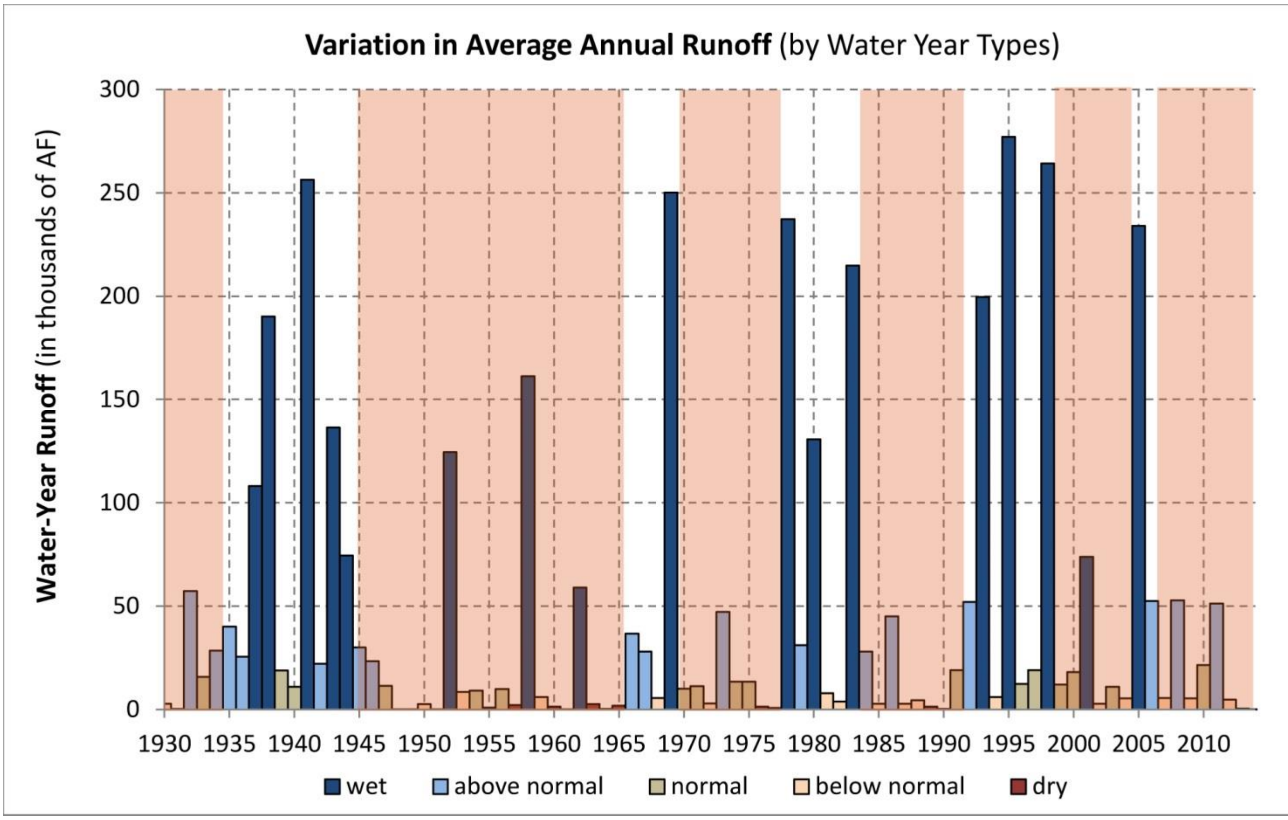


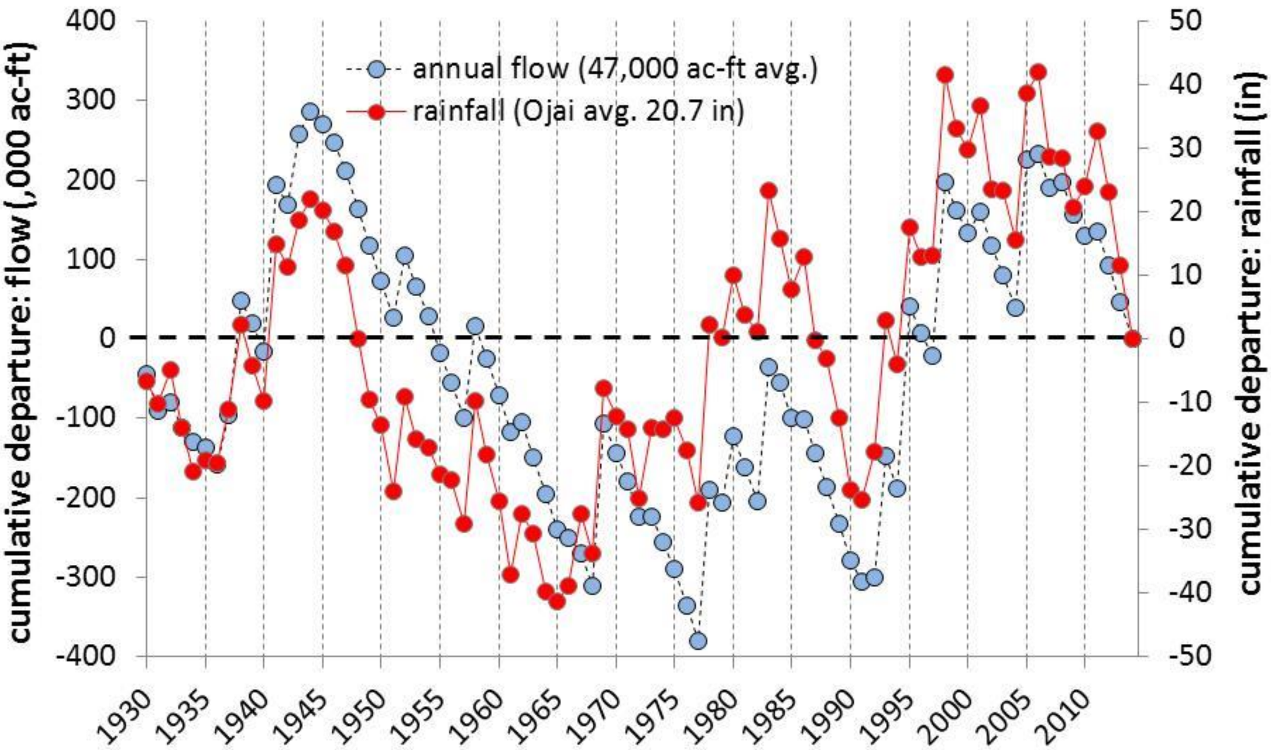
A *really dry sponge*

This is Lorraine's chart of water-year (Oct through Sept) runoff, as measured at Foster Park, from 1930 to 2013. She's subdivided the years into the 5 categories shown at the bottom; each category containing one fifth of the years. The pink bands show time intervals that can be generally defined as dry—the latest, our current dry period, is shown as beginning in 2007. That dry periods dominate is not unexpected since our runoff distribution (and rainfall distribution) is highly unsymmetrical: most years have below-average rainfall and runoff, and the relatively few above-average years provide the majority of runoff when measured over the long term.

The unbalanced nature of the runoff distribution is given by two statistical measures, the mean (arithmetic average) and the median (the mid-point: half the measurements lie above the median, half below). The mean Foster Park water-year runoff is 47,000 acre-feet (AF) a year, the median is 12,000 AF. Runoff could also be expressed as the average daily water-year flow; using this measure the mean and the median would be 65 and 18 cubic feet per second (cfs), respectively. Between 1930 and 2014, 62 years have had below-average runoff and 29 were above average—in other words, 6 out of every 9 years (67%) were below-average.

Rainfall does not directly translate into runoff (other factors like the size and spacing of storms come into play) and the annual rainfall distribution is slightly different, less dramatically skewed towards the low side and spanning a much more restricted range: the average water-year rainfall, as measured at the Ojai Fire Station, is 20.7 inches, the median is 17.5. Roughly two out of every three years have less than average rainfall. Keep that in mind before placing any bets on rainfall this coming winter.

