A Method of Evaluating the Perennial Yield of Fractured Consolidated Rock Aquifers

Michael F. Hoover, Consulting Geologist-Hydrologist

PO Box 30860 • Santa Barbara, California 93130 • United States

(805) 569-9670 • mfhoover@hoovergeo.com

ABSTRACT

A significant portion of southern Santa Barbara County (the study area) relies on groundwater extracted from fractured consolidated rocks. The utilization of these aquifers dates back over a hundred years when "water tunnels" were constructed to supply the domestic and irrigation needs of a growing population in this semi-arid coastal region of Central California. Beginning in the 1920s, water wells replaced the hand-dug tunnels as the preferred method of withdrawing groundwater from the fractured Tertiary-age sandstones and shales that comprise the consolidated rock aquifers in the study area. To this day, these consolidated rock aquifers are often the overlying owners' sole source of water supply, thus it is important for hydrogeologists to develop a reliable method of estimating the long-term yield of these types of aquifers. Few studies exist that provide a reliable method of estimating the long-term or *perennial yield* of the fractured consolidated rock aquifers in the study area. However, pumpage-change in storage data, collected over extended time periods, exists at a sufficient number of sites to allow the development of a reasonably accurate method of estimating the perennial yield of the consolidated rock

aquifers within the study area. Utilizing the methods outlined herein, an estimate of perennial yield can be made for fractured consolidated rock aquifers in any watershed within the study area, even when only limited site-specific data are available. The principles and methods described herein should be universal, applicable to other geographic areas where similar geologic conditions exist.

Key Words: *Fractured consolidated rock, Groundwater hydrology, Hydrogeology, Perennial yield, Streamflow modeling*

INTRODUCTION

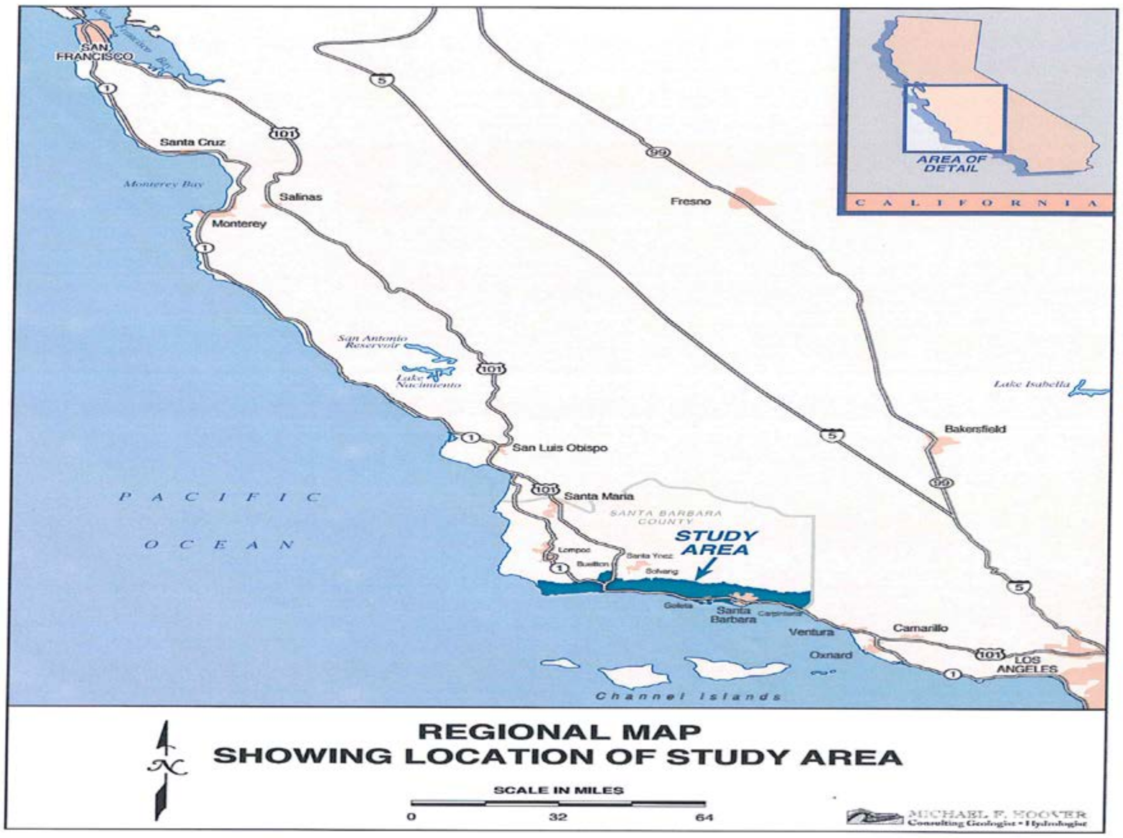
From the time of the European colonization water resources have played an important role in sustaining agriculture and a growing population in the semi-arid region of Central California. In the mid-1800s, many of the cattle ranches that comprised the Spanish and Mexican land grants suffered economic collapse due to the lack of a reliable water resource. Beginning in the late 19th century, groundwater derived from hand dug "water tunnels" provided a much-needed alternative to drought-impacted surface water supplies. Surface water impoundment projects, constructed in the early to mid-1900s, allowed expanded urbanization and agriculture on the Central Coast of California, but by the 1950s, the collective water demand once again exceeded the supply, and more extensive groundwater withdrawals were needed to offset the deficit. In the mid-1970s, from 1988-90, and from 2011-17, the regional water demand exceeded available supplies, and groundwater was once again required to make up the deficit, sometimes resulting in groundwater basin and aquifer overdrafts.

In southern Santa Barbara County, the perennial yield of the alluvial groundwater basins is known from previous work: Upson, 1951; Everson, Wilson & Muir, 1962; Geotechnical Consultants, 1976; Mann, 1976; Martin, 1986; Martin and Freckleton, 1989; and Hoover, 1980. In contrast, only a few studies evaluate the long-term yield of the fractured consolidated rock aquifers in the foothills of Southern Santa Barbara County.

PURPOSE, SCOPE, AND LIMITATIONS

This study provides a method of estimating the average annual rate of recharge (i.e., “perennial yield”) of fractured consolidated rock aquifers in southern Santa Barbara County (the study area). Southern Santa Barbara County is located on the Central Coast of California, (Figure 1).

FIGURE 1



For the purpose of this study, *average annual rate of recharge* is often used interchangeably with the term *perennial yield*. Safe yield, a term usually defined as “a reasonable rate of extraction for the foreseeable future that does not cause a long-term adverse effect” (Mann, 1976), may differ from the long-term average annual recharge (or perennial yield) depending on the definition of “adverse effect”. Thus, the term “safe yield” is not used interchangeably with perennial yield in this study.

The perennial yield of a groundwater basin (or aquifer) is typically determined by one of two methods: The Inventory Method or the Pumpage-Change in Storage Method. The Inventory Method assigns numerical values to each source of inflow (i.e. stream seepage, field recharge) and discharge (i.e. subsurface outflow, pumpage). The Pumpage-Change in Storage Method requires the measurement of groundwater usage and water level response in a defined hydrologic area during a period of representative rainfall. The perennial yield is then determined by calculating the average annual pumpage that would occur when the net change of groundwater held in storage over a period of representative rainfall is zero. Computer modeling is commonly used to assist the investigator in evaluating the above variables.

This study determined (to the extent the data allowed) the perennial yield of the fractured consolidated rock aquifers in six typical watersheds using the Pumpage-Change in Storage Method. Values for the various recharge components were then back-calculated using methods developed by several investigators working independently in diverse geographical areas, then tested utilizing groundwater modeling of several of the watersheds within the study area where the perennial yield is known based on the history of water use.

The parameters used to estimate the perennial yield described herein include: average annual precipitation, watershed size, type of vegetation, topography, the areal extent of aquifer, aquifer properties (including transmissivity and storage coefficient), and stream bottom configuration. A site-specific aquifer test is required to accurately determine the aquifer transmissivity and storage coefficient.

PHYSIOGRAPHY

The study area is located at the western end of the Transverse Range Province on the Central Coast of California. The east-west trending Santa Ynez Mountains are the primary topographic feature in the study area, rising above the coastal plain to an elevation of 4298 feet (1310 meters) above mean sea level. There are 55 north-south trending watersheds within the study area; all watersheds originate in the Santa Ynez Mountains and are tributary to the Pacific Ocean (Figure 2).

CLIMATE

The study area has a Mediterranean climate characterized by average annual rainfall that varies from less than 16 inches (40.64 cm) per year at the coast to over 30 inches (76.20 cm) per year near the crest of the Santa Ynez Mountains. Isohyets, presented on Figure 2, depict the spatial distribution of rainfall in the study area.

FIGURE 2

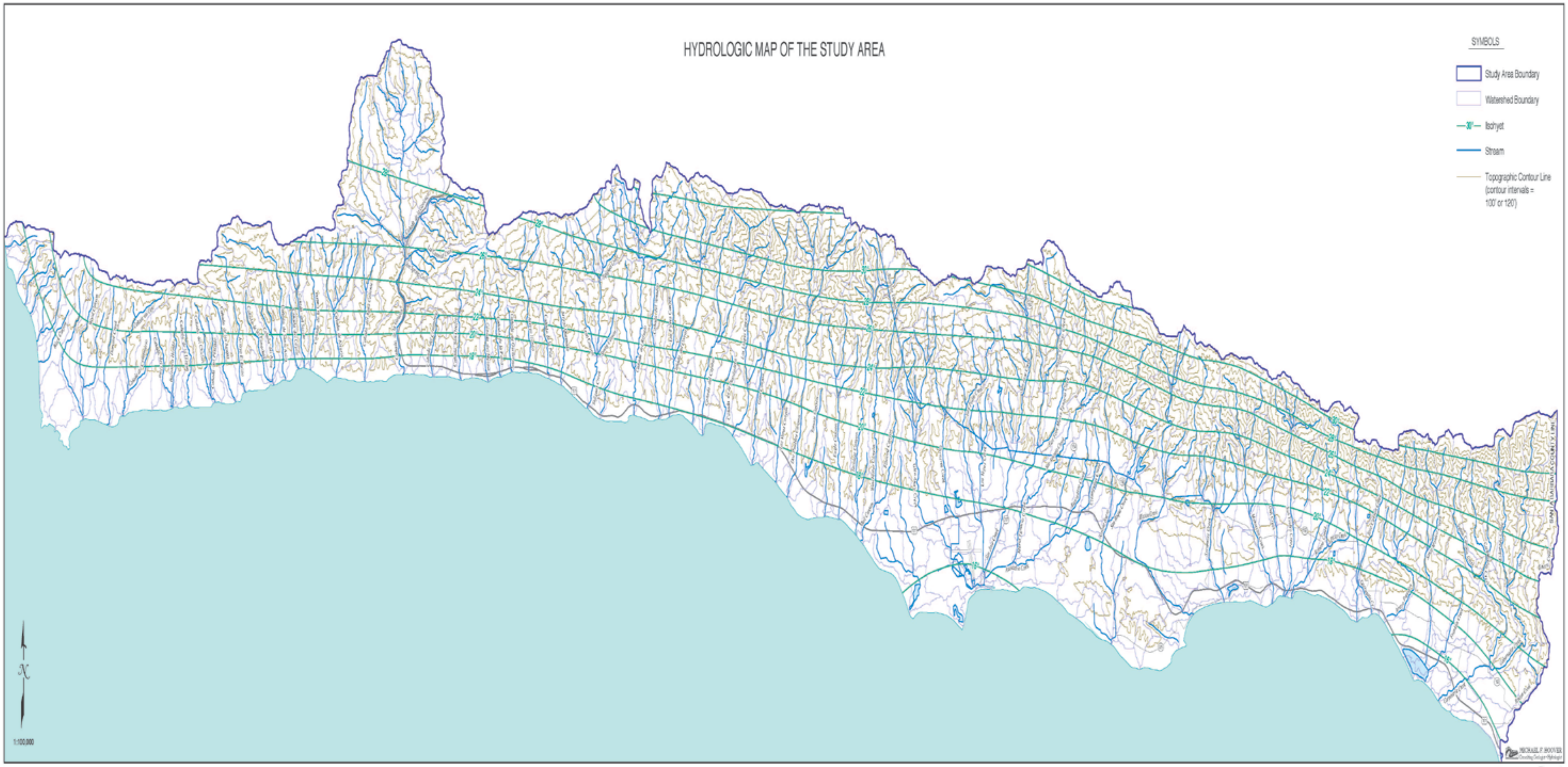
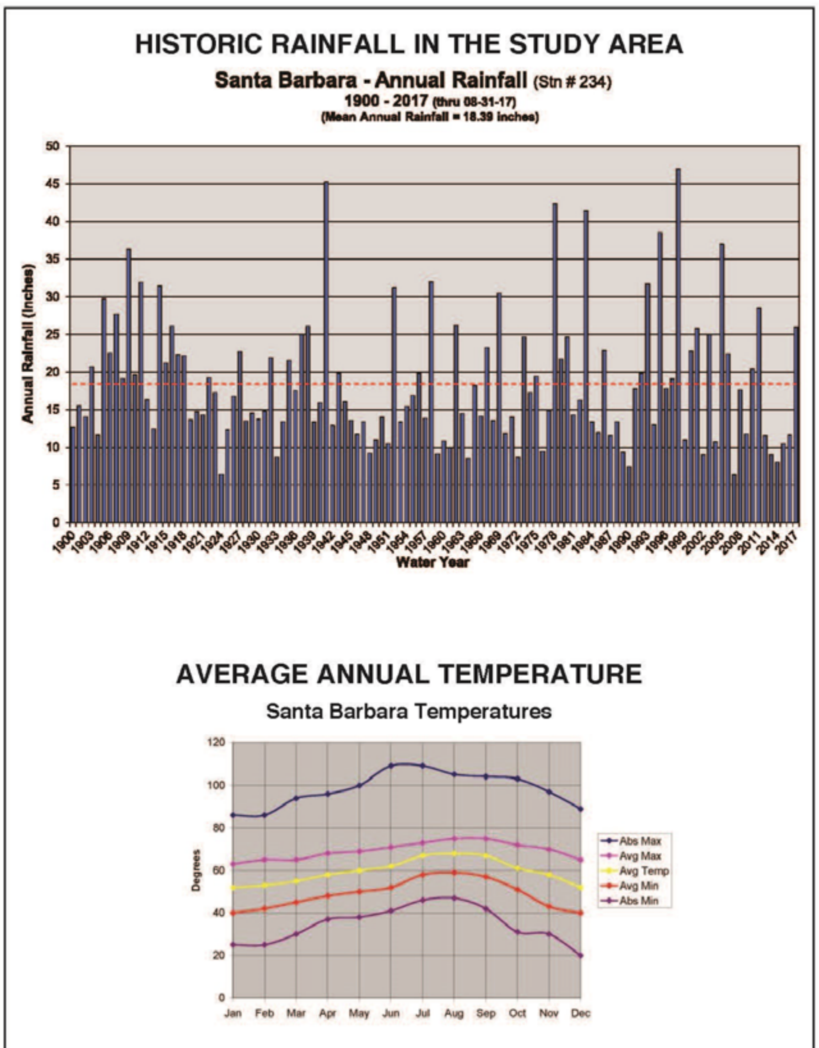


