.

several different times, and water chemistry from two other Redwall springs along the Mogollon Rim north of the PSWID area. Summer's Spring is located in section 5, T17N, R3E in Sycamore Canyon tributary to the Verde River north of Cottonwood. Indian Gardens spring is located in section 20, T11N, R12E, near the Kohls Ranch on Tonto Creek. Also shown are data from one of the mineralized springs on the north side of the Salt River, far east of the PSWID area.

The data for water from Fossil Springs, the Strawberry Borehole, and the two fresh-water springs from the Redwall all plot in field 1 of the Durov plot indicating relatively unmineralized water. Data from the Lake Mary group of wells in the Regional Aquifer system plot across Durov fields 1, 2, and 3; suggesting potential cation exchange of sodium for calcium in the aquifer. However, it is not known to what extent dissolution of minerals within the volcanic deposits overlying the sedimentary rocks in the recharge area of the Regional Aquifer may contribute sodium to the water. Accordingly, the scatter of the regional aquifer data across fields 1 through 3 on the Durvo plot may reflect the influence of minerals in the volcanic rocks overlying the recharge area rather than cation exchange.

All of the Redwall Limestone waters plot in field 1. This initially appears contrary to the scatter of the data from the overlying Schnebly Hill and Supai groundwater of the Regional Aquifer across fields 1 through 3. However, recalling that the Durov plot is based on percentages, not absolute values, addition of calcium to the water by dissolution of the limestone when water from the Regional Aquifer enters the Limestone aquifer can shift the plot back into field 1 of the Durov diagram by increasing the relative proportion of calcium with respect to sodium. Therefore, there appears to be an explanation for field 2 and 3 water reverting back to field 1 water when it flows from the Regional Aquifer into the Limestone Aquifer.

Figure 6-18 shows the same data as Figure 6-17, but with chloride plotted as the seventh parameter instead of total dissolved solids. In the absence of contamination, increasing chloride concentrations in groundwater may be taken as an indication of increasing mineralization due to dissolution of chloride from the rocks through which the groundwater is moving. Generally, chloride concentrations increase with increasing distance from recharge areas and with increasing residence time of water in the aquifer. In shallow aquifers, evapotranspiration may also play a role in concentrating chloride, again with increasing chloride indicating increasing distance from the recharge area and increased residence time of groundwater in the aquifer.

On both Figure 6-17 and 6-18, all the samples shown exhibit low total dissolved solids and low chloride concentrations with the exception of the sample from a Redwall Spring near the Salt River. The spring near the Salt River plots in field 8

Figure 6-18: Regional aquifer data, including other Redwall springs with chloride.

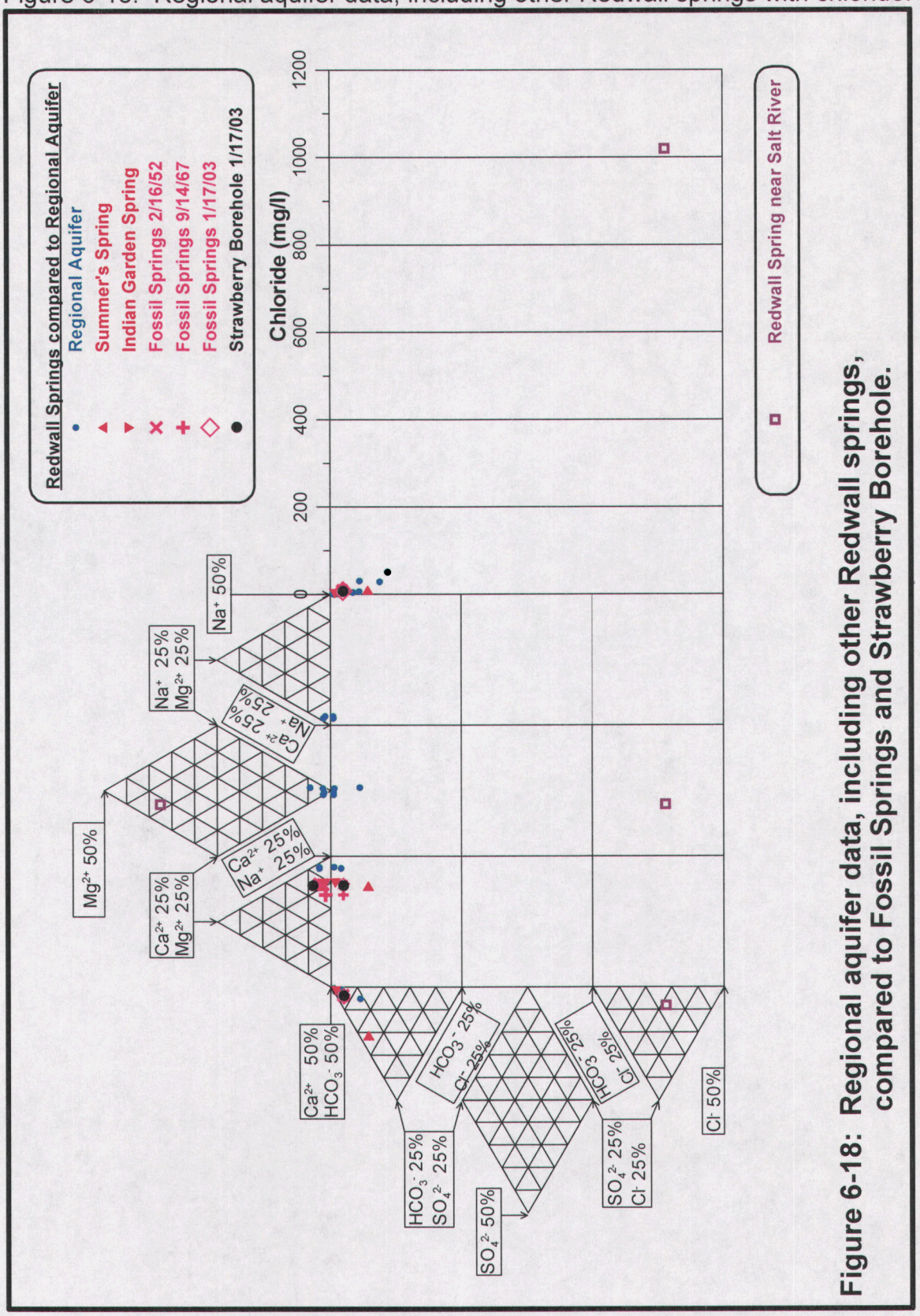


Figure 6-18: Regional aquifer data, including other Redwall springs, compared to Fossil Springs and Strawberry Borehole.

Figure 6-19: Local aquifer data compared to Strawberry Borehole with TDS.

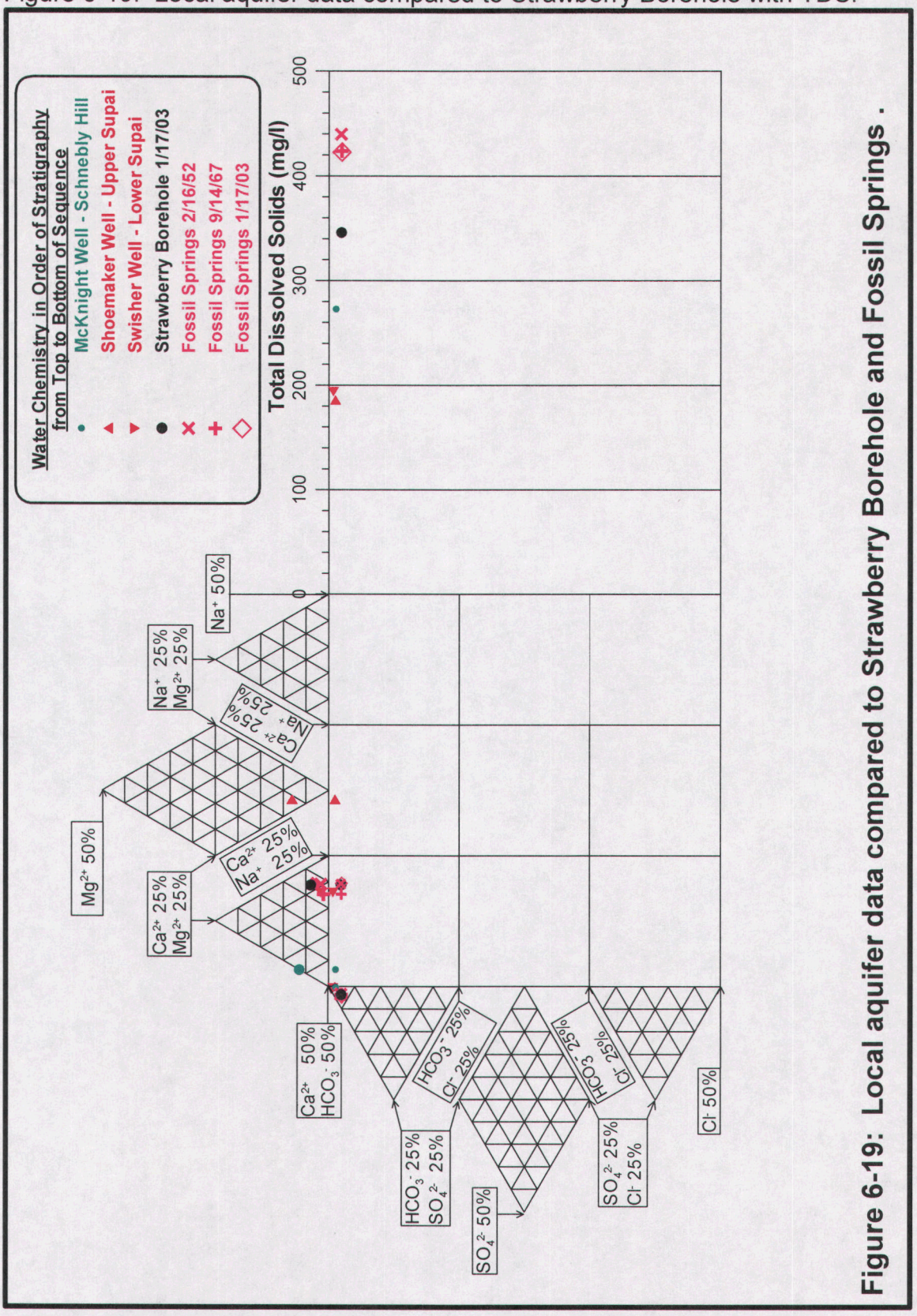


Figure 6-19: Local aquifer data compared to Strawberry Borehole and Fossil Springs .

Figure 6-20: Local aquifer data compared to Strawberry Borehole with chloride.