Lorraine's chart begs the question of how else we might define a "dry period"? One way is through the use of a "*cumulative departure from the mean*" curve such as the one drawn below for both annual Ojai rainfall and annual Foster Park flow (*annual* meaning water-year from this point on). It's simpler than it looks. The mean is determined for each set of annual data and the individual annual values are re-calculated as their variation from the mean, i.e., an annual rainfall of 30 inches is expressed as 9.3 in above the mean (+9.3), the Ojai mean being 20.7 in. An annual rainfall of 10 inches as 10.7 in below the mean (-10.7). The cumulative departure for any year is simply the sum of all the departures (variations from the mean) that have gone before; we could have as easily called it "a running total of variations from the mean."

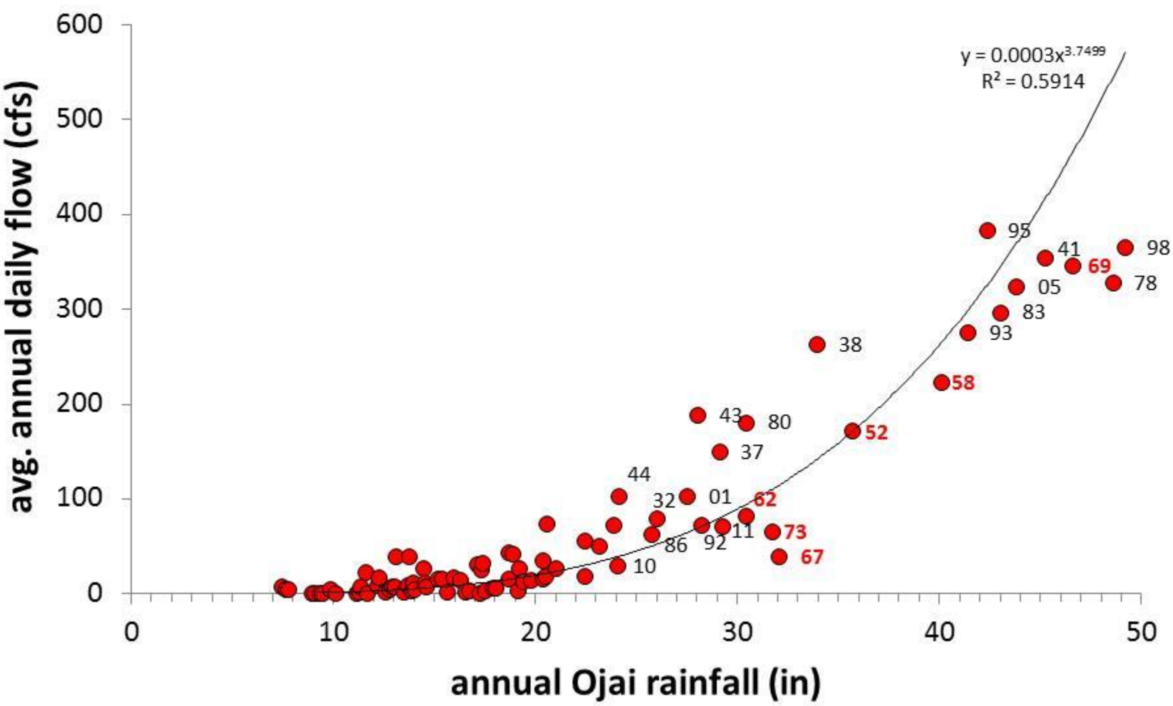


The graph begins with data from 1930, this being the earliest date for which annual Foster Park flow data are available. Since the start date is relatively arbitrary and since the last point on each curve must end back at zero (the sum of all departures from the mean equals zero), the actual values are not all that important. What is important is whether sequential values are increasing, decreasing, or remaining more-or-less the same. If every annual value was equal to the mean the cumulative departure line would be perfectly horizontal, beginning and ending at zero. An upward slope means that values are generally increasing with time; a downward slope indicates a decrease. For annual rainfall and flow, dry periods are indicated by long stretches of decreasing values or downward slope.

The graph starts in the middle of a dry period, this is the Great Dust Bowl Drought, generally given as 1928 to 1935 (although it may have started earlier in the west); this depression-era drought didn't just happen in Oklahoma and Kansas, but was felt throughout most of the west. What interests me, however, and caused me to look more closely at this data is not the progression of wet and dry periods, but the differences between cumulative rainfall and flow.