Figure 2

Annual precipitation varies considerably from year to year; 47.07 inches (119.6 cm) was recorded at the Santa Barbara gauge during water year 1997-98, whereas only 4.49 inches (11.4 cm) was recorded in 1876-77. Approximately 92 percent of the precipitation in the study area occurs between November and April. The temperatures in the urban portion of the study area vary from an average of 70°F (21°C) in summer months to 50°F (10°C) in winter (Figure 3).

FIGURE 3

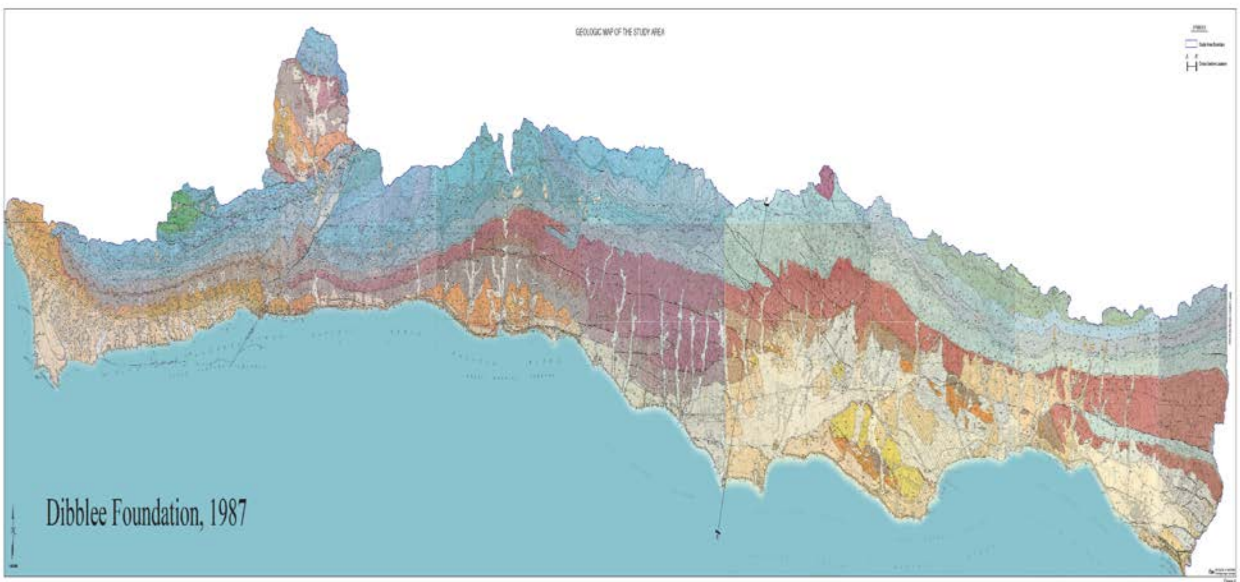


SOURCE: Santa Barbara County Water Agency, 2017.

GEOLOGY

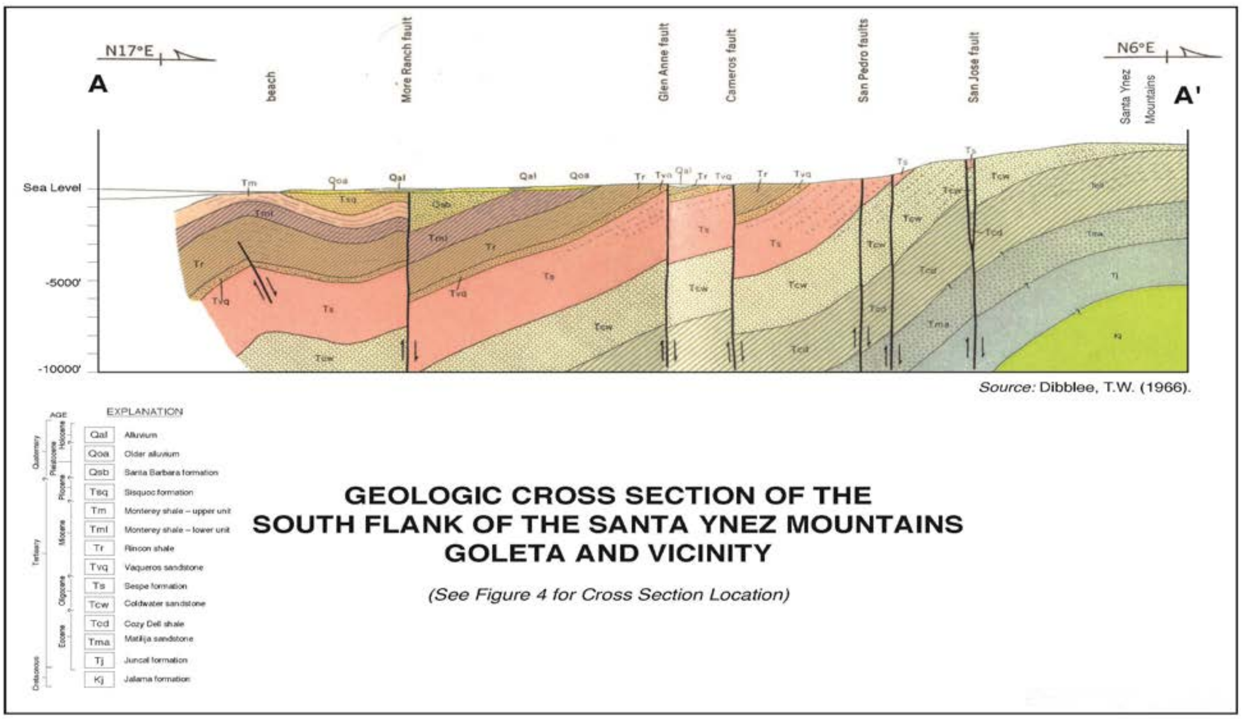
The fractured consolidated rocks that comprise most of the Santa Ynez Mountains are described by several authors, including: Minor, et al., 2009; Miller and Rapp, 1968; Upson, 1951; Dibblee, 1966; Gurrola, 2004; and Rantz, 1960. The most complete geologic maps of the study area are the series of geologic maps prepared by the Dibblee Foundation (Figure 4).

FIGURE 4



The Tertiary-age rocks in the study area consist of a generally south-dipping sedimentary sequence of interbedded sandstones and shales. Localized northwest trending synclines and anticlines are present, as well as numerous east-west and northwest trending near-vertical faults. A typical geologic cross-section is presented as Figure 5.

FIGURE 5



GEOLOGIC CROSS SECTION OF THE SOUTH FLANK OF THE SANTA YNEZ MOUNTAINS GOLETA AND VICINITY

(See Figure 4 for Cross Section Location)

The interbedded sandstones and shales that typify the sedimentary rocks in this study area are both marine and non-marine in origin, however, the marine sequence predominates. We know from observations during the construction of the Tecolote Tunnel that virtually all rock units in the northern portion of the study area are fractured to some degree, and that most transmit water (Rantz, 1960; US Bureau of Reclamation, undated).

HYDROLOGY

Surface Water

The 55 generally north-south trending watersheds within the study area vary in size from less than 1000 acres (404 ha) to over 5000 acres (2,024 ha). Relatively steep stream gradients of 200 feet per mile (38 meters per kilometer) are common in the upper reaches of the watersheds where the streams cross the Tertiary-age sequence. The average annual runoff from individual streams within the study area varies from less than 100-acre feet (123,300 m^3) per year to more than 2300-acre feet (2,837,062 m^3) per year. Significant intra-year (seasonal) fluctuations in streamflow exist.

Year-to-year fluctuations in streamflow occur due to long-term weather cycles. One stream in the study area, San Jose Creek, has a near-continuous 76-year record of daily, monthly, and annual streamflow (Figure 6 and Table I), which indicates that wet year runoff is nearly 200 times greater than dry year runoff.

