Using Isotope Hydrology, Fracture Mapping, and Pump Tests to Characterize Groundwater Flow Through the Fractured Rock Terrane of the Sierra Nevada Foothills

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Introduction

The hydrogeology of the foothills of the Sierra Nevada is mainly dominated by the complex geometry and distribution of fractures in the granitic rocks. Although the role of fracture parameters, such as orientations, density, and continuity, in controlling groundwater flow can be demonstrated based on conceptual and numerical models, the actual effects on groundwater supply availability in field or regional scale are seldom fully understood.

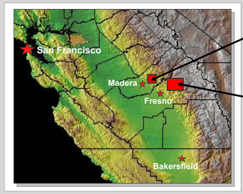


Figure 1. Locations of study areas.

The goal of our field studies is to characterize these effects by using long duration pump tests up to 34 days and stable isotope ratios in conjunction with fracture mapping and satellite/aerial photo interpretation. The study areas are shown in Figure 1.

Objective

To characterize the groundwater flow through the fracture systems based on stable isotope data, field mapping, and pump tests.

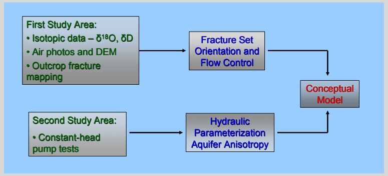
Methodology

(1) Isotopic data ($\delta^{18}O$ and δD) of the 121 surface and groundwater samples were measured (Figure 2).

(2) Regional fracture patterns were identified from aerial photographs, satellite images, and structural attitude of fractures (from 271 locations) to create a fracture distribution map (Figure 3).

(3) The spatial variations of both $\delta^{18}O$ and δD in relation to fracture distribution were investigated by plotting the isotopic data on the fracture map (Figure 4).

(4) Pump tests
- Two test wells and 17 observation wells were installed in a 540-acre study area.
- Result of the pump tests were compared.



Results – Isotope Data and Fracture Mapping

- The $\delta^{18}O$ vs. δD plot shows (Figure 2) a continuous fractionation trend of isotopic enrichment in the groundwater as well as surface water samples with the decreasing elevations, indicating that the main source of recharge in the watershed is precipitation at high elevations. The most isotopically depleted groundwater samples are from the wells in the recharge area at high elevations, with isotopic values close to that of precipitation.

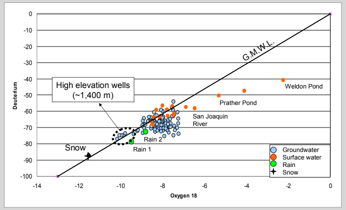


Figure 2. δ18O vs δD diagram representing the four main types of waters investigated in the watershed.

- Two fracture sets can be identified in the area of high elevations. In the northeastern part, the dominant set has a general trending NNW slightly dipping to the SW (Figure 3A). In the southeastern part, the most dominant set has an ENE trend dipping slightly to the SE (Figure 3B).

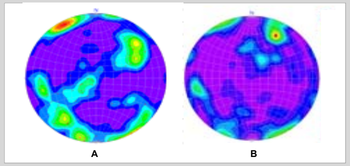


Figure 3. Structural attitude plotted on stereonets: (A) dominating fracture sets in the northeastern part of the recharge area at high elevations, (B) dominating fracture sets to the southeast.

- The northeastern portion of the study area at higher elevations has much higher annual precipitation than the valley below, and can be identified as the main recharge area based on isotopic data (Figure 4). The effect of preferential flow through the fracture system is made evident by the spatial variation of isotopic ratios. Samples located along fracture zones show anomalously less isotope enrichment than samples located away from fracture zones.

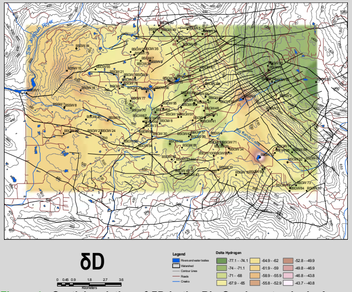


Figure 4. Spatial variation of δD in the Big Sandy watershed. Anomalously low ratios are found in wells located near fracture zones.