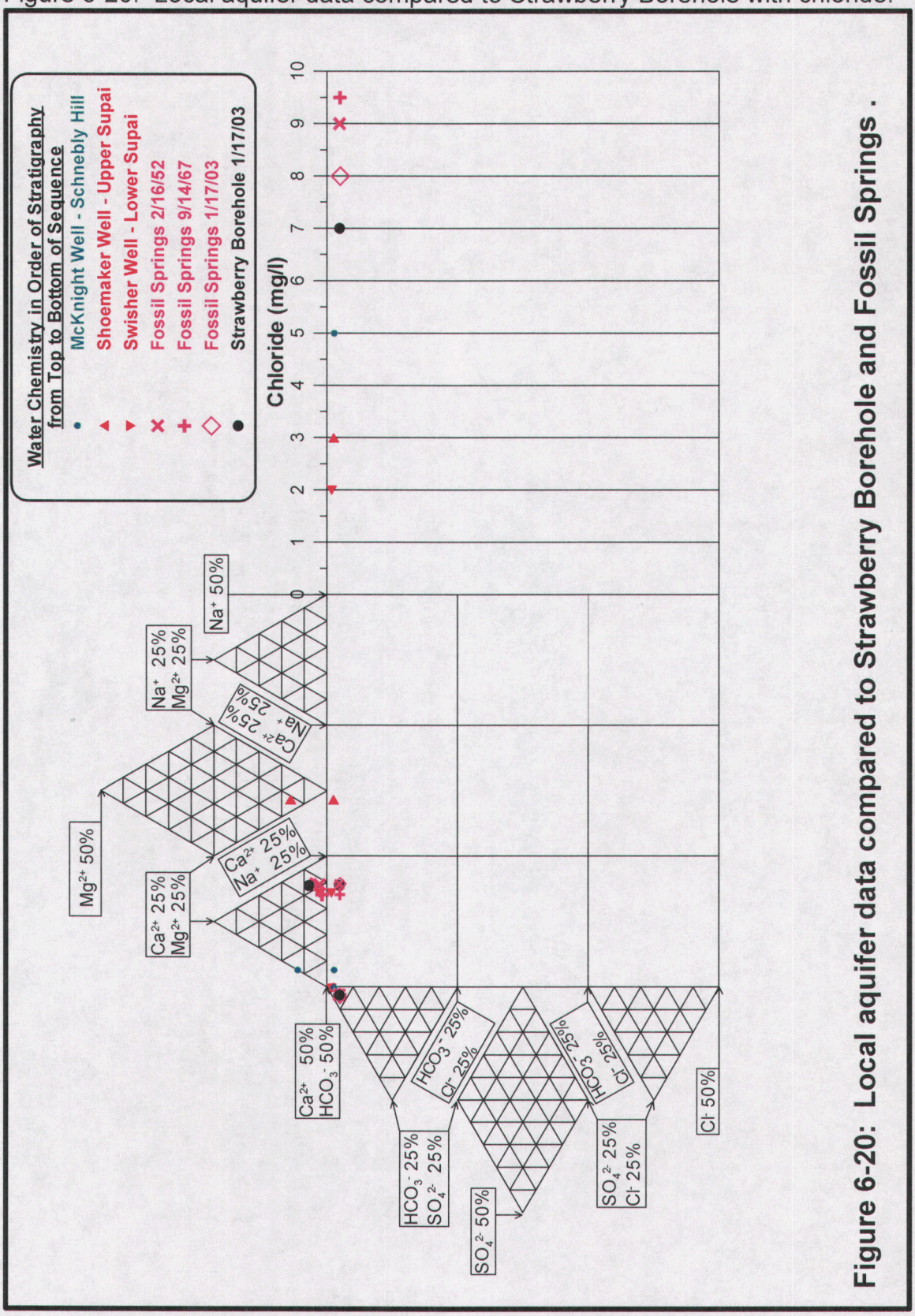


Figure 6-20: Local aquifer data compared to Strawberry Borehole and Fossil Springs .

of the Durov diagram and exhibits relatively high total dissolved solids and chloride concentrations. This water is not a result of reverse ion exchange as suggested by the Durov process concepts shown on Figure 6-16 for field 8, but is rather the result of dissolution of evaporates in the Supai Group north of the spring where the Supai is known to contain salt (halite), gypsum and anhydrite (calcium sulfate). Likewise, the dominance of chloride in the dissolved cations is the result of dissolution of evaporite minerals in the Supai.

Figures 6-19 and 6-20 show Durov plots for water samples taken from three wells in the Pine and Strawberry area and compare the chemistry of those samples to the chemistry of the samples from Fossil Springs and the Strawberry Borehole. The samples from the three wells are shown with respect to the order of the geologic formations they penetrate with the McKnight Well completed in the Schnebly Hill, the Shoemaker Well in the upper Supai, and the Swisher Well starting in the lower Supai with a reported depth exceeding the thickness of the unit, but the completion unknown. The laboratory analytical reports for the water samples from the local wells, Strawberry Borehole, and Fossil Springs are shown in Appendix B.

The wells all exhibit good water quality and plot in field 1 of the Durov diagram except the Shoemaker well that shows slightly more sodium percentage that the other wells. The Shoemaker well is at the bottom of a flow path through all of the strata from the top of the Mogollon Rim, starting with the Coconino and ending in the upper Supai. This might provide some opportunity for cation exchange or introduction of recharge water containing sodium; otherwise, the reason for the higher percentage of sodium is not clear. The total dissolved solids and chloride distributions; however, both exhibit similar patterns. The pattern is one of relatively low chloride and total dissolved solids in the wells completed in the Supai strata whereas the McKnight Well completed in the Schnebly Hill strata exhibits slightly higher chloride and total dissolved solids concentrations than the other two wells. Chloride and total dissolved solids are progressively greater in the Strawberry Borehole followed by Fossil Springs.

The likely cause of the difference between the chemistry of groundwater from the Schnebly Hill and Supai strata is residence time. As previously described, groundwater flows through the Supai strata in fracture zones with little or no groundwater storage in the rock hosting the fractures. This promotes local recharge, short residence time, and distribution of the recharge water across long distances related to the fracture geometry. By comparison, the Schnebly Hill strata contain groundwater in both the fractures and the materials surrounding the fractures, thus providing more opportunity for groundwater residence time and dissolution of minerals from the rock matrix. This probably explains the chemistry of the water in the McKnight well compared to the other two wells. If this interpretation is correct, based as it is on sparse data, comparison of the Schnebly Hill and Supai groundwater on the Durov plot indicates the Supai groundwater does not consist of interformational leakage from the Schnebly Hill,

as suggested conceptually elsewhere in this report, but consists of water recharged into the fractures from sources other than the Schnebly Hill, most likely local recharge from runoff infiltrating into the fractures.

The Durov plots show total dissolved solids and chloride concentrations are least at the Strawberry Borehole, as compared to three analyses of water from Fossil Springs. However, the total dissolved solids and chloride concentrations in the groundwater from the Strawberry Borehole (Redwall or Limestone Aquifer water) are greater than those in the local Schnebly Hill and Supai groundwater. These observations are consistent with the concept of increasing dissolution of minerals from the aquifer rocks with increasing groundwater flow path distance and residency time.

In summary, the dominant cation-anion species of the groundwater chemistry for the Regional Aquifer and Fossil Springs are the same. The major water chemistry parameters indicate interformational leakage from the Regional Aquifer into the Redwall/Martin strata north of Fossil Creek is potentially a major source of groundwater storage supporting the flow from Fossil Springs and therefore may be a major source of groundwater storage supporting the availability of groundwater in the Redwall/Martin strata underlying the northern edge of the PSWID area, depending on the as yet undefined local hydraulic gradients.

There is undoubtedly a need for considerable additional study of the hydrochemistry of the Regional Aquifer and of the Limestone Aquifer discharging water out of the Redwall Limestone at Fossil Springs. Moreover, there is the opportunity for application of tremendously more sophisticated isotopic analyses and other types of hydrochemical analyses than the Durov diagrams presented herein. Future investigations may provide considerable more insight as to how much the groundwater storage supporting the flow from Fossil Springs is supported by recharge on the Naco/Redwall/Martin outcrops south of the Mogollon Rim and east of Milk Ranch Point and how much the flow is supported by interformational leakage out of the Regional Aquifer to the north. However, recognition of the strong likelihood that the flow from Fossil Springs is supported in part by groundwater storage in the Regional Aquifer has significant implications regarding the reliability of the groundwater source in the Redwall/Martin strata, i.e., the Limestone Aquifer, in the PSWID. Interformational leakage out of the Regional Aquifer to the north would greatly increase the reliability of the Limestone Aquifer in the PSWID area and significantly reduce the potential for abstraction of groundwater from the Redwall/Martin strata in the PSWID to have a measurable effect on flow from Fossil Springs.

7. LOCAL OBSERVATIONS

A document titled, "***PS 2002 Perceptions of Water Supply in the Pine-Strawberry area***, prepared by PSWID Board Member John O. Breninger, July 1, 2002, revised August 10, 2002, and accepted by PSWID Board action of August

17, 2002, summarizes many of the local perceptions prevalent at the start of the investigation reported herein. The PSWID Board and their agent for this contract requested that a number of the local perceptions be addressed as the result of these investigations. Most of the local perceptions are addressed, directly or indirectly, by this report. However, three of the local perceptions deserve special comment. These perceptions include stories about the Sam Swisher well, speculation about the significance of Strawberry Hollow to local hydrology, and the observation that a part of Strawberry called "The Cove" is particularly productive of groundwater.

7.1. Sam Swisher Well

The local perception of the Sam Swisher domestic well is that it produces soft water whereas all the other wells in the area produce hard water. Therefore the Swisher well is regarded as a puzzling anomaly that probably represents some hydrogeologic factor of local significance, particularly because the well is reportedly 748 feet deep (Sam Swisher, personal communication, January 22, 2003). A search of the ADWR water well database identifies the well as 55-643372, completed March 8, 1971 at a recorded depth of 734 feet with a static water level of 651 feet and a yield of 13 gpm. No information is given about the depth of the steel casing or perforated intervals. The ADWR file provides UTM coordinates for the well consisting of an easting of 457,934.1 meters and a northing of 3,804,462.9 meters.

The ADWR coordinate location of the well indicates it starts in the lower Supai strata and is at an approximate elevation of 5360 feet, estimated from the 40-foot contours on the published 7.5 minute Pine Quadrangle. This indicates the well depth of 748 feet potentially penetrates entirely through the Redwall Limestone and into Martin strata. The projected depth of the top of the Redwall Limestone (Figure 6-11) at the ADWR coordinate location for the Swisher well is 300 feet. Assuming the Redwall is 180 to 190 feet thick, the base of the Redwall is at an approximate depth of 480-490 feet and the well potentially penetrates the full thickness of the Martin Formation.