FIGURE 6

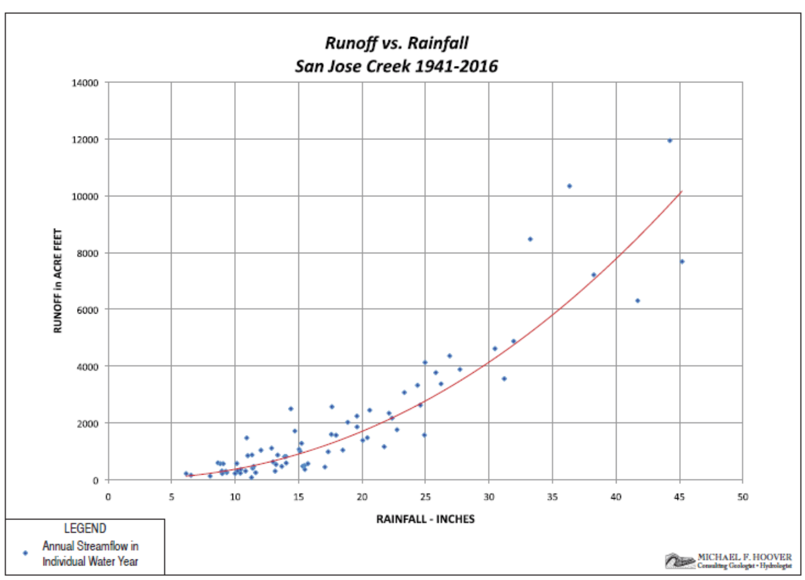


TABLE I

All Values in Acre Feet

SAN JOSE CREEK NEAR GOLETA, CA ESIMATED UNIMPAIRED RUNOFF: 1941 THROUGH 2016
(historic streamflow measurements with small adjustments for upstream diversions)

WtrY	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Totals
1941	4	4	381	1164	1872	2249	1477	165	82	51	35	29	7513
1942	24	27	229	84	31	45	247	48	16	12	10	11	783
1943	14	19	23	1806	361	556	97	45	19	18	15	13	2988
1944	15	14	63	26	520	319	48	41	19	16	14	13	1109
1945	14	222	29	31	410	111	41	25	11	11	10	9	924
1946	10	12	216	13	27	176	40	25	8	8	8	7	548
1947	7	307	222	10	6	23	11	8	6	6	5	5	614
1948	5	4	4	4	4	20	12	3	3	3	2	2	67
1949	2	2	14	10	5	174	7	66	6	1	1	1	290
1950	1	12	43	54	114	25	16	4	2	1	1	1	274
1951	1	5	9	16	10	12	4	8	0	0	0	0	66
1952	0	0	98	2189	61	920	147	56	22	10	26	17	3547
1953	19	74	243	154	19	31	30	26	12	2	3	6	620
1954	2	24	22	146	76	97	47	36	5	2	1	1	458
1955	1	18	54	118	45	39	62	77	12	2	1	1	429
1956	1	11	724	943	131	50	156	172	22	10	6	4	2227
1957	2	3	7	159	267	90	138	101	14	5	1	1	787
1958	5	14	321	229	1225	1163	1726	86	26	23	13	8	4839
1959	8	10	12	108	268	26	16	14	12	6	3	4	485
1960	3	4	9	60	71	34	57	15	3	2	2	2	263
1961	1	82	27	41	14	13	8	4	6	5	4	0	205
1962	2	23	59	35	2964	186	40	21	18	9	6	4	3366
1963	13	11	11	21	254	87	76	37	30	10	7	7	565
1964	10	71	22	54	20	33	66	12	9	6	1	1	306
1965	7	30	219	82	16	42	583	27	19	9	6	6	1046
1966	4	1261	839	195	80	35	23	17	9	6	6	4	2478
1967	8	82	1442	1413	184	231	528	107	34	15	22	18	4084
1968	14	48	42	27	29	124	82	15	8	5	3	4	401
1969	9	16	24	2002	1492	480	307	88	71	25	21	20	4554
1970	13	36	32	98	245	438	21	11	12	8	4	3	921
1971	6	120	152	60	32	34	22	30	20	8	4	4	492
1972	8	16	374	49	24	17	10	10	7	2	3	3	523
1973	8	190	17	645	1318	614	86	84	36	18	9	9	3034
1974	5	28	50	455	34	192	62	21	25	16	10	8	906
1975	11	16	326	23	691	710	65	38	19	16	6	5	1926
1976	6	9	16	10	239	102	22	21	6	3	3	27	463
1977	33	24	13	130	14	26	10	73	8	3	1	1	338
1978	1	1	144	1504	1565	2291	453	124	53	29	40	75	6280
1979	51	57	56	116	226	397	96	37	29	19	9	6	1097
1980	12	15	39	200	1645	409	49	44	27	16	12	9	2476
1981	10	7	24	86	63	551	71	22	9	7	6	6	861
1982	7	20	26	105	35	237	364	38	12	9	6	6	865
1983	5	340	473	1880	1240	1794	810	302	100	60	51	40	7095
1984	394	148	579	107	50	48	26	20	13	16	15	12	1429
1985	14	32	222	25	133	69	30	13	9	7	7	6	566
1986	6	42	39	46	1136	705	93	56	25	16	10	13	2187
1987	10	20	24	35	27	144	14	16	13	5	5	4	316
1988	8	21	43	81	91	43	42	17	5	5	5	4	365
1989	4	5	26	22	76	25	5	3	2	2	2	2	176
1990	2	2	2	14	43	6	2	1	1	1	1	1	76
1991	1	1	1	1	13	1475	33	3	2	2	1	1	1534
1992	1	1	94	246	1115	215	70	17	5	7	3	3	1778
1993	4	3	51	1295	1522	1011	206	59	36	25	16	9	4237
1994	11	14	34	24	292	81	26	21	10	10	9	8	540
1995	8	12	12	3791	286	3674	356	138	62	40	28	21	8427
1996	26	40	71	128	717	322	55	44	34	15	13	12	1476
1997	72	123	422	642	16	19	33	16	12	14	11	9	1389
1998	8	59	206	1096	7018	1306	769	857	254	220	89	56	11939
1999	24	25	53	57	281	290	35	29	21	15	10	10	852
2000	9	18	15	39	798	431	301	73	34	21	14	12	1764
2001	34	23	26	422	500	2403	186	70	44	29	19	17	3773
2002	20	53	60	49	34	29	26	14	8	7	6	6	312
2003	9	142	478	40	82	478	114	149	32	15	27	9	1575
2004	13	19	35	27	397	38	18	8	7	5	4	4	576
2005	161	20	1449	6080	1498	654	173	153	62	40	27	21	10339
2006	30	33	47	361	128	258	1117	92	43	26	19	17	2172
2007	17	14	17	31	50	30	20	10	9	8	7	7	220
2008	7	8	111	1702	257	87	36	23	12	10	9	8	2271
2009	11	22	56	27	182	29	23	8	20	13	11	6	408
2010	199	10	114	505	350	95	102	47	25	18	8	7	1481
2011	17	18	1083	153	236	2094	150	51	36	24	14	13	3887
2012	11	21	22	26	16	55	71	17	9	4	1	1	253
2013	1	11	64	70	34	20	10	6	4	3	1	1	223
2014	1	2	7	6	34	58	6	7	3	3	2	2	132
2015	1	1	155	29	20	15	4	3	3	3	1	0	235
2016	0	0	0	64	18	132	5	2	1	0	0	0	221
Avg.	20	56	168	445	466	415	163	56	23	15	10	9	1845

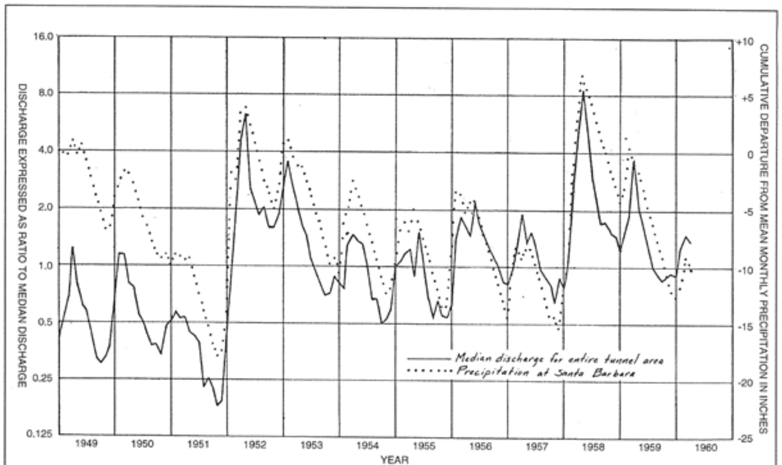
Time = 20:37:23; Date = 19 Sep 2017

Groundwater

Groundwater typically occurs in the form of flow along bedding planes and through fractures (i.e. secondary permeability), although some sandstone units were reported to have primary permeability when encountered during the constructions of the Tecolote Tunnel (US Bureau of Reclamation, undated). Where primary permeability occurs, the magnitude of the permeability is a function grain size, particle sorting, and the degree of cementation among the clasts. Secondary permeability is derived from discontinuities within the rock mass associated with forces applied to the rock after consolidation. These discontinuities may be in the form of faults, bedding planes, fractures, or joints. Each of these features can represent a pathway through which water can pass through the rock. Secondary permeability can be present in any type of rock mass which has undergone brittle deformation. (Crenshaw, 2013).

Aquifer tests indicate that the transmissivities of the fractured rock in the study area vary from a few gallons per day per foot (<1 m^3/day) to several thousand gallons per day per foot (7.57 m^3/day). Storativity values of the fractured rock aquifers range from 10^{-2} to 10^{-5}. We know from water chemistry data that connate water is a minimal contributor to the recharge of consolidated rock aquifers. Aquifer recharge is a direct function of rainfall, as indicated by the relationship between outflow from the Tecolote Tunnel and precipitation as shown on Figure 7 (Rantz, 1960). Rantz also compared the flow of 125 springs within the study area to precipitation with similar results.

FIGURE 7



RELATIONSHIP BETWEEN PRECIPITATION PATTERN AND AVERAGE PATTERN OF DISCHARGE
Tecolote Tunnel 1949-1960
(from Rantz, 1960)

Previous Work

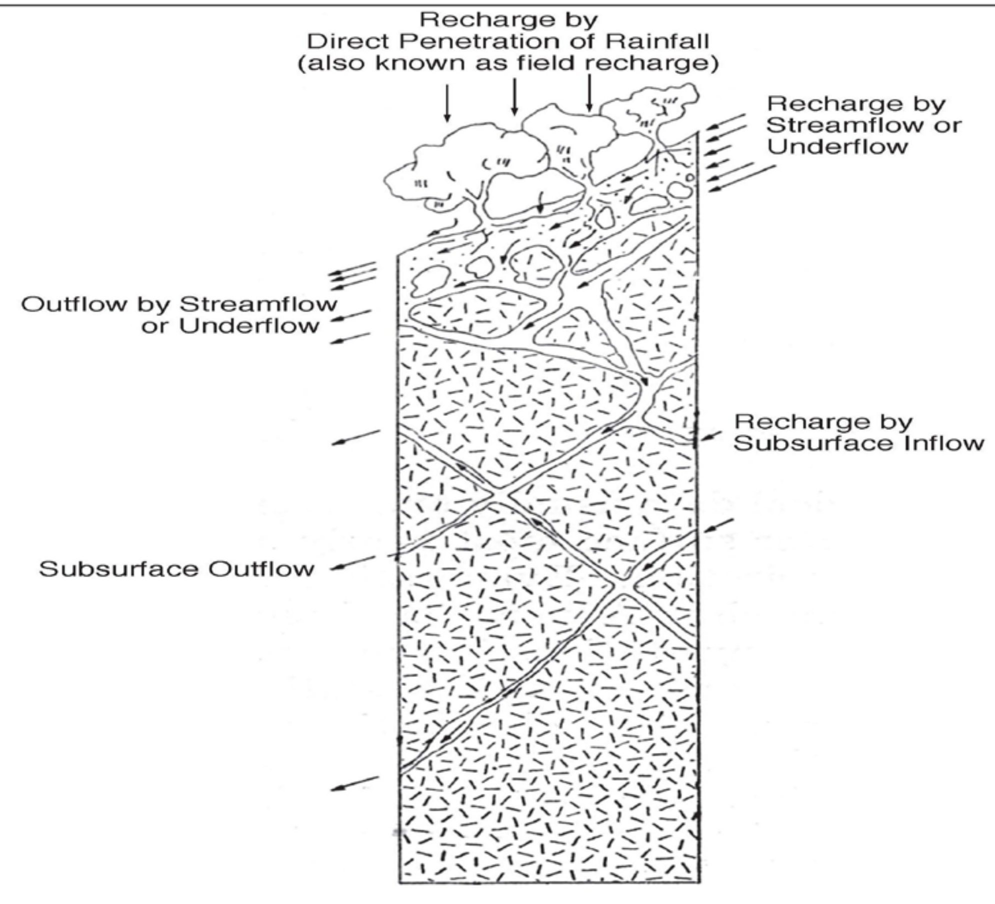
While the geology and hydrology of the study area have been adequately described by several authors (Upson, 1951; Dibblee, 1966; Miller & Rapp, 1968; the Dibblee Foundation, 1987, 1988; Geotechnical Consultants, 1976; Evanson, Wilson & Muir, 1962; Martin and Barenbrock, 1986; Freckleton, 1987; Minor, et al, 2009; and Hoover, 1980), only two references discuss the hydrogeologic properties and perennial yield of the fractured consolidated rocks. Miller & Rapp (1968) provide an estimate of the average annual recharge to the entire Tertiary-age sequence of fractured consolidated rocks in the Ellwood to Gaviota portion of the study area that is based on measurements of low flow discharges (baseflow). Santa Barbara County (1992) provides a theoretical method of determining the perennial yield of fractured consolidated rock aquifers based on estimates of streamflow infiltration and field recharge. Utilizing new information, we now know that past methods used to estimate the perennial yield of the fractured consolidated rock aquifers commonly result in an unacceptably large degree of error.