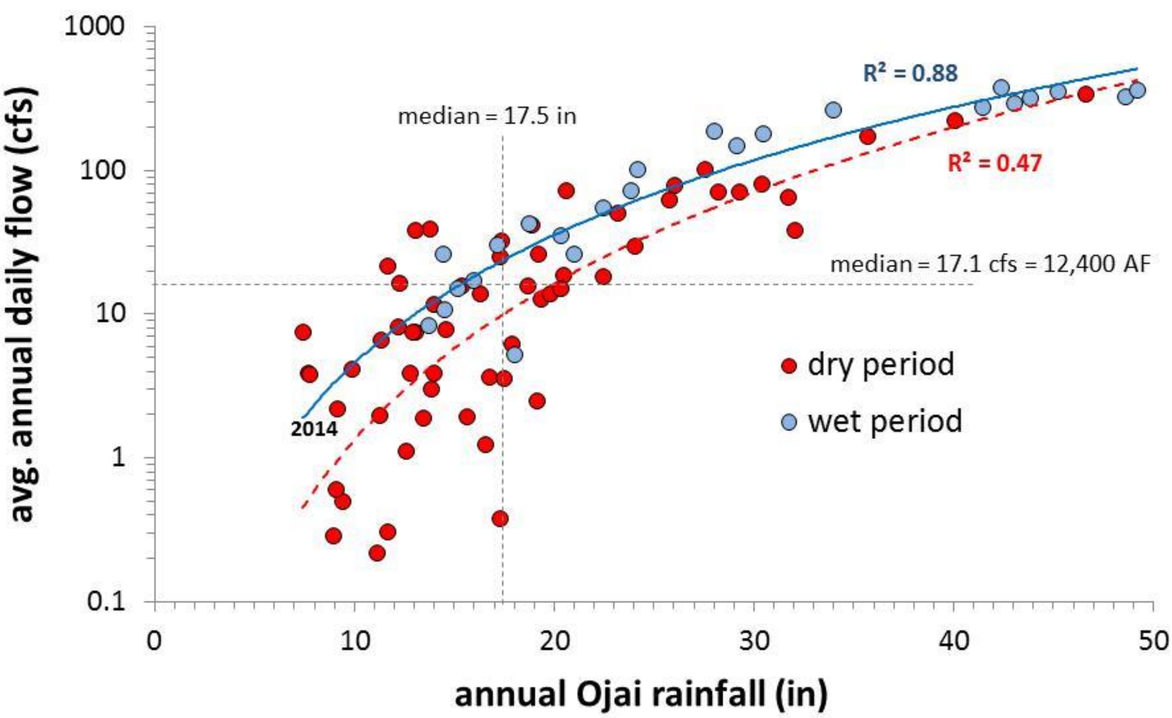
I'm especially intrigued by the period from 1945 to 1977. Lorraine's chart shows this dry period as ending in 1965, but examining cumulative flow (and cumulative *Ventura* rainfall which I've plotted elsewhere) the dry episode appears to extend until 1977. We might better call it a continuous 33 year decrease in Foster Park flow relieved only by three very wet years in 1952 (35.7 in), 1958 (40.1 in) and 1969 (46.6 in); and finally brought to a close in 1978 with 48.6 inches of rain.

Also interesting, besides the three very wet years mentioned, are four additional above-average rainfall winters that occurred during this period (1962, 30.4"; 1966, 23.2"; 1967, 32.1"; 1973, 31.8"). So I decided to look a little more closely at all these years.