The static water level of 651 feet reported at the time of well completion is well below the estimated bottom of the Redwall Limestone, indicating yield is from the Martin Formation or older strata, depending on the nature of the basement rock topography. The static water level elevation, estimated to be elevation 4709 feet, is 364 feet higher than the static water level elevation of 4364.9 feet in the Strawberry Borehole in January 2003, although some allowance must be made for error in estimating the wellhead elevation. This indicates the static water level is a function of the structural elevation at the lower boundary of the water-bearing zone and has nothing to do with a regional water table or potentiometric surface. In view of the latter fact, there did not appear to be any merit to collecting new information from the well to verify the reported values, as the information would

not extend the regional potentiometric surface in the Redwall/Martin strata as far as selecting a site for drilling of a deep test/production well is concerned.

Analysis of water samples collected from the McKnight well in Strawberry and the Swisher and Shoemaker wells in Pine provided hardness values of 248, 186 and 143 mg/l hardness as $CaCO_3$, respectively. Thus, with a hardness of 186 mg/l, the groundwater from the Swisher well falls within the range of hardness for other wells in the area and certainly is not soft water. The plot of the major cation-anion species in groundwater from the Swisher well, shown on Figures 6-19 and 6-20, indicate the chemistry of the water is essentially the same as that in other wells in Pine and Strawberry.

7.2. Strawberry Hollow

It is interesting that laymen residents reviewing the water situation in Pine and Strawberry, local well drillers, operators of some of the public water supply systems, and geologists mapping the Pine and Strawberry quadrangles all perceive Strawberry Hollow as having a special significance to either the availability of groundwater, the geologic structure, or both. However, the significance of Strawberry Hollow has remained elusive in the context of the local perceptions through August 10, 2002.

Jackson (1951) evidently mapped a high angle normal fault through Strawberry Hollow, as referred to by Weisman (1984). Weisman (1984) did not show a fault in Strawberry Hollow but mapped and described a small shear zone in the Fort Apache limestone on the south side of Strawberry Hollow that exhibits about 20 feet of offset. Weisman and Weir (1990) extend the shear zone of Weisman (1984) to the northwest, across the east end of Strawberry, but do not extend it into Strawberry Hollow. Accordingly, the fault zone referred to by Breninger (2002; p. 7) as the "Strawberry Hollow fault line", separating Strawberry Hollow and Strawberry Mountain from the Mogollon Rim, has been peripatetic, coming and going with each new investigation, sometimes with the same investigator, and never exhibiting more than 20 feet of observable offset.

Inspection of Strawberry Hollow during this investigation did not reveal observable evidence of a fault, other than the small shear zone described by Weisman (1984). A geologic structure control point surveyed on the east flank of Strawberry Mountain, west of Strawberry Hollow, indicates that a significant fault does not exist in direct alignment with the topographic expression of Strawberry Hollow and that the fault alignment shown by Weisman and Weir (1990) is unlikely. Based on these latter two observations, it appears likely that Jackson (1951) and Weisman and Weir (1990) put high angle fault alignments on their maps based more on interpretation of structural trends then on actual observation of a fault, however, they were correct in concluding that the structure undergoes a change in the vicinity of Strawberry Hollow.

As shown by this investigation, the structural elevation contours of the Strawberry Mountain mass abruptly bend just west of Strawberry Hollow (Figure 6-4), strongly suggesting an obscure fault boundary or series of small fault offsets must exist along the east side of Strawberry Mountain, somewhere between the eastern toe of the mountain and Strawberry Hollow, as a boundary to the hypothesized graben structure (Figure 6-13) extending southward from the Nash Point and Calf Pen Canyon faults mapped by Weisman and Weir (1990), and with a total offset of at least 50 to 100 feet. The projected graben alignment (Figure 6-13), based in part on surveyed structural elevations, indicates the shear zone described by Weisman (1984), is probably a small secondary feature parallel or sub-parallel to and east of a larger fault. An alternate interpretation is that the southern extension of the Calf Pen Canyon fault degenerates into a series of parallel or sub-parallel shear zones, each with 20 feet or less of offset, but which collectively lower the Strawberry Mountain mass by 50 to 100 feet relative to the geologic structure east of Strawberry Hollow. In this latter interpretation, the shear zone of Weisman (1984) is just one of a number of small shear zones which collectively provide the total offset of 50 to 100 feet in the structure.

Essentially all geologic investigators have recognized that the geologic structure changes in the vicinity of Strawberry Hollow or between Strawberry Hollow and the east flank of Strawberry Mountain; however, no one has been able to recognize the exact location of the fault or flexure where the change occurs. The most precise identification of the structure is on Figure 6-13 where it is evident the structure must be aligned between the three surveyed structural control points on Strawberry Mountain and is likely closest to the easternmost surveyed point. Based on the theory advanced from the results of this investigation, the structural change occurs just west of Strawberry Hollow and is a fault or local flexure that drops the structural elevation of the Strawberry Mountain mass 50 to 100 feet lower than the geologic structure immediately to the east, as part of a fault-related graben.

In the course of the fieldwork for this investigation, another factor was discovered that has no doubt complicated interpretation of the geologic structure in the vicinity of Strawberry Hollow. The geologic map in Weisman (1984) was very useful in guiding this investigation through the effort to survey structural control on the Fort Apache limestone. This is because the map in Weisman (1984) identifies locations where the Fort Apache limestone is exposed at the land surface in an outcrop that can be inspected. This was very useful to the survey effort because the Weisman (1984) map directed the work immediately to locations where the base of the unit could be examined and surveyed; therefore, it was not necessary to search all along the potential outcrop area for such locations.

However, the Weisman (1984) map indicates the top and bottom of the Fort Apache limestone are exposed in an outcrop in the northwest quarter of Section

25, T12N, R8E. Field inspection revealed the outcrop to be poorly exposed with the basal contact covered. When the basal contact was excavated, it had the same appearance as the basal contact of the Fort Apache limestone and it was surveyed. However, the elevation provided by the precision survey is tremendously out of place on the geologic structure indicated by the other outcrops and precision surveyed elevations, being about 200 feet lower in elevation than a reasonable elevation projected for the Fort Apache limestone at that location from the other surveyed points. It is concluded from this interpretation that the outcrop initially thought to be the Fort Apache limestone is in fact one of the other carbonate units in the Bell Rock Member of the Schnebly Hill that is easily mistaken for the Fort Apache limestone. When the latter fact is recognized, the geologic structure along Strawberry Hollow makes a lot more sense.

If the outcrop mapped by Weisman (1984) and Weisman and Weir (1990) is in fact correctly identified as the Fort Apache limestone by those efforts, it is low with respect to the surrounding trends, including Strawberry Mountain, and opposite to the direction of displacement of the Strawberry Hollow fault mapped by Weisman and Weir (1990). These considerations suggest the outcrop was simply misidentified by all concerned; a fact that did not emerge until Kriging was used to project the structural surface based on the other surveyed elevations on the base of the Fort Apache outcrops.

The terrain along the west side of Pine Canyon includes a number of knobs, evidently supported by resistant limestone corresponding to the unit mapped by Weisman (1984) and Weisman and Weir (1990) as Fort Apache Limestone. Weisman (1984) projected the Fort Apache limestone along the west side of Pine Canyon, from the outcrop where it is crossed by Pine Creek, into the limestone unit supporting the knobs on the terrain. Weisman and Weir (1990) show this same projection, which includes a covered interval of about half to three-fourths of a mile from the crossing at Pine Creek.

The knobs on the terrain and their poorly exposed limestone outcrops are seductive and it is very logical to conclude they represent the extension of the Fort Apache limestone to the west side of Pine Canyon. However, this interpretation does not fit the projection of the rest of the geologic structure across the area and the difference of 200 feet between the structural projection and these outcrops suggests the wrong limestone ledge was identified as Fort Apache limestone by Weisman (1984) and by Weisman and Weir (1990) on the west side of Pine Creek. Certainly, without the surveyed structural control points, this investigation would have likely mapped the Fort Apache limestone in exactly the same way as done by Weisman (1984) and Weisman and Weir (1990).

However, the outcrop of Fort Apache Limestone can be traced northeasterly out of Strawberry Hollow and across the pipeline road where it disappears under colluvial debris. At the point where the outcrop becomes buried along the

pipeline road in Strawberry hollow, it is well above the elevation of the outcrop mapped by Weisman (1984) and Weisman and Weir (1990) as Fort Apache Limestone along the west side of Pine Creek canyon. Unfortunately, the thick cover of debris along the west side of the canyon makes it impossible to trace the outcrop back to where Pine Creek crosses the unit; however, the elevation differences leave little doubt that the limestone ledge mapped as Fort Apache Limestone along the west side of the canyon by the previous investigators is not Fort Apache Limestone, but instead a unit in the Schnebly Hill or, possibly, in the uppermost part of the upper Supai.

The west side of Pine Canyon should be re-examined very carefully to look for evidence of covered Fort Apache limestone outcrop at a higher elevation than mapped by Weisman (1984) and Weisman and Weir (1990) and to carefully identify the base of the Coconino Sandstone as a potential horizon from which the average thickness of the Corduroy Member of the Schnebly Hill can be projected downward to estimate the approximate elevation at which the Fort Apache should be present. Verification that the Fort Apache limestone is at the higher elevation shown by the structural projection on Figures 4-2 and 6-10 would confirm the structural interpretations set forth herein. If further field investigation shows that the projection of the Fort Apache limestone along the west side of Pine Canyon as shown by Weisman (1984) and Weisman and Weir (1990) is correct, a new interpretation of the structural geology in the vicinity of Strawberry Hollow will be necessary and would require that the east side of the structure be offset downward with respect to Strawberry Hollow, an interpretation that is inconsistent with any of the other information about the area.

7.3. The Cove

The topographic valley tributary to the south side of the Strawberry Valley is referred to as "The Cove" and is perceived by local residents to be an area of greater groundwater flow and availability than other parts of Strawberry. In describing the local perception, Breninger (2002) states:

> "***Groundwater seems to flow most reliably from the southeast wall of the valley out of a formation designated "The Cove," as evident by the performance of the well field and growth pattern of Ponderosa Pines in that area. The western valley floor well and ranch fields exhibit less moisture from groundwater, except for a band of Ponderosa Pines along the entire southern wall of the valley."*** (Breninger, 2002; p. 7)

Not stated in the above citation is the local perception that wells drilled in Strawberry Valley near the mouth of the Cove are better producers and more reliable than those drilled to the west in Strawberry Valley.

The investigations performed for this report suggest that there are, in fact, geologic reasons for the above stated perceptions. The first geologic factor is that the Strawberry Valley is underlain by the Bell Rock Member of the Schnebly Hill formation that offers somewhat greater well yields and certainly more reliable yields to wells than the Supai strata in the nearby community of Pine. The presence of the Schnebly Hill strata is therefore the most obvious factor in the performance of wells near the mouth of the Cove.