AQUIFER RECHARGE

Components of Recharge

The fractured consolidated rock aquifers located in the study area are recharged by the following components: (1) direct penetration of rainfall into the sub-aerial portion of the aquifer; (2) percolation of streamflow into the sub-aqueous portion of the aquifer, and (3) sub-surface inflow from upgradient fractured consolidated rock aquifers. These three recharge components are illustrated on Figure 8.

FIGURE 8



COMPONENTS OF
RECHARGE (AND DISCHARGE) TO
FRACTURED CONSOLIDATED ROCK AQUIFERS
(modified from Crippen, 1965)

Calculation of Streamflow

The percolation of streamflow is a significant component of recharge into the fractured, consolidated rock aquifers (including stream-fed underflow percolating into the consolidated rock aquifer occurs if a sufficient thickness of alluvium exists). In order to calculate the magnitude of stream recharge, it is first necessary to determine the magnitude and temporal occurrence of streamflow. In this study area, gauged streamflow data are available in only a few watersheds, thus rainfall and runoff in the watershed of interest must be estimated by alternative methods.

One method is to determine annual rainfall in the subject watershed by measuring the size of the watershed in question, then calculating the weighted average rainfall, taking into consideration orographic effects. The isohyets presented on Figure 2 are useful in this regard. An example of this method is in the highlighted columns on Figure 9, the method for which is taken from Crippen (1965). Once the average annual rainfall is determined, streamflow can be determined by the following: Natural Water Loss = (precipitation + subsurface inflow + net change in soil moisture + net change in groundwater storage) – (surface outflow + subsurface outflow). Simplifying this equation yields the following: Recoverable water = Precipitation – Natural Water Loss – Change in Soil Moisture. In this context, recoverable water is runoff. If Precipitation (P) is known, Evapotranspiration (E) and Recoverable Water (R) can be determined by using the nomographs developed by Crippen (Figures 10 and 11). Adjusting the value for recoverable water with geologic factors K*R, yields a value in inches of water, that when multiplied by the watershed area results in a fairly accurate estimate of average annual streamflow. For example, the estimated average annual streamflow for San Jose Creek developed using methods developed by Crippen yields an estimated value of 1,730 acre feet per year (283,720 m^3/year), whereas the USGS gauge data (Table I) yield a measured value of 1,845 acre feet per year (302,580 m^3/year). The difference between the gauged data and the Crippen method of estimating runoff is less than 6.3 percent.

FIGURE 9

SAN JOSE CREEK WATERSHED RECOVERABLE WATER WORKSHEET

(FOLLOWS PROCEDURE DEVELOPED IN USGS PROFESSIONAL PAPER 417-E)

Altitude Range (ft, MSL)	WtrshdArea (Acres)	Area % of Wtrshd	Rainfall (P) (in inches)	Potential ET (E, in.)	Ratios P/E	Ratios R/E	Recovrable Water (R)	Adjusted R (= K*R)	Watershed Loss (L)
2500 - 3000	510	14.5%	30.00	54.00	0.56	0.103	5.54	7.81	22.19
2000 - 2500	1020	28.9%	29.00	55.50	0.52	0.085	4.74	6.69	22.31
1600 - 2000	637	18.1%	28.00	56.00	0.50	0.075	4.18	5.90	22.10
1200 - 1600	361	10.2%	27.00	56.00	0.48	0.067	3.73	5.27	21.73
800 - 1200	297	8.4%	25.50	55.20	0.46	0.058	3.22	4.54	20.96
400 - 800	404	11.5%	24.00	53.50	0.45	0.053	2.84	4.01	19.99
150 - 400	297	8.4%	22.00	51.00	0.43	0.047	2.39	3.38	18.62
TOTALS	3526	100.0%							
Weighted Avgs.			27.30	54.79			4.11	5.80	21.51

ADJ. RECOVERABLE WATER	=	5.80 Inches watershed weighted mean runoff depth.
WATERSHED AREA	=	3526 Acres.
WATERSHED RUNOFF EST. @		1703 Acre Feet / Year.
Lookup table K factor	=	1.411
The TOTAL GEO INDEX K value (see Figure 10 on page E21 of 417-E)...........	=	1.411 Used to calculate adjusted recoverable water.

GEOLOGIC INDEX: (see USGS Prof. Paper 417-E, pp E20 and E21)

Category	% of wtrshd	Index
A. Quaternary, except old alluvium..........(X 1	7%	70
B. Old alluvium...................................(X 10	0%	0
C. Tertiary, except Potato Sandstone.......(X 0	88%	0
D. Potato Sandstone of F.E.Vaughan...(X 100	5%	500
E. Mesozoic..(X 1(	0%	0
F. Paleozoic..(X 2(	0%	0
G. Precambrian.....................................(X 4(	0%	0
	100%	
TOTAL GEO INDEX =		570

LOOKUP TABLE

Geo Index	K Factor
0	1.60
200	1.60
400	1.53
600	1.39
800	1.25
1000	1.11
1200	0.97
1400	0.83
1600	0.71
1800	0.62
2000	0.56
2200	0.52
2400	0.49
2600	0.46
2800	0.43
3000	0.40
3200	0.37

FIGURE 10

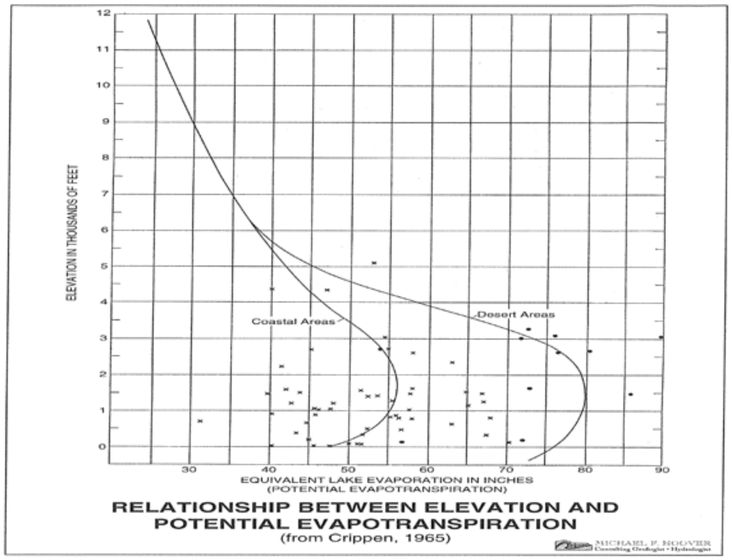
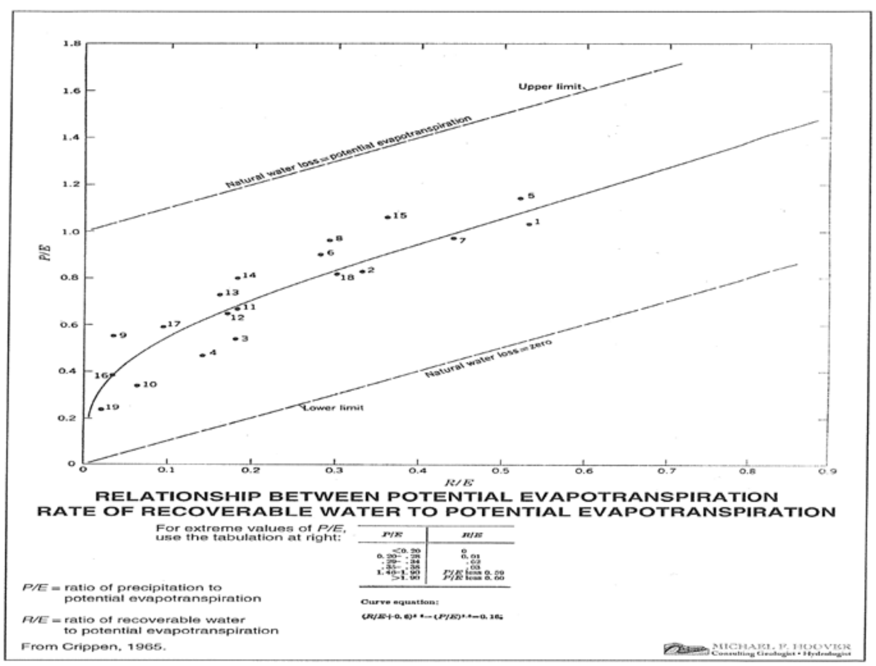


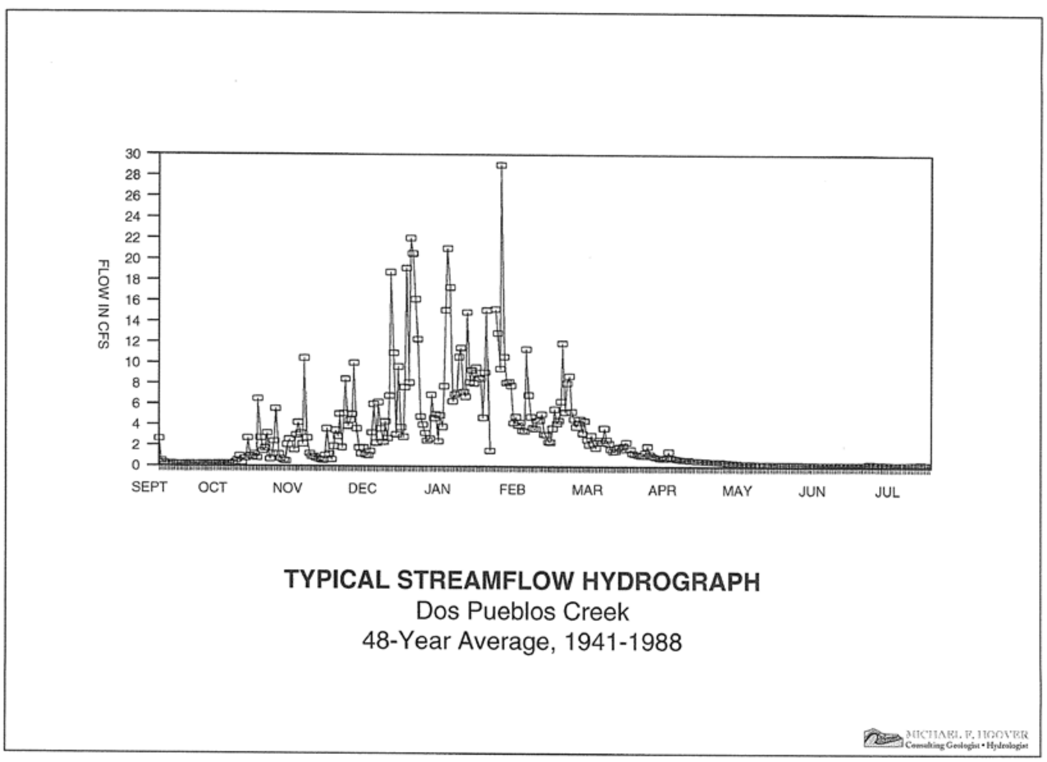
FIGURE 11



Other Applications of Streamflow Modeling

Daily streamflow modeling of any ungauged stream in the study area can be accomplished using the Crippen method to develop annual streamflow of the ungauged stream, then ratioed to San Jose Creek daily streamflow. Using this methodology, diversion to off-stream storage in any watershed within the study area can be estimated. These same methods are useful in developing daily streamflow values in ungauged watersheds being evaluated for the reintroduction of anadromous fish protected by the Endangered Species Act of 1973. In this regard, biologists are increasingly interested in the temporal occurrence of large flows that allow fish passage from the ocean to the spawning grounds, and the ability of a watershed to sustain juvenile fish during times of low flow. Such a study was completed for Dos Pueblos Creek (Hoover, 2016; Figure 12).