Results – Pump Tests

- The value of transmissivity obtained by a 24-hr constant discharge test agrees with that based on a 2-day constant head (H) test, which is 530 gpd/ft (Fig.5a) vs. 480 gpd/ft (Fig.5b). However, the mean transmissivity value is scale dependent. Using longer time data up to18 days, the constant head test results in a lower mean transmissivity value which represents a larger area at the study site.

(a)

Test Well	Pump Test Method	Pumping Duration	Analysis Method	T gpd/ft
1	Constant Head	18 days	Theis-recovery	280
	Cons. Discharge	1 day	Cooper-Jacob	**530**
	Step Drawdown	140 min.	Cooper-Jacob	2,620
5	Constant Head	15 days	Theis-recovery	190
	Cons. Discharge	1 day	Theis-recovery	1,860
	Step Drawdown	120 min.	Cooper-Jacob	3,070

(b)

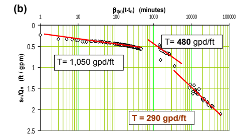


Figure 5. a) Transmissivity values for different duration and pumping test methods (KDSA, 2006). b) Transmissivity values at Well 1 based on Cooper-Jacob method of variable pumping rate (Kruseman and de Ridder, 1990).

- Results of pump test at Well 1 show that the drawdowns at Wells 1, 5, and 6 define an elongated cone of depression (Fig. 6) parallel to a possible fracture zone. Despite the anisotropy, they are reasonably hydraulically connected (Fig. 7a). Distance-drawdown graph (Fig. 7b) indicates that other observation wells farther away are also influenced by the anisotropy of the fracture system.

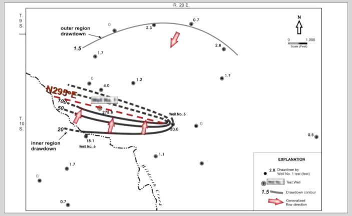


Figure 6. Drawdown contour following Well No. 5 pump test

(a)

Well	Transmissivity (gpd/ft)		Analysis
	Pump test on Well 1		
1	290	Drawdown	
	280	Recovery	
5	1,090	Drawdown	Good hydraulic connection
6	4,070	Drawdown	Moderate hydraulic connection
	2,200	Recovery	

(b)

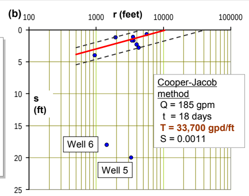
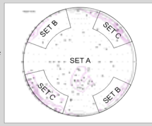


Figure 7. Hydraulic connection based on pump test at Well 1. a) Low transmissivity values indicate Wells 5 and 6 are connected with Well 1. b) Distance-drawdown graph. A high apparent transmissivity value indicates that these observation wells are not connected with Well 1.

- Two near-vertical fracture sets are mapped based on outcrops (Fig. 8). The orientation of elongate drawdown contour observed in Fig. 6 is within the range of fracture set C, which dominates groundwater flow.

Figure 8. Identification of fracture sets, using stereographic projection.



Fracture set	Range of strike (Azimuth)	Mean dip angle (°)
A	220° to 260°	31
B	295° to 310°	85
C	225° to 245°	89

Conclusion

- Study Area A (Big Sandy Valley) has shallow alluvial deposits. The crystalline rock (granite) aquifer is recharged mainly by runoffs from higher elevations with minor contribution from local precipitations. More isotopically depleted waters are found in deeper ground water along an ENE trending fracture zone.
- Furthermore, the ground water samples associated with these fractures has isotopic values more depleted signatures, similar to the precipitation, than those farther away from fracture zones. This spatial pattern of isotopic ratios indicates that the ENE trending fracture set imposes a strong control on the direction and the velocity of the groundwater flow.
- The results of different pump tests in Study Area B suggest that both the flow patterns (radial or linear) and the aquifer parameters (transmissivity and storativity) are dependent on the size of the area of influence.
- Pump test results show that to characterize an extended area of the fractured aquifer for the purpose of water resource investigation, a pump test for at least 15 days is required in order to get a reliable trend line of drawdown versus time. Because of the limited well capacities, the constant-head pumping test method is more practical than constant-discharge or step-drawdown methods.
- Aquifer anisotropy is controlled by the fracture connectivity and orientation, but independent of the pump test methods.
- These preliminary studies demonstrate that stable isotope and pump test data used in conjunction with satellite photo and outcrop fracture mapping can be applied to characterize fracture systems and help assess the sustainability of groundwater supply for fractured rock terranes.

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