However, a different explanation is required for the observation that well yields become progressively smaller and less reliable away from the mouth of the Cove and towards the west along the axis of the Strawberry Valley. The explanation for this local observation may have roots in the observation by Twenter (1962) that more than 2,000 feet of volcanics, mostly basalt flows, are deposited against the ancestral Mogollon Rim in Fossil Creek and at the west end of the Strawberry Valley. It is very possible that the groundwater contained in the Schnebly Hill formation in the west half of the Strawberry Valley drains towards the ancestral Mogollon Rim at the west end of the valley, and out through the basalt layers which are highly jointed and receptive to infiltration of water. If this is the case, the Schnebly Hill strata in west end of the Strawberry Valley are simply dewatered by gravity drainage into the volcanic rocks at the west end of the valley and an east to west gradient probably exists in the potentiometric surface with static water levels in wells becoming progressively deeper toward the west end of the valley.

Another geologic relationship may be the source of the moisture for the band of Ponderosa pines along the southern edge of the Strawberry Valley west of the mouth of the Cove. The south wall of the Strawberry Valley west of the Cove cuts through the Fort Apache limestone immediately above the band of Ponderosa pines, as shown on Figures 4-2 and 6-10. Although the truncated end of the limestone layer is not well exposed along the valley wall, it is present in the subsurface. The Strawberry Valley wall cuts through the limestone layer at the down-gradient end of the sheet of limestone underlying the Strawberry Mountain mass and dipping northward into the Strawberry Valley. Accordingly, the Fort Apache limestone layer in Strawberry Mountain is in a position to collect groundwater seeping down through the mountain from all of the overlying materials, including basalt flows that cap the mountain and provide a receptive surface for infiltration of recharge water.

Since the Fort Apache limestone is probably the most permeable layer in the mountain and it dips down gradient into the south wall of the Strawberry Valley, it is in a perfect position to intercept all of the recharge into that part of Strawberry Mountain and drain it out into the subsurface of the valley wall right along the band of Ponderosa pine on the south edge of the valley, west of the Cove. Therefore, the most likely explanation for the wetter conditions observed along that part of the southern wall of Strawberry Valley is probably drainage of groundwater out of the truncated end of the Fort Apache Limestone.

7.4. Strawberry Valley

A final local observation is not based on any local perception, but is based on a local desire to understand the reason why the Strawberry Valley exists. This question is addressed at the end of section 5.6.1 of this report and is addressed again here.

Strawberry Mountain is a remnant of the surface that existed north of the ancestral Mogollon Rim at some point in the geologic past. That surface sloped from north to south, draining off of the ancestral rim. At some point in time, a portion of the south-sloping surface was covered by a deposit of basalt in the form of a lava flow or multiple flows. Remnants of the basalt cap the modern Strawberry Mountain.

The most likely reason for the present location of Strawberry Valley, in this author's opinion, is that water formerly flowing down the south-sloping surface above the ancestral Mogollon Rim was blocked by the basalt deposits, causing water to flow along the northern edge of the basalt, draining west towards the ancestral Mogollon Rim above Fossil Creek. Eventually, the diverted water cut the Strawberry Valley along the north side of the basalt flow.

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APPENDIX A

Summary of coordinates for surveyed structural control points

Summary of control points on basal contact of Fort Apache Limestone.
Arizona East 201
NAD83
International Feet

Point No.	Easting	Northing	Elevation	Description
50	317035.3297	1249868.0154	5876.97	Base of Fort Apache
51	318387.3327	1241822.6208	6163.67	Base of Fort Apache
52	318130.6616	1242861.6784	6148.13	Base of Fort Apache
54	303766.7047	1241554.2330	5970.63	Base of Fort Apache
55	304299.6372	1236283.6692	6143.58	Base of Fort Apache
56	301823.3450	1231337.9050	6504.05	Base of Fort Apache
57	326023.9813	1230404.9466	6678.06	Base of Fort Apache
58	330873.6769	1233781.1588	6667.99	Base of Fort Apache
59	329902.6934	1245052.1694	6229.96	Base of Fort Apache
61	291797.9923	1241513.7565	5749.65	Strawberry Borehole
65	299149.4037	1238213.3244	6106.74	Base of Fort Apache
67	287679.2392	1250852.1701	5396.89	Base of Fort Apache
68	294889.8587	1258925.69	5400.800	Base of Fort Apache

PINE CONTROL POINTS ARIZONA EAST-201-NAD83 INTERNATIONAL FEET

GRID:

CP#1 N-1241399.2421
E-312087.5492
EL-5842.78
REBAR SET AT TOP OF HILLTOP DR. The point overlooks pine from the north.

CP#2 N-1233827.2376
E-311130.3004
EL-5371.61
REBAR SET @ HARDSCRABBLE RD (downtown pine)

CP#4 N-1241367.3458
E-281444.7441
EL-5852.82
FOUND FOREST SERVICE BOUNDARY BC 57A. At north end of strawberry from sr87 turn west on fossil creek rd, continue 3 miles, BC on s. side of rd.

CP#5 N-1250201.7053
E-311274.9318
EL-7088.10

REBAR SET ON RIM. South from seven-mile tank trail, to end of jeep trail. Point in clearing.

CP#6 N-1251716.6798
E-296170.4331
EL-6744.60
REBAR SET. Rebar set +/- 50' west of SR87, +/- 50' east of barbed wire fence with gate. Small rd to 5 mile tank on the east side of SR87.

CP#7 N-1262201.1483
E-308634.3334
EL-6862.97
REBAR SET @ CALFPEN CANYON. From SR87 north of strawberry to jct. Sr260(zane gray hwy) north to east/west dirt road(twentynine mile lake rd). Head west +/- 2 miles, take left at fork in road and continue to small clearing just past pond. Point is west of trail 20' west of fallen tree.

CP#20 N-1224835.2658
E-323282.5591
EL-5578.52
REBAR SET NORTH OF CONTROL RD. +/-1500 ft of sr87

CP#21 N-1221224.9147
E-320279.8327
EL-5635.38
SPIKE SET SOUTH OF CONTROL ROAD. The point is +\-40 feet east of sr87 just past end of the northbound safety lane.

CP#30 N-1240508.3104
E-337054.5374
EL-5483.47
SET SPIKE IN FIELD @ CAMP GERONIMO. Point is in the north field E. of the basketball court.

CP#31 N-1226144.4980
E-332423.1693
EL-5401.21
X @ CATTLE GUARD ON CONTROL RD. Point is on a cattle guard east on control rd. +/- 3 miles.

POINTS ON GEOLOGIC STRUCTURE:

CP#50	N-1249868.0154 E-317035.3297 EL-5876.97	Base of Fort Apache Limestone
CP#51	N-1241822.6208 E-318387.3327 EL-6163.67	Base of Fort Apache Limestone
CP#52	N-1242861.6784 E-318130.6616 EL-6148.13	Base of Fort Apache Limestone
CP#53	N-1240377.8867 E-308717.1297 EL-5909.89	Stray limestone unit mistakenly identified as Fort Apache Limestone – point not used.
CP#54	N-1241554.2330 E-303766.7047 EL-5970.63	Base of Fort Apache Limestone
CP#55	N-1236283.6692 E-304299.6372 EL-6143.58	Base of Fort Apache Limestone
CP#56	N-1231337.9050 E-301823.3450 EL-6504.05	Base of Fort Apache Limestone
CP#57	N-1230404.9466 E-326023.9813 EL-6678.06	Base of Fort Apache Limestone
CP#58	N-1233781.1588 E-330873.6769 EL-6667.99	Base of Fort Apache Limestone
CP#59	N-1245052.1694 E-329902.6934 EL-6229.96	Base of Fort Apache Limestone
CP#60	N-1235992.6628 E-307417.4837 EL-5503.38	Top of casing, Strawberry Hollow Well

CP#61 N-1241513.7565 Top of casing without cap, Strawberry Borehole
E-291797.9923
EL-5749.65

CP#65 N-1238213.3244 Base of Fort Apache Limestone
E-299149.4037
EL-6106.74

CP#67 N-1250852.1701 Base of Fort Apache Limestone
E-287679.2392
EL-5396.89

CP#68 N-1258925.69 Base of Fort Apache Limestone
E-294889.8587
EL-5400.80

BENCH MARKS AT PINE/STRAWBERRY

#1 The bench mark is a brass cap flush in rock. C-496.
Located .7miles southeast along sr87 from the post office in pine. .05miles southeast of milepost 267, in top of a rock outcropping at southeast end of turn area. 46 feet west of highway centerline.
N-1230927.7308
E-313071.3146
EL-5389.63

#2 The bench mark is a brass cap flush in concrete. L-29.
Located 105 feet west of sr87@ intersection of hardscrabble rd. The point is south of hardscrabble rd in the yard of the house on the corner, 9 feet north of centerline of old cabin.
N-1233755.6585
E-311297.4150
EL-5364.20

#3 The bench mark is a point on top of wellhead. Rick's Lane.
Located from sr87 and hardscrabble rd. West .85miles on hardscrabble rd, left on dirt road with house address 6732, point is S.E.of E. end of home.
N-1232429.4450
E-307665.0164
EL-5539.63

#4 The bench mark is a brass cap flush in rock outcrop. Y-494.
Located .3 miles north on sr87 from the post office in pine on east side of the highway. East of Texaco station, 50 feet north of Art gallery sign.
N-1236044.6902
E-311320.6915
EL-5437.72

#5 The bench mark is a small pin on a concrete post.
To get to point travel north on sr87 from pine to top of pass. The point is north side of road at the west end of the passing lane at top of pass. The point is just south of fence line.
N-1241907.4692
E-302841.2497
EL-6024.67

#6 The bench mark is a brass cap flush. P-29.
Located 3 miles northwest along sr87 from the post office in pine. 2.5 miles west along fossil creek rd, in a group of pine trees at the top of a low cut, .05 miles west of end of pavement, 48 feet north of road centerline, 177 feet east of a cattle guard.
N-1242494.3404
E-287394.9368
EL-5744.01

#7 The bench mark is a brass cap flush in rock outcrop. D-495.
Located 3 miles northwest along sr87 from the post office in pine. The point is just north of fossil creek road and 24 feet west of sr87 centerline.
N-1242605.3473
E-299887.6923
EL-5898.57

#8 The bench mark is a forest service brass cap and section line.
USFS brass cap west 1/16 corner of section 27.
N-1238897.6705
E-298593.2639
EL-5945.08