FIGURE 12



TYPICAL STREAMFLOW HYDROGRAPH
Dos Pueblos Creek
48-Year Average, 1941-1988

It is important to note that the Crippen method for determining streamflow assumes that there is no upstream pumping or stream diversions (i.e. a “virgin watershed”). If upstream diversions or pumping are occurring, then downward adjustments to the calculated streamflow must be made (Figures 13, 20).

FIGURE 13

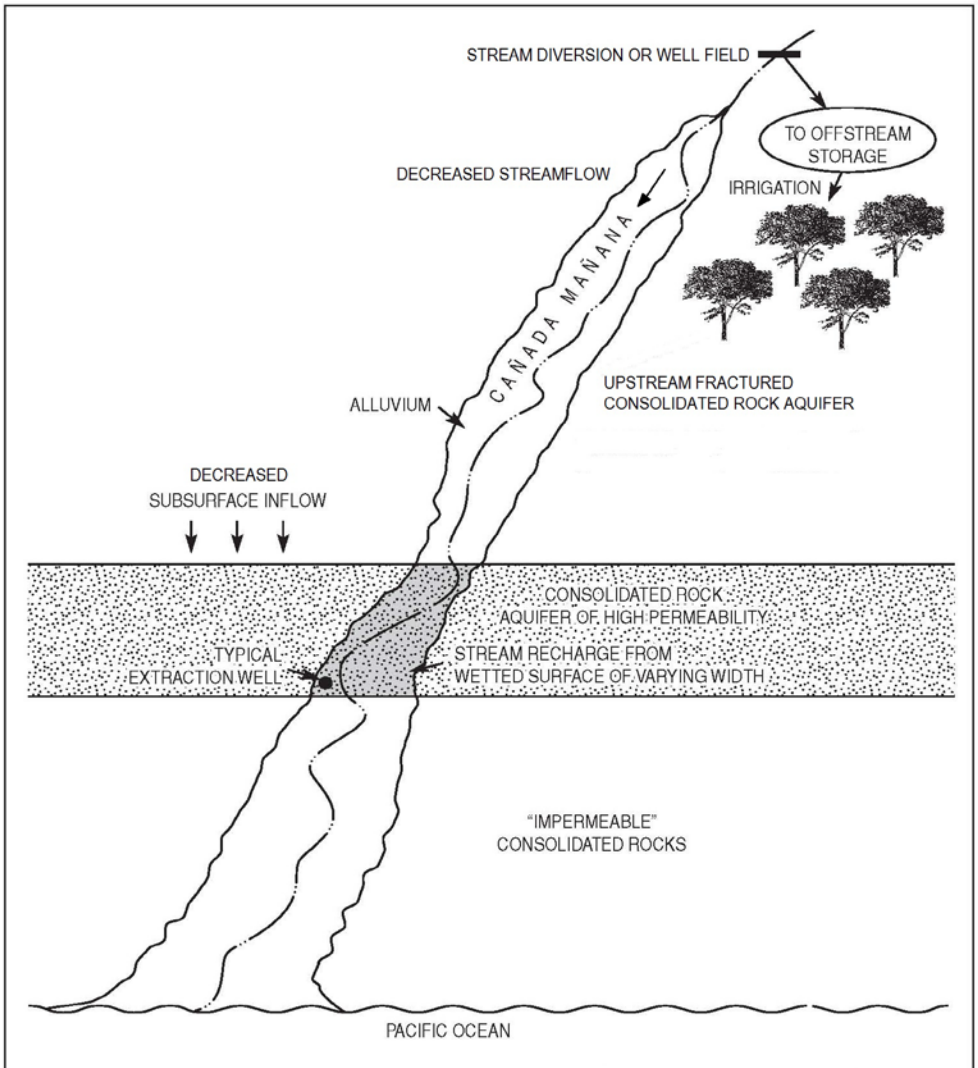


DIAGRAM SHOWING RELATIONSHIP OF UPSTREAM DIVERSION OR WELL FIELD TO DOWNSTREAM AQUIFER

Infiltration of Streamflow

It is relatively straightforward to calculate stream recharge to an underlying aquifer if the daily streamflow, the wetted area of the stream bottom, and the aquifer permeability are known, keeping in mind that the calculated rate of streambed infiltration cannot not exceed permeability of the aquifer (Figure 14).

Previous studies (Santa Barbara County, 1992) utilized a single seepage factor for stream bed permeability in the entire study area. The data from 25 fractured consolidated rock aquifers in the study area indicate that aquifer permeabilities average approximately 9.5 gpd/ft^2 (.0559 liters per day/m^2), close to the average used by other studies, data developed within the study area indicate that aquifer permeabilities range from less than 1 gpd/ft^2 (.0929 liter per day/m^2) to over 50 gpd/ft^2 (4.6 liters per day/m^2), thus site-specific streambed permeability values are preferred in order to obtain accurate stream seepage values.

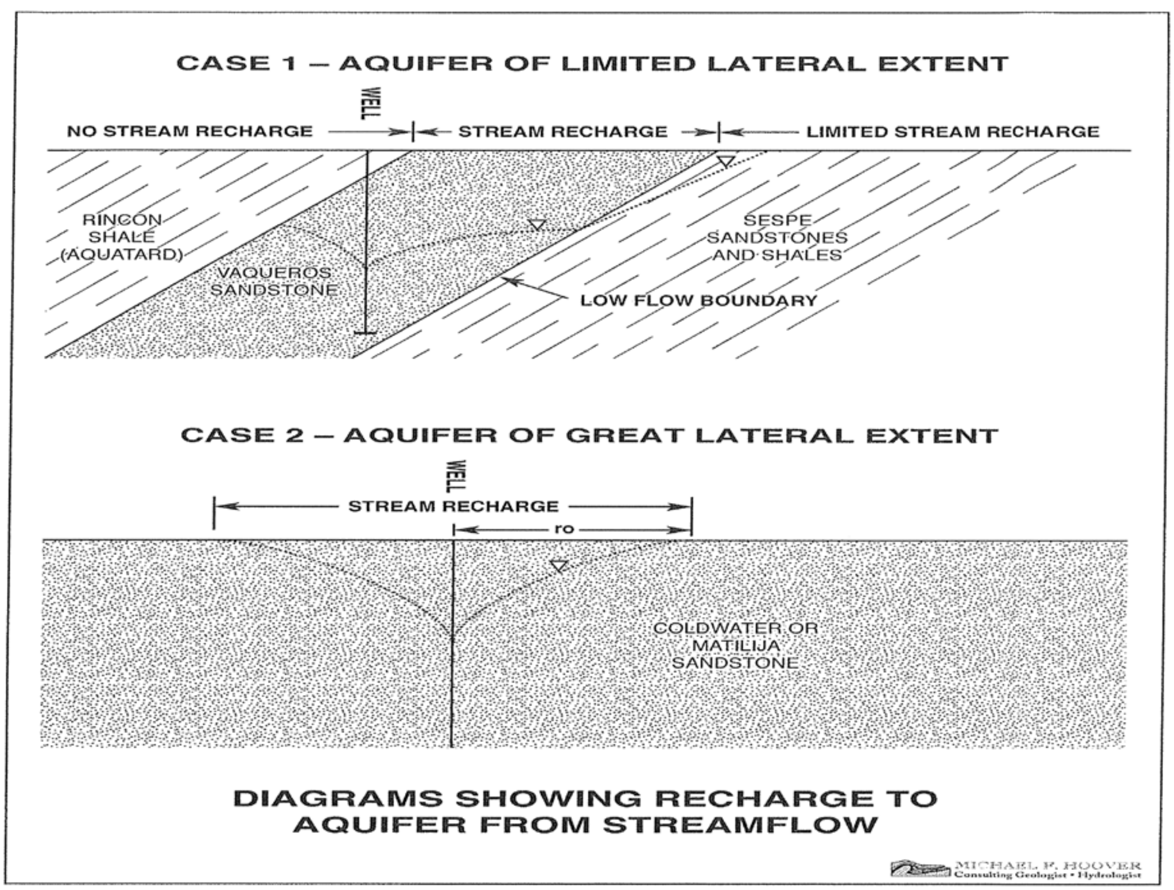
FIGURE 14
Typical Values for Transmissivity and Permeability in Selected Aquifers

Watershed	Transmissivity (gpd/ft^2)	Formation/Aquifer Thickness (feet)	Average Permeability (gpd/ft^2)
Hondo	120	Vaqueros/570	0.21
Venadito	3300 320 7500 733	Vaqueros/294 Vaqueros/550 Vaqueros/294 Vaqueros/542	11 0.58 25 1.35
El Capitan	2000 800	Vaqueros/522 Vaqueros/410	3.83 1.95
Distiladera	1000 660	Vaqueros/570 Vaqueros/570	1.98 0.86
Llagas	1500 1500	Vaqueros/570 Vaqueros/570	4.53 3.51
Gato	235	Vaqueros/271	0.86
San Ysidro	4400	Coldwater/230	19
Dos Pueblos	520	Vaqueros/764	0.68
Ellwood	3400 16,000 10,000	Vaqueros/244 Vaqueros/295 Vaqueros/427	13.9 54.2 23.4 0.98
Hot Springs	330 516	Coldwater/335 Coldwater/460	1.12
Los Carneros	795 320 2031 1659 2165 3120	Coldwater/470 Coldwater/1450 Vaqueros/413 Vaqueros/236 Vaqueros/460 Vaqueros/428	1.69 0.22 4.9 7.03 4.70 7.28
Canada Guillermo	170	Vaqueros/580	0.29
Cold Springs	183	Coldwater/343	0.53
San Jose	6000	Coldwater/149	40.3
Average Aquifer Permeability			9.5 gpd/ft^2

Rejected recharge may occur if the piezometric surface of the (leaky artesian) consolidated rock aquifer is above the streambed. Using formulas developed by Theis (1952), the area of the consolidated rock aquifer where the piezometric surface has been depressed by pumping can be calculated.

If a production well is drilled into a specific (and hydrologically discrete) aquifer, such as the Vaqueros Sandstone, then the portion of the stream that crosses that aquifer, <u>and which has been dewatered by pumping</u>, is the area likely to be recharged by streamflow. This dewatered area is typically asymmetric due to boundary conditions (Figure 15).