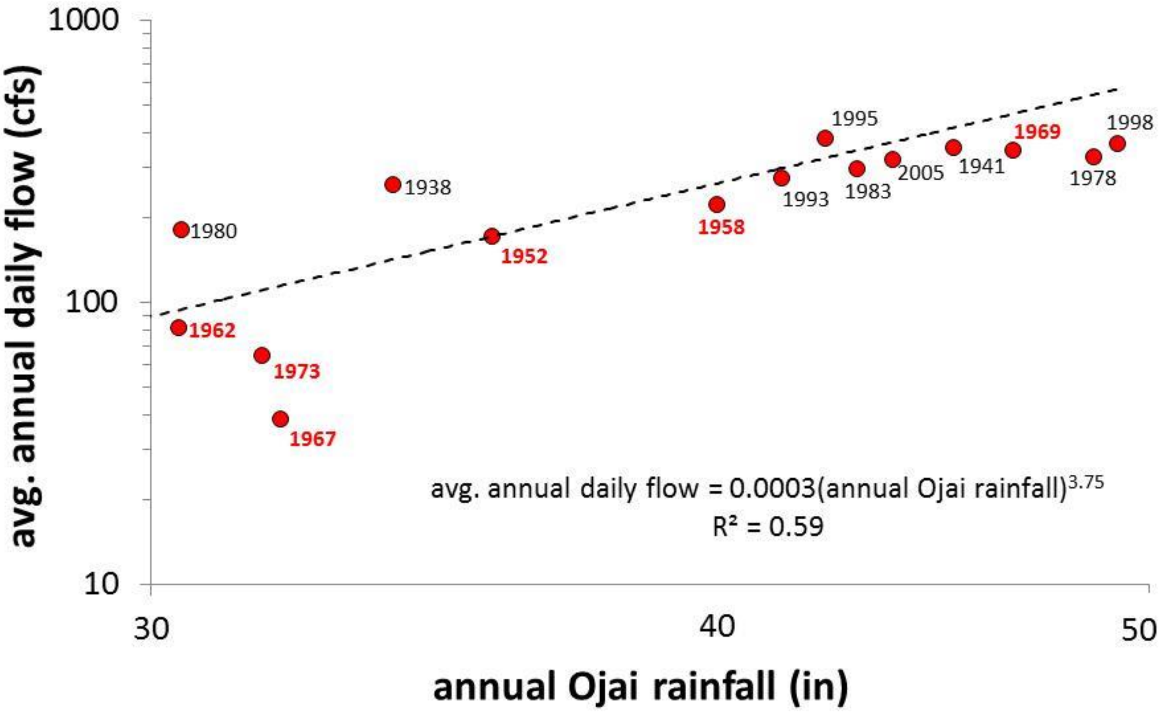
The above graph shows average annual daily flow at Foster Park in cfs (the total water-year flow divided by the number of seconds in a year, i.e., had the flow been constant throughout the year it would have flowed at this rate) plotted against annual Ojai rainfall. All 85 years since 1930 are included and the numbers (e.g. "67" meaning 1967) indicate every year in this period with more than 24 inches of rainfall—numbers in red indicate the wet and very wet years that occurred during the 1945-1977 dry period. The curved line on the graph is the line-of-best-fit for the data; it describes a power function (the equation on the graph) and explains about 60% of the relationship between annual flow and rainfall (i.e. differences in rainfall can explain 60% of the differences in flow).

Notice that almost all (1952 being the sole exception) wet years during this dry period fell below the line. One interpretation could be that the catchment water deficit during a dry spell becomes so large that less runoff than expected results from the occasional wet year. Call it the "really dry sponge" theory. Normally at the end of our rain-less "Mediterranean" summer the watershed sits there like a dry sponge and it takes a lot of initial rainfall to "soak" it enough that runoff begins to flow in the river and tributary creeks. [*However this explanation begs the question of what happened in the two wettest years: 1978 and 1998? Why, with so much rainfall, was there* *noticeably less runoff? While Ojai, located near the center of the watershed, is a pretty good proxy for overall watershed rainfall (which is why it's being used here) it's not perfect. Rainfall over a given area varies considerably from point to point (as mentioned previously, 1966 and 67 were years of increased Ojai rainfall, while Ventura rainfall decreased). Similarly, the Foster Park flow records do not account for diversions into Lake Casitas, nor domestic water utility withdrawals via the shallow gallery placed just below the upstream riverbed. And while it would be nice to have flow measured closer to Main Street, there is no alternative long-term record; the Foster gauge is the only game in town. Stream gauge records, and those of rainfall, are also prone to simple error. A major part of the flow in very wet years occurs during surprisingly short intervals of time, and these extraordinarily high measurements are often inaccurate—very low flow measurements, equally inaccurate, have much less impact on the annual flow record.*]



Taking another look at my *really dry sponge* theory I've redrawn the last graph. This time using a logarithmic scale (which allows a much closer look at very low values) for average annual daily flow. I've also divided the data into two classes: based on the kind of period, either wet or dry—based on the classification in Lorraine's chart—that a particular year fell into. I've drawn a power function for each of the data sets (the red and blue lines) and also included dashed-lines showing the median rainfall and flow. And finally, just for the hell of it, I've labeled the point that represents 2014.