APPENDIX B

Analytical reports for water samples

ENERGY LABORATORIES, INC. • P.O. Box 30916 • 1120 South 27th Street • Billings, MT 59107-0916
800-735-4489 • 406-252-6325 • 406-252-6069 fax • eli@energylab.com

LABORATORY ANALYTICAL REPORT

Client: Morrison Maierle
Project: Pine/Strawberry WID
Lab ID: B03010996-001
Client Sample ID: Strawberry Borehole

Report Date: 01/31/03
Collection Date: 01/17/03
Date Received: 01/23/03
Matrix: Aqueous

Analyses	Result	Units	Qual	RL	MCL/ QCL	Method	Analysis Date / By
PHYSICAL PROPERTIES							
pH	7.2	s.u.		0.1		E150.1	01/23/03 14:13 / jb
Conductivity	568	umhos/cm		1		A2510 B	01/23/03 14:09 / jb
Langelier Index	0.2					A203	01/29/03 12:29 / lab
Solids, Total Dissolved TDS @ 180 C	346	mg/L		10		A2540 C	01/24/03 11:17 / qed
INORGANICS							
Alkalinity, Total as CaCO3	313	mg/L		2		A2320 B	01/27/03 15:44 / car
Bicarbonate as HCO3	382	mg/L	D	3		A2320 B	01/27/03 15:44 / car
Carbonate as CO3	ND	mg/L		1		A2320 B	01/27/03 15:44 / car
Chloride	7	mg/L		1		E300.0	01/24/03 18:00 / car
Sulfate	12	mg/L		1		E300.0	01/24/03 18:00 / car
Fluoride	0.17	mg/L		0.10		A4500-F C	01/30/03 16:30 / ddb
Hardness as CaCO3	307	mg/L		1		A2340 B	01/27/03 09:54 / rlh
NUTRIENTS							
Nitrogen, Nitrate+Nitrite as N	0.21	mg/L		0.05		E353.2	01/27/03 12:32 / bls
METALS, DISSOLVED							
Calcium	76	mg/L		1		E200.7	01/24/03 21:44 / rlh
Iron	ND	mg/L		0.03		E200.7	01/24/03 21:44 / rlh
Magnesium	28	mg/L		1		E200.7	01/24/03 21:44 / rlh
Manganese	0.10	mg/L		0.01		E200.7	01/24/03 21:44 / rlh
Potassium	2	mg/L		1		E200.7	01/24/03 21:44 / rlh
Sodium	11	mg/L		1		E200.7	01/24/03 21:44 / rlh
METALS, TOTAL							
Antimony	ND	mg/L		0.003	0.006	E200.8	01/28/03 16:15 / jjw
Arsenic	ND	mg/L		0.005	0.01	E200.8	01/28/03 16:15 / jjw
Barium	0.2	mg/L		0.1	2	E200.7	01/25/03 01:06 / rlh
Beryllium	ND	mg/L		0.001	0.004	E200.7	01/25/03 01:06 / rlh
Cadmium	ND	mg/L		0.001	0.005	E200.8	01/28/03 16:15 / jjw
Chromium	ND	mg/L		0.01	0.1	E200.8	01/29/03 18:32 / jjw
Mercury	ND	mg/L		0.0002	0.002	E200.8	01/28/03 16:15 / jjw
Nickel	ND	mg/L		0.01	0.1	E200.7	01/25/03 01:06 / rlh
Selenium	ND	mg/L		0.005	0.05	E200.8	01/28/03 16:15 / jjw
Thallium	ND	mg/L		0.001	0.002	E200.8	01/28/03 16:15 / jjw

Report Definitions:
RL - Analyte reporting limit.
QCL - Quality control limit.
D - RL increased due to sample matrix interference.
MCL - Maximum contaminant level.
ND - Not detected at the reporting limit.

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LABORATORY ANALYTICAL REPORT

Client: Morrison Maierle
Project: Pine/Strawberry WID
Lab ID: B03010996-005
Client Sample ID: Fossil Creek Springs

Report Date: 01/31/03
Collection Date: 01/22/03 09:00
Date Received: 01/23/03
Matrix: Aqueous

Analyses	Result	Units	Qual	RL	MCL/ QCL	Method	Analysis Date / By
PHYSICAL PROPERTIES							
pH	6.8	s.u.		0.1		E150.1	01/23/03 14:18 / jb
Conductivity	710	umhos/cm		1		A2510 B	01/23/03 14:10 / jb
Langelier Index	0.0					A203	01/29/03 12:30 / lab
Solids, Total Dissolved TDS @ 180 C	423	mg/L		10		A2540 C	01/24/03 17:09 / qed
INORGANICS							
Alkalinity, Total as CaCO3	399	mg/L		2		A2320 B	01/27/03 16:16 / car
Bicarbonate as HCO3	486	mg/L	D	3		A2320 B	01/27/03 16:16 / car
Carbonate as CO3	ND	mg/L		1		A2320 B	01/27/03 16:16 / car
Chloride	8	mg/L		1		E300.0	01/24/03 19:42 / car
Sulfate	19	mg/L		1		E300.0	01/24/03 19:42 / car
Fluoride	0.17	mg/L		0.10		A4500-F C	01/30/03 16:30 / ddb
Hardness as CaCO3	382	mg/L		1		A2340 B	01/27/03 09:54 / rlh
NUTRIENTS							
Nitrogen, Nitrate+Nitrite as N	0.14	mg/L		0.05		E353.2	01/27/03 12:37 / bls
METALS, DISSOLVED							
Calcium	94	mg/L		1		E200.7	01/24/03 22:08 / rlh
Iron	ND	mg/L		0.03		E200.7	01/24/03 22:08 / rlh
Magnesium	36	mg/L		1		E200.7	01/24/03 22:08 / rlh
Manganese	ND	mg/L		0.01		E200.7	01/24/03 22:08 / rlh
Potassium	2	mg/L		1		E200.7	01/24/03 22:08 / rlh
Sodium	12	mg/L		1		E200.7	01/24/03 22:08 / rlh
METALS, TOTAL							
Antimony	ND	mg/L		0.003	0.006	E200.8	01/28/03 16:53 / jjw
Arsenic	0.005	mg/L		0.005	0.01	E200.8	01/28/03 16:53 / jjw
Barium	0.2	mg/L		0.1	2	E200.7	01/25/03 01:42 / rlh
Beryllium	ND	mg/L		0.001	0.004	E200.7	01/25/03 01:42 / rlh
Cadmium	ND	mg/L		0.001	0.005	E200.7	01/25/03 01:42 / rlh
Chromium	ND	mg/L		0.01	0.1	E200.8	01/29/03 19:27 / jjw
Mercury	ND	mg/L		0.0002	0.002	E200.8	01/28/03 16:53 / jjw
Nickel	ND	mg/L		0.01	0.1	E200.7	01/25/03 01:42 / rlh
Selenium	ND	mg/L		0.005	0.05	E200.8	01/28/03 16:53 / jjw
Thallium	ND	mg/L		0.001	0.002	E200.8	01/28/03 16:53 / jjw

Report Definitions:
RL - Analyte reporting limit.
QCL - Quality control limit.
D - RL increased due to sample matrix interference.
MCL - Maximum contaminant level.
ND - Not detected at the reporting limit.

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LABORATORY ANALYTICAL REPORT

Client: Morrison Maierle
Project: Pine/Strawberry WID
Lab ID: B03010996-004
Client Sample ID: McKnight Well

Report Date: 01/31/03
Collection Date: 01/22/03 10:30
Date Received: 01/23/03
Matrix: Aqueous

Analyses	Result	Units	Qual	RL	MCL/ QCL	Method	Analysis Date / By
PHYSICAL PROPERTIES							
pH	7.4	s.u.		0.1		E150.1	01/23/03 14:16 / jb
Conductivity	465	umhos/cm		1		A2510 B	01/23/03 14:10 / jb
Langelier Index	0.2					A203	01/29/03 12:30 / lab
Solids, Total Dissolved TDS @ 180 C	273	mg/L		10		A2540 C	01/24/03 11:23 / qed
INORGANICS							
Alkalinity, Total as CaCO3	268	mg/L		2		A2320 B	01/27/03 16:08 / car
Bicarbonate as HCO3	327	mg/L	D	3		A2320 B	01/27/03 16:08 / car
Carbonate as CO3	ND	mg/L		1		A2320 B	01/27/03 16:08 / car
Chloride	5	mg/L		1		E300.0	01/24/03 19:29 / car
Sulfate	1	mg/L		1		E300.0	01/24/03 19:29 / car
Fluoride	0.16	mg/L		0.10		A4500-F C	01/30/03 16:30 / ddb
Hardness as CaCO3	248	mg/L		1		A2340 B	01/27/03 09:54 / rlh
NUTRIENTS							
Nitrogen, Nitrate+Nitrite as N	0.32	mg/L		0.05		E353.2	01/27/03 12:36 / bls
METALS, DISSOLVED							
Calcium	59	mg/L		1		E200.7	01/24/03 22:04 / rlh
Iron	ND	mg/L		0.03		E200.7	01/24/03 22:04 / rlh
Magnesium	24	mg/L		1		E200.7	01/24/03 22:04 / rlh
Manganese	ND	mg/L		0.01		E200.7	01/24/03 22:04 / rlh
Potassium	ND	mg/L		1		E200.7	01/24/03 22:04 / rlh
Sodium	10	mg/L		1		E200.7	01/24/03 22:04 / rlh
METALS, TOTAL							
Antimony	ND	mg/L		0.003	0.006	E200.8	01/28/03 16:47 / jjw
Arsenic	ND	mg/L		0.005	0.01	E200.8	01/28/03 16:47 / jjw
Barium	0.2	mg/L		0.1	2	E200.7	01/25/03 01:38 / rlh
Beryllium	ND	mg/L		0.001	0.004	E200.7	01/25/03 01:38 / rlh
Cadmium	ND	mg/L		0.001	0.005	E200.7	01/25/03 01:38 / rlh
Chromium	ND	mg/L		0.01	0.1	E200.8	01/29/03 19:21 / jjw
Mercury	ND	mg/L		0.0002	0.002	E200.8	01/28/03 16:47 / jjw
Nickel	ND	mg/L		0.01	0.1	E200.7	01/25/03 01:38 / rlh
Selenium	ND	mg/L		0.005	0.05	E200.8	01/28/03 16:47 / jjw
Thallium	ND	mg/L		0.001	0.002	E200.8	01/28/03 16:47 / jjw

Report Definitions:
RL - Analyte reporting limit.
QCL - Quality control limit.
D - RL increased due to sample matrix interference.
MCL - Maximum contaminant level.
ND - Not detected at the reporting limit.