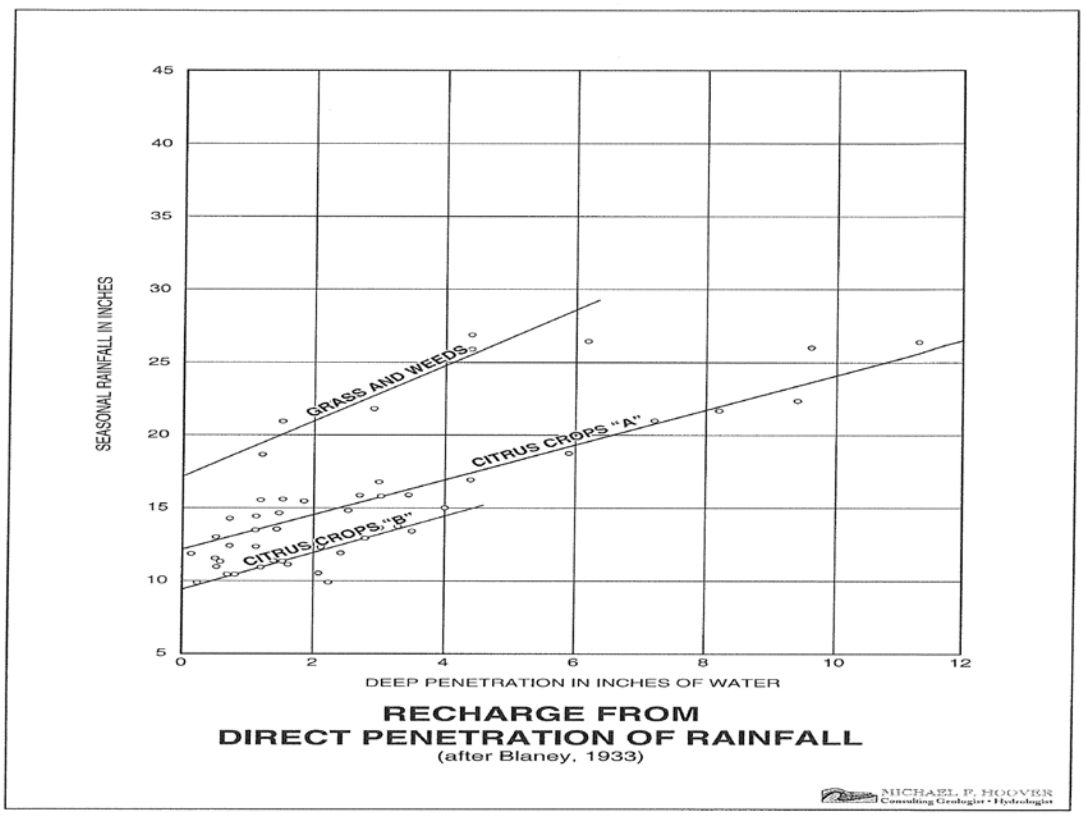
<u>FIGURE 15</u>



Recharge from Direct Penetration of Rainfall

Direct recharge to the sub-aerial portion of the aquifer from rainfall, also known as *field recharge*, is another source of aquifer replenishment. Blaney (1933) studied what he called "deep penetration of rain" in Ventura County, California, not far from the study area, in fields that included irrigated citrus and unirrigated grass and weeds. Blaney developed infiltration curves for each land use (Figure 16). Note that Blaney's infiltration curves do not go through the origin because no recharge occurs when annual rainfall is less than 10 or 12 inches (25.4 to 30.5 cm) on irrigated land, and less than 17 inches (43.2 cm) on grassland, brush, or weeds.

FIGURE 16



RECHARGE FROM
DIRECT PENETRATION OF RAINFALL
(after Blaney, 1933)

The utilization of the Blaney curves to calculate field recharge is quite simple: Only the delineation of the sub-aerial extent of the aquifer within the subject basin (or watershed), a calculation of the annual rainfall at the point of recharge, and knowledge of the type of vegetation is required. Whereas field recharge can be approximated utilizing a single calculation and the average annual rainfall, calculating recharge for each individual year over a period of representative rainfall is preferred, because the very wet years will result in recharge values that more than offset the dry years. The use of average rainfall in the application of the Blaney recharge curves will result in artificially low field recharge values (Figure 17). (Note that a degree of complexity (and accuracy) is added to Figure 17 by including soil moisture in the analysis of field recharge.)

FIGURE 17

EXAMPLE OF FIELD RECHARGE UTILIZING "BLANEY CURVES"

(all values in inches)

VENADITO CANYON UPPER Tvq NATIVE VEG SOIL MOISTURE BALANCE (file is VenTvqNU)

(Oct-Sep WtrYr vals shown; soil cap 21.00 in.; watershed ET max= 23.73 in.)

Water	Wtrsh Avg	Net*	Total Irrig	Beginning	Available	Total Evpo	Ending	Deep
1941	58.84	47.79	0.00	5.73	47.79	22.27	7.48	**23.77**
1942	16.72	15.57	0.00	7.48	15.57	20.22	2.83	0.00
1943	31.65	27.26	0.00	2.83	27.26	20.77	6.27	**3.06**
1944	23.34	21.71	0.00	6.27	21.71	22.36	5.62	0.00
1945	19.88	18.52	0.00	5.62	18.52	20.79	3.36	0.00
1946	14.73	13.93	0.00	3.36	13.93	15.06	2.22	0.00
1947	17.44	16.54	0.00	2.22	16.54	16.24	2.52	0.00
1948	11.96	11.87	0.00	2.52	11.87	12.08	2.30	0.00
1949	14.24	13.81	0.00	2.30	13.81	13.81	2.30	0.00
1950	18.73	18.32	0.00	2.30	18.32	17.14	3.49	0.00
1951	13.08	12.98	0.00	3.49	12.98	14.32	2.16	0.00
1952	40.64	35.42	0.00	2.16	35.42	20.60	7.47	**9.51**
1953	17.39	16.47	0.00	7.47	16.47	20.86	3.08	0.00
1954	20.09	19.42	0.00	3.08	19.42	19.05	3.45	0.00
1955	21.99	21.36	0.00	3.45	21.36	20.61	4.20	0.00
1956	25.79	22.51	0.00	4.20	22.51	21.22	5.49	0.00
1957	18.80	17.65	0.00	5.49	17.65	19.76	3.38	0.00
1958	41.88	34.77	0.00	3.38	34.77	21.21	8.50	**8.44**
1959	11.44	10.73	0.00	8.50	10.73	17.00	2.23	0.00
1960	14.06	13.67	0.00	2.23	13.67	13.67	2.23	0.00
1961	13.06	12.75	0.00	2.23	12.75	12.98	2.01	0.00
1962	33.98	29.03	0.00	2.01	29.03	20.81	4.38	**5.85**
1963	19.88	19.05	0.00	4.38	19.05	18.84	4.59	0.00
1964	10.03	9.58	0.00	4.59	9.58	12.33	1.84	0.00
1965	23.77	22.23	0.00	1.84	22.23	19.95	4.12	0.00
1966	18.28	14.64	0.00	4.12	14.64	16.38	2.37	0.00
1967	30.42	24.41	0.00	2.37	24.41	20.92	5.86	0.00
1968	17.44	16.85	0.00	5.86	16.85	19.74	2.98	0.00
1969	38.39	31.69	0.00	2.98	31.69	20.62	4.38	**9.67**
1970	15.38	14.03	0.00	4.38	14.03	16.02	2.38	0.00
1971	18.21	17.48	0.00	2.38	17.48	17.23	2.63	0.00
1972	11.24	10.47	0.00	2.63	10.47	11.23	1.87	0.00
1973	32.11	27.64	0.00	1.87	27.64	20.89	5.02	3.60
1974	22.46	21.12	0.00	5.02	21.12	21.94	4.21	0.00
1975	25.24	22.41	0.00	4.21	22.41	21.37	5.24	0.00
1976	17.58	16.90	0.00	5.24	16.90	14.67	7.47	0.00
1977	14.15	13.65	0.00	7.47	13.65	18.58	2.54	0.00
1978	56.63	47.39	0.00	2.54	47.39	20.24	8.83	**20.87**
1979	27.85	26.24	0.00	8.83	26.24	23.69	6.23	**5.15**
1980	30.86	27.22	0.00	6.23	27.22	22.35	6.98	**4.12**
1981	18.60	17.33	0.00	6.98	17.33	21.01	3.30	0.00
1982	22.86	22.50	0.00	3.30	22.50	19.84	6.06	0.00
Avgs	23.20	20.82	0.00	5.73	20.82	18.51	5.73	**2.31**

* Estimated runoff depth= Total-Net rainfall. 18:04:21 21 Nov 2010

Surface Inflow

Subsurface inflow occurs when groundwater flows from an upgradient aquifer into a downgradient aquifer, induced by gravity and/or the dewatering of the downgradient aquifer by pumping (Figure 18).

FIGURE 18

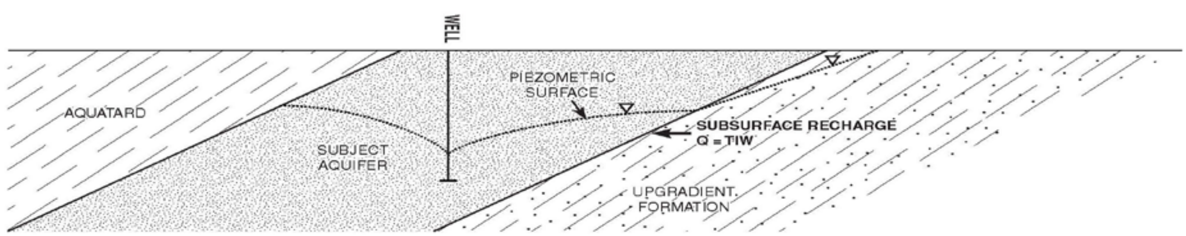


Figure 18-- **AQUIFER RECHARGE FROM SUBSURFACE INFLOW**

In order to quantify subsurface inflow, the gradient (i) and transmissivity (T) of the aquifers should be determined from pumping test data within the same watershed or a nearby watershed. Subsurface inflow can then be calculated utilizing a formula modified from Darcy (1856): Q = Tiw, where T = Transmissivity, Q = flow, w = aquifer width and i equals the hydraulic gradient. In this study area, the gradient, where known, varies from 0.066 to 0.175 feet per foot.

It has been argued that the aquifer transmissivity parallel to the bedding planes is much higher than the aquifer transmissivity across bedding planes, resulting in an anomalously high transmissivity value when using pump test data to evaluate subsurface inflow, since pump test data is typically developed from flow parallel to bedding planes and subsurface inflow typically occurs sub-perpendicular to the dip of the bedding (Figure 18). This is the vertical permeability versus the horizontal permeability problem common in an alluvial aquifer with horizontal bedding. While it may be true that pumping tests overstate aquifer permeability perpendicular to bedding in the fractured sandstones and shales, the fracture zones appear to provide ample groundwater movement independent of the bedding planes. Second, in most watersheds of known safe yield, data presented on Table II indicate that stream recharge and field recharge are insufficient in magnitude to equal the total recharge calculated from long term pumpage-change in storage studies, thus subsurface inflow must be a component of recharge.

DISCHARGE

Discharge from the consolidated rock aquifers occurs by gravity (i.e. baseflow) and by pumping. Subsurface outflow to the ocean is limited in the study area due to the impermeable nature of the mudstone and shale of the Rincon and Sisquoc formations, respectively, which crop out at the southern (or downgradient) portion of the sandstone sequence.

OTHER ISSUES

“Poaching”

The term poaching is used herein to describe the process by which groundwater can be induced to move from one watershed to another due to pumping. We know from field evidence (water level data gathered from well fields in adjacent watersheds and at the watershed divide) that groundwater will migrate, in response to pumping, from one watershed to another, perpendicular to the natural gradient. This phenomenon usually occurs when the pumpage in one watershed is significantly greater than the pumpage in the adjacent watershed. Groundwater flow also occurs between watersheds along northwest or east-west trending zones that are preferential “carriers” of groundwater. This latter phenomena explains the extraordinarily high yields of some wells located in the vicinity of the San Jose, San Pedro, and Carneros fault zones.

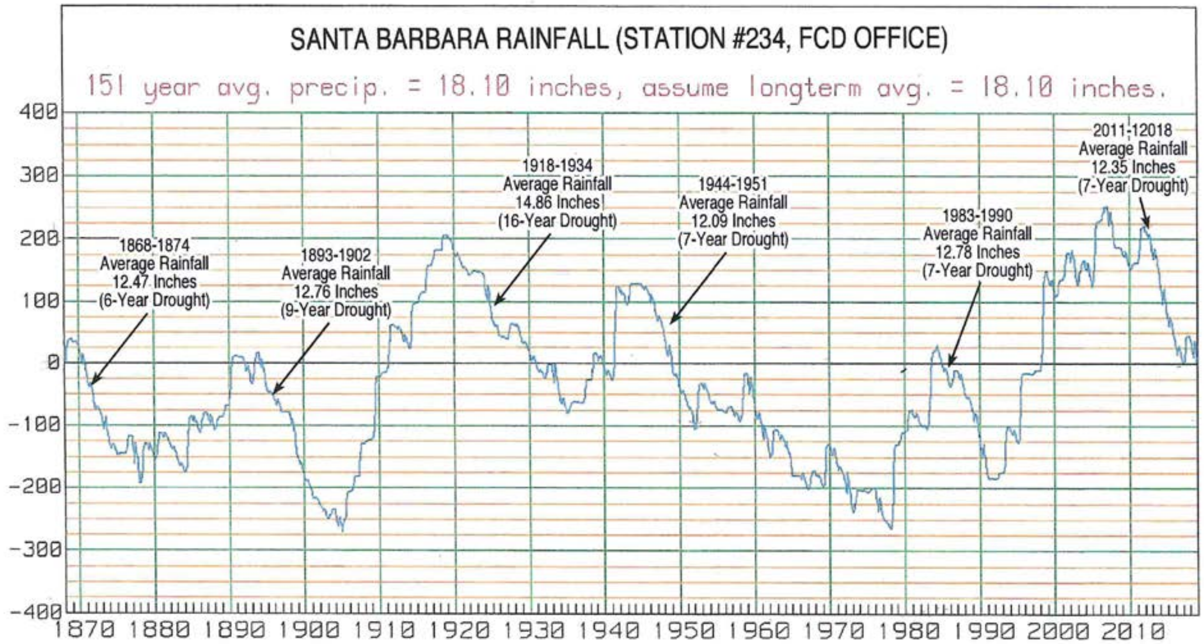
Fault Barriers

Faults may also be barriers to groundwater migration. A case in point appears to be Corral/Las Flores Canyon where the perennial yield of the Vaqueros aquifer (determined by pumpage-change in storage analysis over an 11-year period) is roughly half of the calculated perennial yield determined by the methods described herein (Table II). The best explanation for the disparity between the predicted and actual perennial yield of the southern Vaqueros aquifer in Las Flores Canyon is the presence of an east-west striking fault that acts as a barrier to groundwater migration and subsurface inflow. The fact that the fault is a barrier to groundwater migration is confirmed by differential water levels on the upgradient and downgradient sides of the fault.