The equation describing how flow during wet periods varied with rainfall turns out to be very good (an R-value of 1.00 would mean perfect correlation—rainfall exactly predicting flow, an R-value of 0.88 can be interpreted as saying the equation gets it 88% right), not quite as good for the dry period years (almost half right: a lot more data—a majority of the years occurred during dry periods—and a lot of scatter on the low end causing problems). But even so, the significant difference between both sets of data offers some support to the idea that we can expect much lower runoff for the same amount of rainfall during dry periods. And since we seem to be in an extended dry period, the implications are obvious.



I'm going to try the same graph once again. This time using a logarithmic scale on both axis (doing this allows the power function to be shown as a straight line) and showing only those years with rainfall greater than 30 inches. As it happens, there appears to be no need for a complicated analysis to determine whether or not we are in a dry or wet period. Looking at the relative frequency of big rainfall years (rainfall >30 in) is enough. The 1945-77 dry period had six of them, roughly one every six years (years shown in red). In contrast, the following wet period, 1978-83, had three, one every two years. Other wet periods: 1993-98 had three (again, one every two years); 1935-44 had only two (1938 and 1941, a 1 in 5 frequency), but four of the other eight years had above-average rainfall and another came pretty close. To state the obvious, since we've only had one big year since 1999 (2005) it pretty much looks like we are in a dry period (saved somewhat because another 4 of those 16 years had above average rainfall and 2 others were reasonably close).

I could juggle the figures by modifying the definition of a "big" rainfall year, but the basic message is simple. Table 1, which summarizes rainfall statistics for all dry and wet periods since 1930, tells all. The normal expectation is that we will be in a dry period—in the past we've been in a dry period more than 70% of the time (62 of the 85 years). An above-average annual rainfall occurs only a third of the time (29 out of the 85 years) and an annual rainfall above 30 inches is even rarer—less than 1 year out of 5. Any interval of years where annual rainfall falls below these norms becomes, almost by definition, a dry period: where less than half the years have above the median rainfall; where less than a third of the years are above average; and where the interval between big rainfall years becomes greater than 5. Conversely, a wet period can be defined as an interval where more than half the years have above the median rainfall, more than a third are above average, and big years occur more than 20% of the time.

Table 1. Water-years from 1930-2014 subdivided into wet and dry periods showing the number of years in each period with above median (>17.5 inches), above average (>20.7 inches)and above 30 inches (defined as a big rainfall year) of rainfall in Ojai. Summary data for the entire period are also shown. "Dry period" is being defined as a long-term trend of declining cumulative rainfall departure from the mean; "wet period" being an increasing cumulative rainfall departure (see my second graph).

Years	Period	Total Yrs.	yrs. rainfall above median	Ratio	yrs. rainfall above average	ratio	yrs. rainfall above 30 in	ratio
1930-1934	Dry	5	1	**0.20**	1	**0.20**	0	**0.00**
1935-1944	Wet	10	7	**0.70**	6	**0.86**	2	**0.20**
1945-1977	Dry	33	13	**0.39**	8	**0.24**	6	**0.18**
1978-1983	Wet	6	5	**0.83**	3	**0.50**	3	**0.50**
1984-1992	Dry	9	4	**0.44**	2	**0.22**	0	**0.00**
1993-1998	Wet	6	4	**0.67**	4	**0.67**	3	**0.50**
1999-2014	Dry	16	7	**0.44**	5	**0.31**	1	**0.06**
1930-2014	**--**	**85**	**42**	**0.49**	**29**	**0.34**	**15**	**0.18**