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LABORATORY ANALYTICAL REPORT

Client: Morrison Maierle
Project: Pine/Strawberry WID
Lab ID: B03010996-003
Client Sample ID: Sam Swisher Well

Report Date: 01/31/03
Collection Date: 01/22/03 12:30
Date Received: 01/23/03
Matrix: Aqueous

Analyses	Result	Units	Qual	RL	MCL/ QCL	Method	Analysis Date / By
PHYSICAL PROPERTIES							
pH	7.6	s.u.		0.1		E150.1	01/23/03 14:16 / jb
Conductivity	336	umhos/cm		1		A2510 B	01/23/03 14:09 / jb
Langelier Index	0.2					A203	01/29/03 12:29 / lab
Solids, Total Dissolved TDS @ 180 C	194	mg/L		10		A2540 C	01/24/03 11:22 / qed
INORGANICS							
Alkalinity, Total as CaCO3	199	mg/L		2		A2320 B	01/27/03 16:01 / car
Bicarbonate as HCO3	242	mg/L	D	3		A2320 B	01/27/03 16:01 / car
Carbonate as CO3	ND	mg/L		1		A2320 B	01/27/03 16:01 / car
Chloride	2	mg/L		1		E300.0	01/24/03 19:16 / car
Sulfate	1	mg/L		1		E300.0	01/24/03 19:16 / car
Fluoride	0.11	mg/L		0.10		A4500-F C	01/30/03 16:30 / ddb
Hardness as CaCO3	186	mg/L		1		A2340 B	01/27/03 09:54 / rlh
NUTRIENTS							
Nitrogen, Nitrate+Nitrite as N	0.31	mg/L		0.05		E353.2	01/27/03 12:35 / bls
METALS, DISSOLVED							
Calcium	48	mg/L		1		E200.7	01/24/03 21:52 / rlh
Iron	ND	mg/L		0.03		E200.7	01/24/03 21:52 / rlh
Magnesium	16	mg/L		1		E200.7	01/24/03 21:52 / rlh
Manganese	ND	mg/L		0.01		E200.7	01/24/03 21:52 / rlh
Potassium	ND	mg/L		1		E200.7	01/24/03 21:52 / rlh
Sodium	3	mg/L		1		E200.7	01/24/03 21:52 / rlh
METALS, TOTAL							
Antimony	ND	mg/L		0.003	0.006	E200.8	01/28/03 16:42 / jjw
Arsenic	ND	mg/L		0.005	0.01	E200.8	01/28/03 16:42 / jjw
Barium	ND	mg/L		0.1	2	E200.7	01/25/03 01:34 / rlh
Beryllium	ND	mg/L		0.001	0.004	E200.7	01/25/03 01:34 / rlh
Cadmium	ND	mg/L		0.001	0.005	E200.7	01/25/03 01:34 / rlh
Chromium	ND	mg/L		0.01	0.1	E200.8	01/29/03 19:16 / jjw
Mercury	ND	mg/L		0.0002	0.002	E200.8	01/28/03 16:42 / jjw
Nickel	ND	mg/L		0.01	0.1	E200.7	01/25/03 01:34 / rlh
Selenium	ND	mg/L		0.005	0.05	E200.8	01/28/03 16:42 / jjw
Thallium	ND	mg/L		0.001	0.002	E200.8	01/28/03 16:42 / jjw

Report Definitions:
RL - Analyte reporting limit.
QCL - Quality control limit.
D - RL increased due to sample matrix interference.
MCL - Maximum contaminant level.
ND - Not detected at the reporting limit.

ENERGY LABORATORIES, INC. • P.O. Box 30916 • 1120 South 27th Street • Billings, MT 59107-0916
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LABORATORY ANALYTICAL REPORT

Client: Morrison Maierle
Project: Pine/Strawberry WID
Lab ID: B03010996-002
Client Sample ID: Shoemaker Well

Report Date: 01/31/03
Collection Date: 01/22/03 12:00
Date Received: 01/23/03
Matrix: Aqueous

Analyses	Result	Units	Qual	RL	MCL/ QCL	Method	Analysis Date / By
PHYSICAL PROPERTIES							
pH	7.4	s.u.		0.1		E150.1	01/23/03 14:14 / jb
Conductivity	294	umhos/cm		1		A2510 B	01/23/03 14:09 / jb
Langelier Index	-0.3					A203	01/29/03 12:29 / lab
Solids, Total Dissolved TDS @ 180 C	186	mg/L		10		A2540 C	01/24/03 11:20 / qed
INORGANICS							
Alkalinity, Total as CaCO3	166	mg/L		2		A2320 B	01/27/03 15:53 / car
Bicarbonate as HCO3	203	mg/L	D	3		A2320 B	01/27/03 15:53 / car
Carbonate as CO3	ND	mg/L		1		A2320 B	01/27/03 15:53 / car
Chloride	3	mg/L		1		E300.0	01/24/03 18:13 / car
Sulfate	ND	mg/L		1		E300.0	01/24/03 18:13 / car
Fluoride	0.12	mg/L		0.10		A4500-F C	01/30/03 16:30 / ddb
Hardness as CaCO3	143	mg/L		1		A2340 B	01/27/03 09:54 / rlh
NUTRIENTS							
Nitrogen, Nitrate+Nitrite as N	0.05	mg/L		0.05		E353.2	01/27/03 12:35 / bls
METALS, DISSOLVED							
Calcium	31	mg/L		1		E200.7	01/24/03 21:48 / rlh
Iron	ND	mg/L		0.03		E200.7	01/24/03 21:48 / rlh
Magnesium	16	mg/L		1		E200.7	01/24/03 21:48 / rlh
Manganese	ND	mg/L		0.01		E200.7	01/24/03 21:48 / rlh
Potassium	1	mg/L		1		E200.7	01/24/03 21:48 / rlh
Sodium	12	mg/L		1		E200.7	01/24/03 21:48 / rlh
METALS, TOTAL							
Antimony	ND	mg/L		0.003	0.006	E200.8	01/28/03 16:20 / jjw
Arsenic	ND	mg/L		0.005	0.01	E200.8	01/28/03 16:20 / jjw
Barium	0.2	mg/L		0.1	2	E200.7	01/25/03 01:26 / rlh
Beryllium	ND	mg/L		0.001	0.004	E200.7	01/25/03 01:26 / rlh
Cadmium	ND	mg/L		0.001	0.005	E200.7	01/25/03 01:26 / rlh
Chromium	ND	mg/L		0.01	0.1	E200.8	01/29/03 19:11 / jjw
Mercury	ND	mg/L		0.0002	0.002	E200.8	01/28/03 16:20 / jjw
Nickel	ND	mg/L		0.01	0.1	E200.7	01/25/03 01:26 / rlh
Selenium	ND	mg/L		0.005	0.05	E200.8	01/28/03 16:20 / jjw
Thallium	ND	mg/L		0.001	0.002	E200.8	01/28/03 16:20 / jjw

Report Definitions:
RL - Analyte reporting limit.
QCL - Quality control limit.
D - RL increased due to sample matrix interference.
MCL - Maximum contaminant level.
ND - Not detected at the reporting limit.

APPENDIX C

Summary of estimated costs to drill and pump test well

DRILLING COST CONSIDERATIONS

The cost to drill the test/production well will depend on the level of difficulty experienced during drilling. The biggest problem will be loss of circulation into voids and fractures, i.e., loss of the drilling fluid and loss of ability to sample the formation and determine what part of the stratigraphic sequence is penetrated at a specific depth. These problems were experienced during drilling of the Strawberry Borehole and prevented installation of casing to the total depth of the hole, resulting in the hole presently plugged and caved at about 1,420 feet, at the end of the casing. The caved material has blocked off the open borehole from 1,420 to 1,872 feet.

The problems posed by the type of severe lost circulation problems experienced with drilling deep boreholes in this area can be addressed in two ways – well design and selection of appropriate drilling methods. The opinion of potential drilling costs provided herein is based on the assumption that the well drilling specifications will require the contractor to provide the type of drilling equipment and drilling technology required to appropriately deal with the anticipated problems. The specifications will require the contractor to provide equipment that can use dual wall drill pipe capable of flooded reverse circulation, conventional mud rotary, or reverse circulation air drilling (inverse drilling) in borehole with a minimum diameter of 17-1/2 inches.

Likewise, the opinion of potential drilling costs assumes the well will be designed and constructed in a way that maximum flexibility is provided to deal with problems. Specifically, the well will be designed with a large enough surface casing that the hole can be reamed to a larger diameter several times, as needed, to install intermediate casings to seal off lost circulation zones and stabilize caving areas.

In the above approach, a wide range of drilling costs may result, depending on how many times it is necessary to ream the hole and telescope in a new size of casing. Accordingly, the opinion of potential costs to drill a well under these conditions is structured for three levels of difficulty, ranging from straight forward installation of one casing size to the top of the Redwall Limestone to a worst case with four different diameters of casing in the well, including the surface casing.

All three levels of difficultly assume installation of a 34-inch diameter surface casing to a depth of 50 feet, cemented into a 38-inch borehole. A 34-inch diameter surface casing is necessary to preserve the possibility of reaming the hole to a larger diameter later in the drilling, if it becomes necessary to do so.

In the best-case scenario, 12-inch diameter casing and well screen are set in a 17-1/2 inch hole from surface to the estimated total depth of 2,110 feet. With a mobilization cost of $140,000 and a cost to drill and case the well of $407,230, the total cost to drill the well is estimated to be about $547,230.

In the intermediate cost scenario, 20-inch diameter casing is installed into 24-inch borehole to the top of the Redwall Limestone at an estimated depth of 1,560 feet. A 12-inch casing and screen is telescoped through the 20-inch casing into 17-1/2 inch borehole from 1,560 to 2,110 feet. The mobilization cost of $140,000 and the drilling and casing cost of $563,370 total $703,370 to drill the well with this design.

In the worst-case scenario, it is necessary to install 26-inch casing into 31-inch borehole from the surface to 50 feet followed by 20-inch diameter casing in 24-inch borehole from 350 to 1,560 feet and 12-inch casing and screen in 17-1/2 inch borehole from 1,560 to 2,110 feet. The mobilization cost of $140,000 and the drilling and casing cost of $670,980 total $810,980 to drill the well with this design.

It is estimated that test pumping equipment capable of delivering up to 300 gpm will cost about $38,000 with the total pumping lift associated with an estimated static water level of 1,505 feet and 1,900 feet of pump column. It is estimated that development of the well with a combination of air-lift pumping and direct pumping followed by pumping tests of the well will cost about $21,600. Accordingly, the total cost for provision of test/production pumping equipment and the accomplishment of the well and aquifer performance tests is $59,600 for each of the above cost scenarios.