Allowance for Drought

In addition to *seasonal* fluctuations in rainfall, significant variation in rainfall occurs from year to year, thus diminished recharge during drought is commonplace in the study area. For example, during the 7-year period from 1944-51 the average rainfall in the study area was only 66 percent of normal. The droughts of 1969-73, 1986-90, and 2012–16, although shorter, were even more severe (Figure 19). Very little runoff (and therefore little streamflow) occurs when rainfall is less than 11 inches per year, approximately 62 percent of the long-term average rainfall (Table I, Figure 6). Likewise, recharge to fractured consolidated rock aquifers by field recharge occurs only three months of the year, and then typically in only in the wettest 20 percent of all years (Figure 17). It is therefore necessary for the investigator to evaluate diminished recharge during drought when evaluating the long-term yield of the aquifer. One method of doing this is to evaluate the recharge that occurs during a 4 or 6-year "design drought", then to determine the amount of water that can be removed from (aquifer) storage during that 4 to 6-year period of recharge shortfall. To accomplish the latter task, the investigator first needs to calculate drought recharge from direct penetration of rainfall (usually zero), streamflow, and subsurface inflow utilizing methods described above. Then, calculate the groundwater in storage that must be removed to balance the lost recharge, keeping in mind that the specific yield of the consolidated rock aquifers is likely between 1 percent and 5 percent of the rock mass (Miller & Rapp, 1960), and that no more than 2/3 of the total groundwater in storage can be harvested, probably less.

FIGURE 19

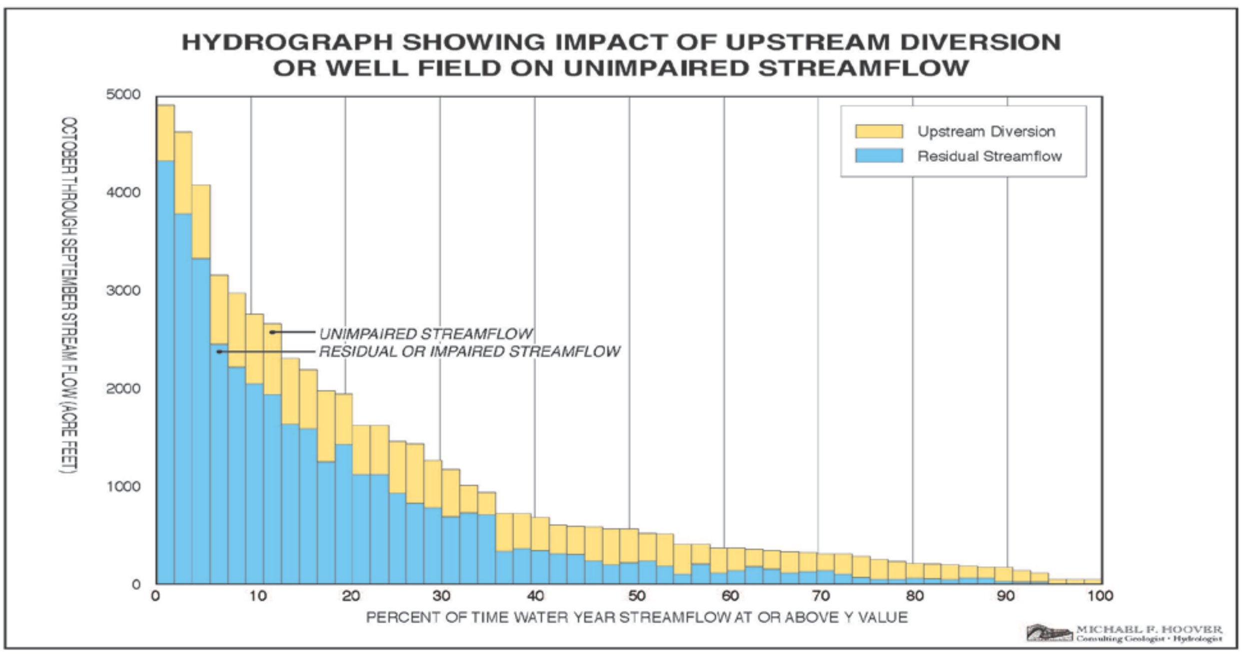


DEVIATION FROM MEAN IN %: TIME SCALE = SEPTEMBER-AUGUST WATER YEARS
SHOWING PRIMARY DROUGHT CYCLES

The Impact of Upstream Diversions

Many of the well fields in the study area are located downgradient from surface water diversions or well fields. The impact of the upstream diversion on aquifer recharge can be determined utilizing the Ahlroth model, which is based on Crippen (1965), as modified by San Jose Creek daily data and site specific diversions (Figure 20).

FIGURE 20



Enhanced Recharge

Enhanced recharge to an aquifer may occur if the natural vegetation is removed and replaced with irrigated crops. Adjustments for this enhanced recharge can be made using the methods of Blaney (1933), Crippen (1965), or Zhang (2001) to calculate field recharge.

COMPONENTS OF RECHARGE

Utilizing methods described above, the magnitude of the components of recharge for each of the aquifers in the six watersheds has been calculated. On average, stream seepage represents 12 percent of total recharge; field recharge represents 38 percent of total recharge; and subsurface inflow represents 50 percent of total recharge (Table II).

TABLE II
CALCULATED COMPONENTS OF RECHARGE IN SELECTED WATERSHEDS IN SANTA BARBARA COUNTY

Watershed	Annual Rainfall at Aquifer (inches)	Average Annual Rainfall in Watershed Above Outcrop (AFY)	Average Annual Streamflow (AFY)	Infiltration Rate (based on Site-Specific Consolidated Rock permeability)	Stream Seepage based on Aquifer Permeability (AFY)	Area of Outcrop (acres)	Field Recharge (AFY)	Calculated Subsurface Inflow(1)	Total Annual Recharge-Modified Inventory Method (Field Recharge + Stream Seepage & Subsurface Inflow)	Estimated Perennial Yield-Pumpage Change in Storage Method (Year of Test)	Comments
Gato/Las Varas Canyons (Northern and Southern Vaqueros Sandstone)	20”	2758 + 4812 = 7570	1020 + 300 = 1320	0.86 gpd/ft^2	11	531	110	50 AFY	171	150 AFY (1994-2004)	Wet cycle
El Capitan/Destilatera/ Llagas Canyons (Northern and Southern Vaqueros Aquifers)	20”	8159 + 2920 + 844 = 11,924	2068 + 26 + 234 = 2328	2.77 gpd/ft^2	16	196	70	235 AFY	321	450 AFY (1980-2010)	Multiple wet and dry cycles
Carneros Canyon (Northern and Southern VaquerosAquifers)	21”	3958	520	4.3 gpd/ft^2	20	46 + 86 = 132	17 + 24 = 41	40 AFY + 40 AFY = 80 AFY	141	200 AFY (1982-93)	Wet and dry cycles
Venedito Canyon (Northern and Southern Vaqueros Aquifers)	22”	1514	247	9.48 gpd/ft^2	38	140	50	73 AFY	161	143 AFY (1993-2004)	Wet cycle
Tajiguas /Leon Canyon (Sacate, and Vaqueros Aquifers)	20”/27.5”	6280	1276	5.5 gpd/ ft^2	51 (2)	1945	364	329	744	600 AFY (2010-2017)	Dry cycle Loss of storage
Las Flores Canyon (Northern and Southern Vaqueros Aquifers)	20”	9349	1826	9.48 (4) gpd/ft^2	86	265	36	134 (3)	267 (3)	139 AFY	Wet and dry cycles

(1) Subsurface inflow based on Formula Q = Tiw
(2) Stream seepage adjusted from Ahlroth model based on site specific permeability
(3) Calculated Annual Recharge likely impacted by impaired subsurface recharge due to east-west trending fault
(4) Estimate based on nearby Venadito Canyon

COMPARISON OF METHODS FOR CALCULATING AQUIFER RECHARGE

General

Long-term water level and pumpage data have been developed for several watersheds within the study area. These long-term aquifer tests provide the most accurate estimates of long-term recharge to the aquifers, but unfortunately data limitations may make the pumpage-change in storage method of analysis impractical at other sites, requiring the use of alternative methods of analysis.

Miller and Rapp (1965) suggest that approximately 6 percent of the rainfall could be available to recharge aquifers in the study area. While this method may be correct when used for the entire Ellwood-Gaviota area, it overestimates the long-term recharge in some watersheds, and underestimates recharge in others, resulting in significant error (Table III). Rejected recharge may also account for some of the error. In short, Miller and Rapp (1965) never intended their study to be utilized as a basis for estimating the perennial yield in individual watersheds or aquifers, and it should not be used in this manner.

Another method of estimating the long-term recharge to the consolidated rock aquifers is presented in the County Thresholds Manual (Santa Barbara County, 1992). The County Thresholds Manual commonly underestimates perennial yield, because it ignores subsurface inflow, but may also, on occasion, overestimate perennial yield, since the County methodology does not require the development of site-specific aquifer data.

A method of estimating perennial yield (in lieu of pumpage-change in storage data) that provides the most accurate values is provided herein. The only watershed where significant error occurs is Corral/Las Flores Canyon, where special geologic conditions exist that inhibit surface inflow. Adjusting for the special geologic conditions in Corral/Las Flores Canyon results in an acceptable level of error; approximately ±22 percent of the known value.

Comparing the calculated average annual recharge determined using methods described herein results in an estimate of annual average yield of 1797 AFY for all six watersheds, compared to the measured perennial yield using the pumping-change in storage method (1683 AFY), a difference of 6.8 percent.

TABLE III
COMPARISON OF PERENNIAL YIELD IN SELECTED WATERSHEDS USING VARIOUS METHODS OF ANALYSIS

WATERSHED	SANTA BARBARA COUNTY THRESHOLD MANUAL (AFY)/(ERROR)	MILLER & RAPP (AFY)/(ERROR)	HOOVER METHOD USING CRIPPEN-BLANEY STREAM/FIELD RECHARGE AND SUBSURFACE RECHARGE/(ERROR)	PERENNIAL YIELD PUMPAGE-CHANGE IN STORAGE METHOD
Gato/Las Varas Canyons (Vaqueros Sandstone)	266/(+77%)	360/(+140%)	171/(+15%)	150
El Capitan / Destilatera / Llagas Canyons (Vaqueros Sandstone)	132/(-70%)	275/(-38%)	321/(-28%)	450
Carneros Canyon (Vaqueros Sandstone)	87/(-56%)	91/(-54%)	141/(-30%)	200
Venedito Canyon (Vaqueros Sandstone)	90/(-37%)	35/(-75%)	161/(+13%)	143
Las Flores / Corral (Vaqueros Sandstone)	122/(-12%)	216/(+55%)	256/(+84%)	139
Tajiguas Canyon (All Aquifers)	756/(+26%)	282/(-47%)	744/(+24%)	600
Average Error	46%	68%	33%/22% [(4)]	--

[(1)] Value impacted by upstream diversion.
[(2)] Assumes ½ of the calculated watershed recharge is allocated to Vaqueros Sandstone. Remainder of recharge allocated to upstream aquifer.
[(3)] Value impacted by upstream fault.
[(4)] Average error is presented with and without adjustment for unique geologic conditions in Las Flores/Corral Canyon.