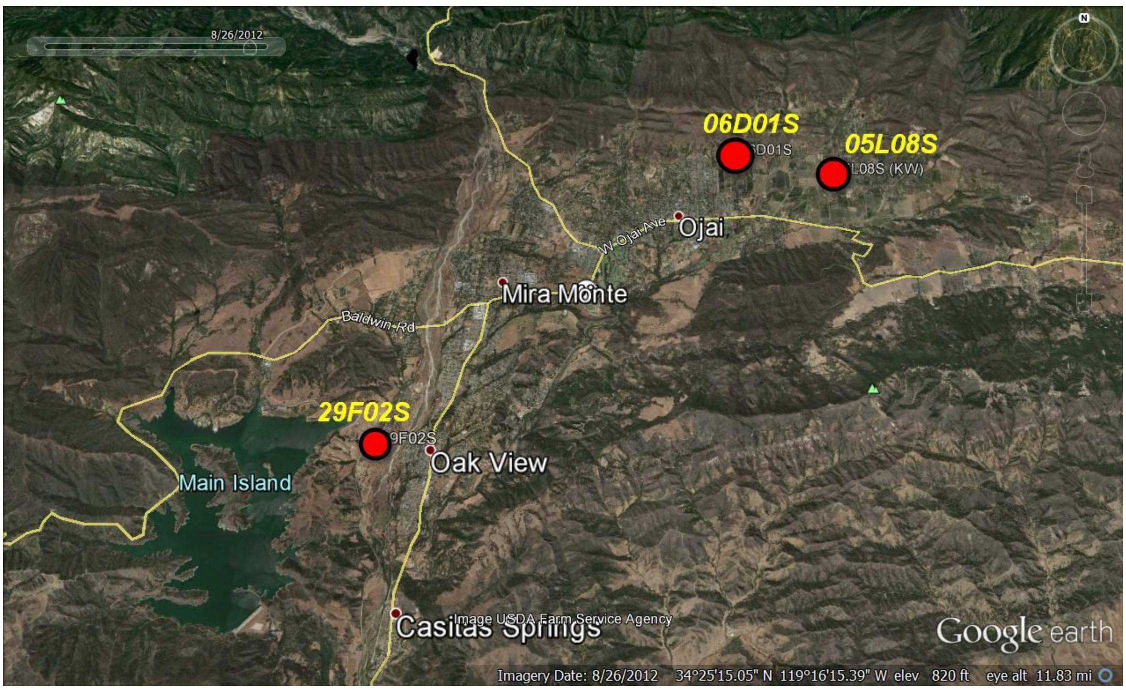
The implications are clear. As are the mathematics. If we treat predicting the likely rainfall this coming winter as similar to tossing a coin, or rolling a pair of dice, there is a only a 50/50 chance of getting more than 17.5 inches, 2:1 odds against more than 20.7 inches, and 4:1 against more than 30 inches. But as we are in the midst of a dry period these odds get much rougher. Even more so should the drought continue (a drought being a particular bad patch during an extended dry period).

And now for something completely different Or perhaps not completely . . .