The above opinions of costs to drill the test/production well under a range of assumptions is summarized as follows:

	Low Cost	Intermediate Cost	High Cost
Mobilize/Demobilize Equipment	$140,000	$140,000	$140,000
Construct Well	$407,230	$563,370	$670,980
Test/Production Pump Package	$38,000	$38,000	$38,000
Development and testing	$21,600	$21,600	$21,600
Total Costs:	$606,830	$762,970	$870,580

Special recognition is offered to Mr. Mark List, P.E. and Contracts Engineer, and his associates at Lang Exploratory Drilling in Elko, Nevada for providing the details of the above opinion of costs to drill a well for the PSWID, based on their extensive experience in using drilling technology calculated to overcome the type of lost circulation problems known to existing in the subsurface of the PSWID area.

PSWID Agent, John Breninger
PINE / STRAWBERRY WATER IMPROVEMENT DISTRICT
P.O. Box 134
Pine, Arizona 85544

October 1, 2003

PSWID PROJECT PS 2002-01 REPORT

POSTSCRIPT to PSWID Project PS 2002-01 Final Report

Comments and Dialog between Brooke Utilities, Inc. President, Robert T. Hardcastle (RTH), and PSWID Agent, John Breninger (JB)

RTH - I have finished reading the Investigative report. I found it well done and interesting. I think it is a very technical affirmation of much of what BUI has been saying for years with some exceptions. Sometime when we have additional time there is a lot about its contents that I would like to discuss further with you as I think it needs some strengthening in several areas.

JB - Thanks for your comments. It would be a good thing to examine the report with you and look at the areas needing some reinforcement. To this end, I have copied Mike Kaczmarek, Morrison-Maierle Inc. (M-M). Because of the critical comments on the works of others in this report, Mike (M-M) had taken a somewhat delicate approach in which he framed his comments. He is awaiting the full release of the report documents to the public by the PSWID Board, when he expects some sharp responses to his findings and analysis from sources that may feel they were wounded. The full value of this report is what we can learn from matching it to the conditions and performance in operating the well field.

RTH - I think the biggest thing missing in the report is affirmation of his conclusions. With regard to radial versus linear flow he has formed a conclusion that is contrary to 30-40 years worth of examination by numerous previous experts. That is a substantial difference. His reasoning as to why prior conclusions are inaccurate is fine but, by itself, is hollow and unsupported. In has the air of "just another opinion" and is available for attack from different fronts. I think that position desperately needs professional support from, probably, more than one unrelated professional. It would be ideal if one or more of the authors of previous reports joined his conclusions.

What do you think?

JB - Point well taken!

However, the issue here is that the prior assessments were similar and consistent in mis-applying the methodology to the circumstances, and then making the generality a rule from which a detailed assumption was applied as reality. Just lining up the list of opinions and taking a vote doesn't balance the facts in reality. That may be the legal approach to resolving differences of opinion in court, but it has very little effect on how much, and which, water will reach the wells doing the pumping. Ergo, we still don't get the projected water that those analyses have projected.

Mike (M-M) recognized the nature and consequences of having to take issue with other recognized experts putting forth their opinions to support the justifications that their employers were addressing. What the PSWID contract required was a realistic evaluation of these reports and to provide a valid baseline of interpretation, so that the District doesn't get entangled into a balancing act of diverse opinions as it proceeds into the business of becoming a water supplier (wholesale, or whatever). The presentation and description of these findings, that Mike (M-M) chose to employ, aimed primarily at meeting the PSWID requirement, and secondarily at minimizing a confrontation among the professionals and recipients of these prior works. As a result, the language and references may appear to be too thin, but are still rock solid in the technology.

[By my observation, Mike (M-M) wished to avoid conducting elementary hydrology school lessons publicly to the other hydrologists involved. Also, I believe that the interpretation Mike (M-M) provided is broadly supported among the professional community - notwithstanding that some hydrologists have taken the courses that they have.] As the PSWID Agent, I knowingly chose not to apply the project funding into making a bullet-proof documentation of the merits, or lack thereof, of the prior works.

Consequently, the District has invested in the GIS/Database Management System (GIS/DMS) of a Wells Database that will enable the collection and evaluation of data to realistically test the hydraulic truth of the groundwater behavior in the various strata. The District will proceed on the assumption that the Kaczmarek (M-M) opinion is valid, but ultimately, the results of the data collection, analysis and evaluation will depict the reality for us. This GIS/DMS tool is capable of portraying this scenario in very understandable and practical means. If the water fails to show up as predicted, it will be considered absent. If more water shows up than predicted, or we can learn how to manage its migratory paths better, that is good and we will continue to study and enhance those improvements. Either way, we grow away from analytical speculation toward a more proven way of dealing with our sources of water.

Respectfully,
John Breninger
PSWID Agent

FILE: Postscript2 PSWID Project PS2002-01 Final Report.doc

PSWID Project PS 2002-01

PINE / STRAWBERRY WATER IMPROVEMENT DISTRICT
P.O. Box 134
Pine, Arizona 85544

October 22, 2003

PSWID SPECIAL REFERENCE DOCUMENT COLLECTION VOLUMES I, II and III

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[Extracted from the Annotated Bibliography from the Project Final Report to PSWID]:
"Investigation of Groundwater Availability for the Pine/Strawberry Water Improvement District" - REFERENCES CITED
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Preliminary List of Studies for Pine-Strawberry Area Revised May 28, 2002
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1) ~~"Hydrologic Analysis and Report for the Pine Canyon Watershed", Unpublished Report # 2530, Payson District, Tonto National Forest, Forest Service, U.S. Dept. of Agriculture, 1967. [Surface water in Pine Creek Basin and Watershed Management considerations]~~ [Moved to Volume I, No.29]

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3) "Basic Data for Selected Wells and Springs in the Pine-Payson-Kohl's Ranch Area, Gila County, Arizona" Prepared in cooperation with the U.S. Geological Survey, Arizona Water Commission - Report No.9, Phoenix, Arizona, August 1977. [Contains explanation of well and spring information for Arizona (well numbering system based on location), and water depth/flow data]

4) ~~"A Hydrogeologic Investigation of the Pine-Strawberry Area, Arizona", Gary L. Hix, under the supervision of John S. Sumner, Ariz. Cert. No. 6832, Prepared for the E & R Water Company, Mesa, Arizona, May 1978. [Contains well numbering description, initial phase of a total hydrogeologic development plan, well data, and detailed hydrogeologic description of the area]~~ [Moved to Volume I, No. 15]

5) ~~"Hydrologic Evaluation of the Portals Subdivisions in the Pine Canyon, Pine, Gila County, Arizona", for Austin Meyers by Paul A. Manera, Ariz. Cert. No.4788, February 28, 1979. [Describes elements of supply, including the geologic framework, Static water levels, Transmissivity, and well data from six (6) wells in The Portal Subdivisions]~~ [Part 1 Moved to Volume I, No.21], [Part 2 Moved to Volume I, No. 20]

6) ~~"Water Supply of the Pine-Strawberry Area, Gila County, Preliminary Report, June 1987, Gila County Development Office, Globe, Arizona 85501 [Summarizes water supply for the Pine Creek Area, Strawberry Hollow, Strawberry Creek Areas, Supply vs. Demand, data from a "wet" period, Conclusions]~~ [Moved to Volume I, No.3]

7) ~~"Report on Pine Area Water Shortage", July 17, 1989, Arizona Department of Water Resources [Includes ADWR Statement of Position Regarding Groundwater conditions in the Pine-Strawberry Area, Greg Wallace, Chief Hydrologist, Arizona Dept. of Water Resources, October 16, 1987. Letter communication to Mike Peterson, Gila County Planning Department, Globe, Arizona; Also includes Preliminary Report dated June 1987. This report is reportably the basis for ADWR considering the water supply for the area to be "inadequate" to support additional development from the 1989 level, concludes that additional "dry" years data is needed]~~ [Moved to Volume I, Nos.1 & 2]

8) ~~"ENVIRONMENTAL ASSESSMENT Proposed Underground Waterline from Strawberry to Pine, Arizona along Highway 87", Responsible Official, Charles Bazan, Forest Supervisor, United States Department of Agriculture, Forest Service, Southwest Division, July 20, 1999. [Includes biblio., selected well data for Strawberry]~~ [Moved to Volume I, No. 24]

9) "Preliminary Hydrology Report in Support of Aquifer Protection Permit (APP) Application, Pine Meadows Wastewater Treatment Plant, ADEQ file no. 21397".Haley & Aldrich, Inc., Tucson, Arizona, November 20, 2000. [Includes: Addendum Report, Additional Geology and Hydrology Information in Support of Aquifer Protection Permit Application" Haley & Aldrich, Inc., Tucson, Arizona, January 19, 2001.]

10) "Letter Report, Water Resources Study, Strawberry/Pine, Arizona" Marvin F. Glotfelty, R.G., Principal Hydrogeologist, Clear Creek Associates, PLC. March 27, 2002 [Includes hydrographs in the Strawberry and Pine areas, flow net analysis, and regional groundwater elevation contour maps.]

11) Corkhill, Frank, "Report on the Drilling of an Exploratory Borehole near Strawberry, Arizona (May 18 - June 2, 2000), A Hydrogeologic Investigation for the Northern Gila County Water Plan Alliance, Arizona Department of Water Resources, Hydrology Division, August 9, 2000. [Includes identification of the major lithologic zones for the site, geologist's notes and well log, and logs of geophysical testing.]

12) ~~Weisman, Melanie K., "Geology of the Pine and Northern Buckhead Mesa Quadrangles Mogollon Rim Region, Central Arizona": 1984, U.S. Geological Survey, Department of the Interior, [Copy of Plate I only with Correlation of Map Units][Also have portions of Weisman thesis paper with detailed stratigraphy held in Special Collections at Cline Library, Northern Arizona University, Flagstaff]~~ [Moved to Volume I, No.32]

13) ~~Weisman, Melanie K. and Weir, Gordon W., "Geologic Map of the Pine 7.5' Quadrangle, Coconino and Gila Counties, Arizona" MAP MF-2123, Miscellaneous Field Studies Map, Publ. by U.S. Geological Survey, 1990 [Map Scale 1:24,000]~~ [Moved to Volume I, No.33]

14) ~~Weir and Beard, "Geologic Map of Fossil Springs Roadless Area, Yavapai, Gila and Coconino Counties, Arizona, MAP MF-1568-C, Miscellaneous Field Studies Map, Publ. by U.S. Geological Survey, 1990 [Map Scale 1:24,000]~~ [Moved to Volume I, No.31]

15) Montgomery, E.L. and Harshbarger, J.W., "Arizona Hydrogeology and Water Supply" reprint from Jenney, J.P. and Reynolds, S.J., [1989 Arizona Geological Society Digest 17, p. 827-840, [Includes Maps for 1) AZ Avg. Annual Precip., 2) AZ Avg Annual Evaporation and 3) AZ Designated Groundwater Basins and biblio.]