SHORTCOMINGS OF THE STUDY

The studies that are the basis of pumpage-change in storage values (Tables II and III) were commissioned by various entities over timeframes that did not always coincide with the most desirable base period. A base period should consist of a representative period of rainfall that does not begin or end on a particularly wet or dry year. While the pumpage-change in storage values present in this study are as accurate as possible using the available data, new information is always beneficial.

The impact of the 2011-18 drought will likely generate new data with respect to groundwater held in storage in the fractured consolidated rock aquifer. In most cases, it is unlikely that the average annual recharge (or perennial yield) will be available from most aquifers during the latter years of such an extended drought, which gives rise to the question of whether or not the average annual recharge is synonymous with the term perennial yield.

CONCLUSIONS

The most accurate method of determining the perennial yield of an aquifer is a long-term study over a period of representative rainfall during which water levels and aquifer production are monitored. Unfortunately, it is not often feasible to conduct such tests due to time constraints and the vagaries of precipitation. An estimate of the perennial yield of the combined aquifers is available for the study area (Miller and Rapp, 1965), but is inaccurate when applied to aquifers in a specific watershed. Such a result is not surprising since Miller and Rapp never intended their study to be used for such purposes.

With respect to the County Groundwater Thresholds Manual (Santa Barbara County, 1992), the County's dismissal of subsurface inflow as a recharge component typically results in estimates of perennial yield that are less than the value determined by the more accurate pumping–change in storage method. Using the methods described herein, the average error when comparing "known" values of perennial yield to calculated values of perennial yield in the six watersheds studied in detail is 33 percent. The error is lowered to 22 percent when unique geologic conditions that occur at one site are taken into consideration. The error within individual watersheds is -30 percent to +84 percent. Adjusting for unique geologic conditions at the Las Flores site results in a more acceptable error within individual watersheds of +24 percent to -30 percent. Overall accuracy between the theoretical method and the pumpage-change in storage method is within 6.7 percent when values for all watersheds are averaged.

In lieu of long-term pumpage and water level data, an alternative method of determining the perennial yield of fractured consolidated rock aquifers in southern Santa Barbara County has been developed that allows the investigator to estimate aquifer recharge from streamflow, direct rainfall on the aquifer (field recharge), and subsurface inflow. A short aquifer test utilizing at least one well is needed to perform this analysis, as well as topographic and geologic maps. Setting aside sites with atypical geologic or hydrologic conditions, an accuracy of ± 22 percent can be expected.

It can be concluded from inspection of Table IV that the upper threshold of the long-term or perennial yield of a sandstone aquifer in this study area is less than 10 percent of the average annual rainfall within the watershed. In cases where groundwater production from the fractured consolidated rock aquifers within the watershed is greater than 10 percent of the rainfall, such production is likely unsustainable (i.e. “one-shot water”), or is water that is migrating from another watershed due to enhanced gradients (poaching).

While this study is intended to apply to southern Santa Barbara County, the principles should apply to other geographic areas.

TABLE IV

CALCULATED COMPONENTS OF RECHARGE IN SELECTED WATERSHEDS IN SOUTHERN SANTA BARBARA COUNTY

WATERSHED	ANNUAL RAINFALL AT OUTCROP (INCHES)	AVERAGE ANNUAL RAINFALL IN WATERSHED (AFY)[1]	AVERAGE ANNUAL STREAMFLOW (AFY)	INFILTRATION RATE (BASED ON SITE-SPECIFIC AQUIFER PERMEABILITY)	STREAM SEEPAGE BASED ON CONSOLIDATED ROCK AQUIFER PERMEABILITY (AFY)	AREA OF OUTCROP (ACRES)	FIELD RECHARGE – SCS (AFY)	CALCULATED SUBSURFACE INFLOW[6] (AFY)	TOTAL ANNUAL RECHARGE MODIFIED INVENTORY METHOD	ANNUAL RECHARGE (PUMPAGE CHANGE IN STORAGE METHOD/ YEAR)	PERENNIAL YIELD AS PERCENTAGE AND RAINFALL
Gato/Las Varas (Northern and Southern4 Vaqueros Sandstone)	20”	7570	1320	0.86 gpd/ft^2	11	531	110	50	171 AF	150 AF (1994-2004)	2.05%
El Capitan/ Destilatera/ Llagas (Northern and Southern Vaqueros Sandstone)	20”	11,924	2328	2.77 gpd/ft^2	16	196	70	235	321 AF	450 AF (1980-2010)	3.77%
Carneros (Northern and Southern Vaqueros Sandstone)	21”	3958	520	4.3 gpd/ft^2	20	132	41	80	141 AF	200 AF (1982-93)	5.05%
Venadito (Northern and Southern Vaqueros Sandstone)	22”	1794	247	9.48 gpd/ft^2	38	140	50	73	161 AF	143 AF (1993-2004)	7.97%
Tajiguas All Sandstone Aquifers	20”/27”	6030	1068	5.5 gpd/ft^2	51	1945	364	329	744 AF	600 AF (2009-2017)	9.95%
Las Flores (Vaqueros Sandstone)	20”	9349	1826	10 gpd/ft4	86	265	36	134	256	139 AF (1993-2013)	4.09%

NOTE: Perennial yield as percentage of rainfall utilizes pumpage-change in storage value for perennial yield.

ACKNOWLEDGMENTS

This study significantly benefited from work performed by Hydrologist Jon Ahlroth who digitized and evaluated the San Jose Creek stream gauge data, and applied the "Crippen" and "Blaney" methods of determining streamflow and field recharge at the six watersheds of known perennial yield. Ahlroth also developed an algorithm used to back-calculate the stream recharge component in the six coastal watersheds studied by the author.

REFERENCES

Blaney, H. F., 1933, Rainfall penetration in Ventura County investigation: *California Public Works, Water Resources*, Division Bulletin 46, pp. 82-90.

Crenshaw, Brad, 2013, Mitigating Inflow Due to Both Primary and Secondary Permeability in Mining: *AEG News*, Vol. 56, 12 pages.

Crippen, John R., 1965, *Natural Water Loss and Recoverable Water in Mountain Basins of Southern California*: U.S. Geological Survey Professional Paper 417-E, 24 p.

Darcy, Henry, 1856, *The Water Supply of Djon*: Victor Dalmont, Paris, 647 p.

Dibblee Foundation, 1987, *Geologic Maps of Quadrangles of Southern Santa Barbara County*

Dibblee, Thomas W., 1966, *Geology of the Central Santa Ynez Mountains, Santa Barbara County, California*: California Division of Mines and Geology Bulletin 186, 99 p.

Evenson, R.E., Wilson, H.D., & Muir, K.S., 1962, *Yield of the Carpinteria and Goleta Groundwater Basins, Santa Barbara County, California, 1941-58*: U.S. Geological Survey Water Resources Investigation, 112 p.

Freckleton, John R., 1989, *Geohydrology of the Foothill Groundwater Basin Near Santa Barbara, California*: U.S. Geological Survey Water Resources Investigation Report 89-4017, 46 p.

Geotechnical Consultants, Inc., 1976, unpublished source, Hydrogeologic Investigation of Carpinteria Ground Water Basin, 205 p.

Hoover, M.F., 1980, unpublished source, Safe Yield Evaluation of the Montecito Basin and Toro Canyon Area, 24 p.

Ji, F., M. Littleboy and G. Summerell, 2009, *Water Balance Modelling—Impact of Land Use, Soil Properties and Rainfall Seasonality*. 18th World Imacs/Modsim Congress, Cairns, Australia, July 2009.

Leeds, Hill and Jewett, Inc., 1969, unpublished source, Ground Water Resources Available to Goleta County Water District, 49 p.

Mann, John F. Jr., 1976, unpublished source, Safe Yield of the Goleta Ground Water Basin, 20 p.

Martin, Peter and Berenbrock, Charles, 1986, *Groundwater Monitoring at Santa Barbara, California: Phase 3—Development of a Three-Dimensional Digital Groundwater Flow Model for Storage Unit 1 of the Santa Barbara Groundwater Basin*: U.S. Geological Survey Water Resources Investigations Report 86-4103, 58p.

Miller, G.A. and Rapp, J.R., 1968, *Reconnaissance of the Groundwater Resources of the Ellwood-Gaviota Area, Santa Barbara, California*: U.S. Geological Survey Open-File Report, 50 p.

Minor, S.A., Kellog, K.S., Stanley, R.G., and Gurrola L.D., 2009, *Geologic Map of the Santa Barbara Coastal Plain Area, Santa Barbara County, California*: U.S. Geological Survey Scientific Investigations Map 3001, Scale 1:25000.

Muir, K. S., 1968, *Groundwater Reconnaissance of the Santa Barbara-Montecito Area, Santa Barbara County, California*: U.S. Geological Survey Water Supply Paper 1859-A, 28 p.

Pueblo Water Resources, 2013, unpublished source, ExxonMobil 2001 Santa Ynez Unit-Las Flores Canyon Ground Water Management Plan 2012-2013 Annual Report.

Rantz, S.E., 1960, *Flow of Springs and Small Streams in the Tecolote Tunnel Area of Santa Barbara County, California*: U.S. Geological Survey Open-File Report, 282 p.

Santa Barbara County, 1992, *Groundwater Thresholds Manual for Environmental Review of Water Resources in Santa Barbara County*, 40 p.

Theis, C.V., 1935, *Relationship Between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a Well Using Groundwater Storage*: U.S. Geologic Survey Note 5, 1952, 5 p.

Upson, J.E., 1951, *Geology and Groundwater Resources of the South Coast Basins of Santa Barbara County, California*: U.S. Geological Survey Water Supply Paper 1108, 144 p.

U.S. Bureau of Reclamation, (undated), *Technical Record of Design and Construction, Tecolote Tunnel*, 109 p.

Zhang, L., W.R. Dawes, and G.R. Walker, March 2001, *Response of Mean Annual Evapotranspiration to Vegetation to Changes at Catchment Scale*: Water Resources Volume 37, No. 3, pp. 701-708.

DEFINITIONS

Annual Yield: The average annual rate of groundwater withdrawal over a period of representative rainfall that results in the long-term stability of water levels. Also known as perennial yield.

Direct Penetration of Rainfall: Also known as field recharge, it is the downward percolation of rainfall through the host rock and into the aquifer.

Field Recharge: Also known as direct penetration of rainfall, it is the downward percolation of rainfall through the host rock and into the aquifers.

Perennial Yield: The average annual rate of groundwater withdrawal over a period of representative rainfall that results in the long-term stability of water levels. Also known as Annual Yield.

Poaching: A term used to describe the flow of groundwater from one watershed to another in response to the lowering of water levels, usually by pumping, such that groundwater flows in a direction that would not occur in a natural state.

Safe Yield: The average annual rate of groundwater withdrawal that does not result in adverse effects such as subsidence uneconomic pumping levels of water quality degradation.

Storativity (*S*): The volume of water released from storage, or taken into storage, per unit of surface area of the aquifer per unit change in head. In water-table aquifers, *S* is the same as the specific yield of the material unwatered during pumping. In artesian aquifers, *S* is the result of two elastic effects—compression of the aquifer and expansion of the contained water—when the head or pressure is reduced during pumping. The coefficient of storage is a dimensionless term.

Subaerial: Occurring or existing in the open air, immediately on or near the earth's surface.

Subsurface Inflow: The subsurface flow of groundwater from one aquifer to another.

Transmissivity (*T*): The rate at which water will flow through a vertical strip of the aquifer one foot wide and extending through the full saturated thickness, under a hydraulic gradient of 1.00 or 100 percent.

Underflow: The subsurface flow of groundwater beneath a streambed, typically within the alluvium.