- END of Preliminary List...- (Vol. III continued)

Volume III Additional Documents, (not referenced)

16) Sabels, Bruno E., Mogollon Rim Volcanism and Geochronology, Desert Research Institute, University of Nevada, Reno, NV, New Mexico Geological Society – Thirteenth Field Conference, P. 100 – 106

17) Hart, Robert J., Ward, John J., Bills, Don J., and Flynn, Marilyn E., Generalized Hydrogeology and Ground-Water Budget for the C Aquifer, Little Colorado River Basin and Parts of the Verde and Salt River Basins, Arizona and New Mexico, Water-Resources Investigations Report 02-4026, U.S. Geological Survey, Tucson, Arizona, February 2002

- END of Vol. III -

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AHS 2003 ANNUAL SYMPOSIUM FINAL ABSTRACT

R-AQUIFER IN NORTHERN ARIZONA

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Synopsis

The R-aquifer is the source of water for most large springs in northern Arizona and is a partly-developed source of large and sustained municipal water supply.

Abstract

The R-aquifer is the most important aquifer system in northern Arizona with respect to regional extent, amounts of groundwater transmitted, and potential yield to wells. Geologic units that comprise the R-aquifer include, in ascending order, Tapeats Sandstone, Muav Limestone, Martin Formation and Temple Butte Limestone, Redwall Limestone, Naco Formation, and brittle rocks of the Lower Supai Group. At many locations, close hydraulic connection occurs between these units. However, at places the Tapeats is separated from overlying formations by poorly permeable Bright Angel Shale; at these places groundwater in the Tapeats may be saline. Depth to the top of the R-aquifer beneath the Coconino Plateau, and near Flagstaff and Williams is 2,500 feet or more. Because much of the R-aquifer consists of brittle carbonate rocks, the occurrence of fractures and solution openings is important to lateral and vertical transmission of groundwater.

R-aquifer strata crop out in the walls of the Grand Canyon and in other more limited areas including Big Chino basin, Verde Valley, and at places along the Mogollon Rim. The units occur in the subsurface in much of the area between the Colorado and Verde Rivers. Near the Arizona border with New Mexico, the units pinch out along the margins of the Defiance Uplift. Thickness of the R-aquifer ranges from a featheredge near the Defiance Uplift, to more than 3,000 feet near Lake Mead; average thickness is about 1,000 feet. Except near outcrop areas, the entire thickness of the R-aquifer is saturated in much of the area between the Colorado and Verde Rivers. Small saturated thickness occurs near Peach Springs, where groundwater level is near the top of the Tapeats Sandstone.

Patterns of groundwater recharge, movement, and discharge for the R-aquifer are not fully understood. The principal recharge zone is believed to occur in a broad band located parallel to and a short distance north from the Mogollon Rim, passing near Williams and Flagstaff. Important recharge occurs by downward groundwater movement through fractured rocks of the Supai Group from the overlying C-aquifer at large structural features such as the East Kaibab monocline and Mesa Butte Fault, and at structural depressions such as the Anderson Mesa Fault and Lake Mary graben, and the Lyman Lake trough. Milky-appearing water containing fine gas bubbles is often pumped from C- and R-aquifer wells located adjacent to large structures associated with important recharge to the R-aquifer. Although recharge along large structural features is important, amounts of diffuse downward groundwater movement through sparsely fractured and poorly permeable rocks of the Supai Group may be predominant. Principal

lateral movement of groundwater in the R-aquifer is believed to occur through arterial zones along solution enhanced fracture systems controlled by geologic structures of regional scale. These structural systems include the East Kaibab Monocline, the northern part of the Mesa Butte Fault system, and the Oak Creek Fault system. Groundwater from the R-aquifer provides about 500 cubic feet per second base-flow discharge to the Colorado and Verde Rivers and tributaries, and includes:
70 cfs near Havasu Spring,
220 cfs in the Blue Spring area along the Little Colorado River,
75 cfs along the Verde River near Clarkdale,
60 cfs along Oak Creek at and near Page Springs, and
42 cfs from Fossil Springs near the town of Strawberry.

The R-aquifer presently provides much or all of water supply for Tusayan, Valle, Williams, and Sedona.
Yields from wells at Tusayan, Valle, and Williams are 250 gallons per minute or less; these yields are controlled by small well diameter and pump size rather than by aquifer conditions.
Present pumping rates from R-aquifer municipal wells at Sedona range from about 500 to 1,000 gpm, although analysis of aquifer conditions indicates that larger yields may be obtained.
Yields from R-aquifer production water wells located near Clarkdale are more than 600 gpm.
Near Page Springs, several R-aquifer wells have been constructed recently; initial artesian flow from these wells was more than 1,000 gpm.

Largest yields from wells appear to occur where drilling conditions permit construction of large diameter wells, and under favorable geologic conditions where fractures are abundant and where fracture openings have been enhanced by dissolution of carbonate minerals.

Future large-scale groundwater withdrawals from the R-aquifer are most likely to occur under favorable geologic conditions near Flagstaff where the overlying C-aquifer is almost fully exploited, in Verde Valley where groundwater in the Verde Formation contains large concentrations of arsenic, and near Williams and other locations where the C-aquifer is not saturated.

Errol L. Montgomery: President, Errol L. Montgomery & Associates, Inc. from 1979. Wyoming State Engineers Office 1963-65; Wright Water Engineers, Denver, 1965-67; Professor, Northern Arizona University, 1970-77; Harshbarger and Associates, 1969-70 & 1977-79. PhD Hydrogeology and Geophysics, University of Arizona, 1971.

Edwin H. McGavock: Project Hydrologist, Errol L. Montgomery & Associates, Inc. from 1994. U.S. Geological Survey, Water Resources Division, 1962-93. M.S. Geology, University of Virginia, 1962.

[Format edited for emphasis by John Breninger, PSWID, 9-22-03]

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ATTACHMENT "E", Intervener Testimony by J. Breninger, Docket No. W-03512A-03-0279, Oct. 28,2003

PSWID Agent, John Breninger
PINE / STRAWBERRY WATER IMPROVEMENT DISTRICT
P.O. Box 134
Pine, Arizona 85544-0134

October 3, 2003

Reference: PSWID Project P/S 2002-01
REPORT: **Purpose and Scope of the PSWID Wells Database System**

PURPOSE:

Understanding the nature and character of the groundwater supply in the Communities of the Pine / Strawberry Water Improvement District (PSWID) became part of the vision, "...in securing long term and reliable sources of water for the Communities..."

A geohydrological study of the northern Gila County area was commissioned by PSWID in 2002 to provide, "Engineering Services to Develop a District Water Resource and Action Plan for the purpose of Documenting Present Conditions and Identifying Potential New Sources of Groundwater in the Pine / Strawberry Area of Gila County, Arizona". Factual data on the performance of the local wells and the broader geophysical characteristics of the area were notably absent or dispersed and unavailable for this study.

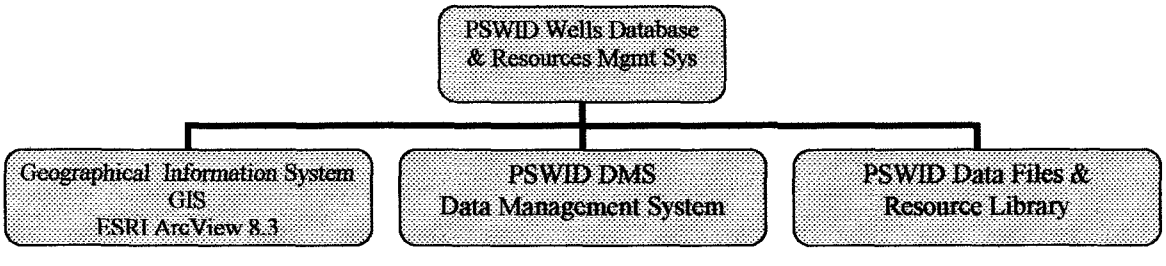
Therefore, the invitation for bids for the requested engineering services included a firm requirement to: "Establish an inventory of wells into a database suitable for collection and integration of groundwater data. Provide operational guidelines to gather and utilize well data and to produce reports from the database."

The system, as designed for PSWID, was built around a Geographical Information System (GIS) software package that could integrate a wide range of geophysical data and mapping capability with the groundwater data. The database management system (DMS) was fully matched with the GIS capability. The result is a tool that includes study, analysis, display and data management components suitable for infrastructure and resources operations, organization and management far into the future. This system integrates well with other GIS based systems, and may well become a core system to serve a wider functionality than just the PSWID.

SCOPE:

The PSWID Wells Database System consists of the major -elements shown in Figure 1.

FIGURE 1 – PSWID Wells Database Functional Block Diagram



The functions and usage of the PSWID Wells Database & Resources Management System include:

1. Provide a working database for the well registrations information and the related locations, output performance data, and hydrologic characteristics for the area. (Database will consist of entire set of registered wells for the Pine and Strawberry area from the ADWR and USGS files, including: active, inactive, un-completed and abandoned wells. Database may be maintained with update additions and changes). Code P
2. Provide a suitable mapping capability for the topographic, geologic, streets and highways, property parcels, and political boundaries. (Updates may include Gila County data when available)
3. Identify and display patterns of well pumping output and static water levels. Provides clear understanding of water conditions, using present and/or past data. (doesn't require complex interpretations or training to read a 3-D picture - displays the true elevations of water levels in a 3D contour map – not just depths to water from unrelated well heads). Code P
4. Provide tracking of the well performance under seasonal and multi-year performance patterns. (System will accept automatic data collection and input files – not just manual data) Code P
5. Provide a display of static water levels in true elevations for selected wells in the Communities, and provide a simplistic 3-dimensional pictorial view of the historic and dynamic effects of changes to the groundwater status. (Capable of animation for displaying water level changes dynamically). Code P
6. Provides guidance on pumping patterns as cause-and-effect history is captured. Can display effects of interactions among wells, horizontal and vertical connections and couplings, and slope gradients of water levels. Codes A, P
7. Identify patterns of well performances under stressful pumping and provide for the analysis of possible ground fracture patterns to improve and optimize the output of the well field. (capable of selected well sets and time periods for display reports). Codes A,P
8. Subsequent additions to the database include satellite geophysical maps and provisions for water quality reports to display overlays of water quality characteristics. Code P
9. The Security and Password permission structures remain to be developed to safeguard the reliability and integrity of administration of the system and data files under both investigative and operational conditions. Codes A, P

DATABASE STATUS CODES:

A – Further ANALYSIS programming required and is under way

P – Further application software and/or system PROGRAMMING required and is under way

Respectfully submitted,
John Breninger
PSWID Agent

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