Long-term trends in groundwater elevation

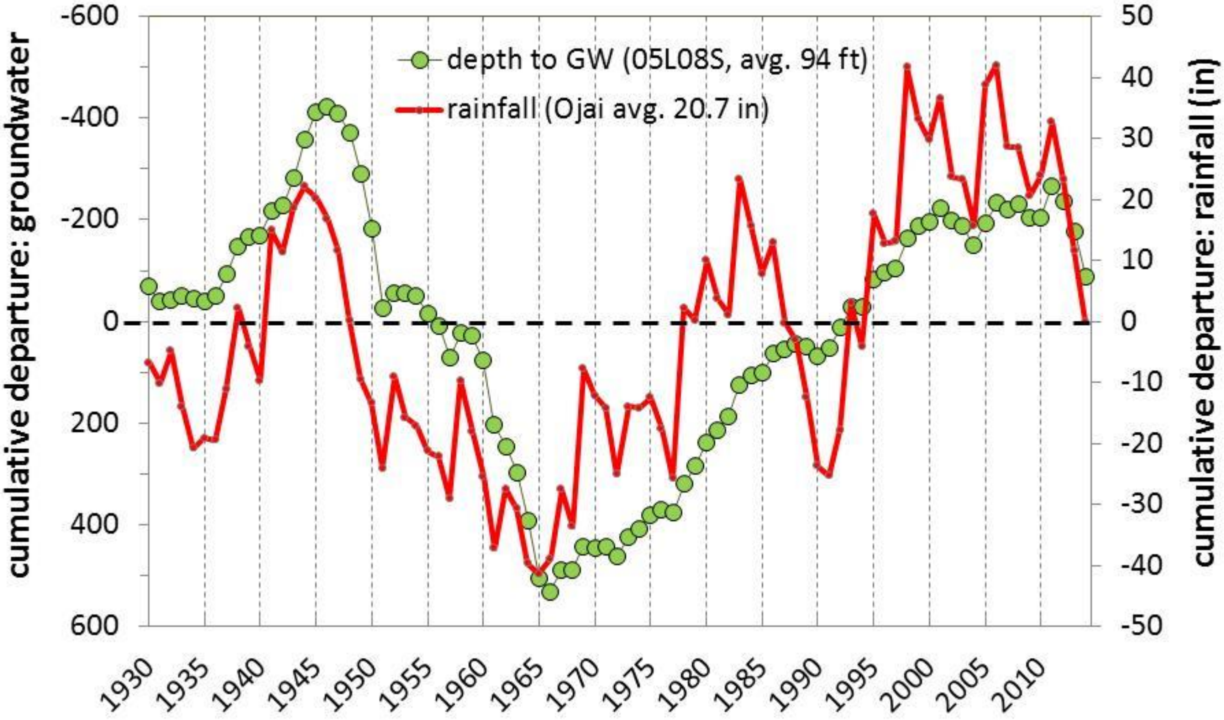
The thought occurred that if annual rainfall and annual flow can be plotted on a cumulative departure from the mean graph, why not groundwater? How might some index of groundwater status compare with rainfall? Or Foster Park flow? Obviously, groundwater withdrawals can't be used since we lack any accurate measure of these, but what about the average depth to groundwater from some surface benchmark? That turned out not to be a very good idea since the spacing of these measurements in the County database varied considerably from year to year—some years having only two measurements while others had almost one every month. But what did work was an *end-of-water-year* depth to groundwater. A goodly number of wells had relatively consistent measurements taken around September 30th—mostly in September or October, but in a few cases extending into August or November. Occasionally, I had to estimate an end-of-year depth to water from earlier and later dates, but these few points made up a very small percentage of the overall data.

The next step was to find wells with a long enough data record to make the exercise worthwhile. I found three: 29F02S is in the upper Ventura watershed, relatively close to and west of the river below the Highway 150 bridge; its record extended back to 1928. 05L08 is in the Ojai Valley near the intersection of Grand and Carne and is regarded as the "key well" for analysis and management of the Ojai groundwater basin; its record began in 1949 but the older well it replaced (05L01S), located a hundred or so feet away, could be used to extend groundwater elevations back to 1927. The last well, 06D01S, also located in the Ojai basin but further to the west and north of Grand Ave, also has a record going back only to 1949; it serves as a check on any conclusions drawn using 05L08S data. All three well locations are shown in the Google image below.



Starting with "key" well 05L08, the results were gratifying . . . and slightly surprising. The Ojai Valley has a "bowl" shaped groundwater basin, and the expectation, since it rarely completely fills (years like 1983, 1995 and 2005, which produce artesian conditions in lower elevations of the valley, being the exception), was that the cumulative departure of groundwater depth from its mean would closely resemble that for rainfall. Particularly so since the intensity of groundwater pumping would reinforce the rainfall trend: lower pumping in wet years, more sustained withdrawals in dry. Indeed, as Figure 6 shows, this is more or less the case.

The surprise being that it produces a greatly simplified pattern, depth acting somewhat as a low-pass filter, smoothing out the data and making the overall trend more obvious. As to why this is so remains an open question. Perhaps because groundwater recharge somewhat resembles a moving-average (itself a smoothing method) as recharge from more distant parts of the watershed may travel years to reach the basin and inflow during any single year may include rainfall from a number of previous winters. And big rainfall winters, as they produce dramatically increased amount of surface runoff (as shown in Figures 3 & 4) contribute proportionally less recharge. Then too, not all changes in groundwater elevation are created equal. Since the basin is bowl shaped, the same amount of groundwater pumping during a dry period will cause a



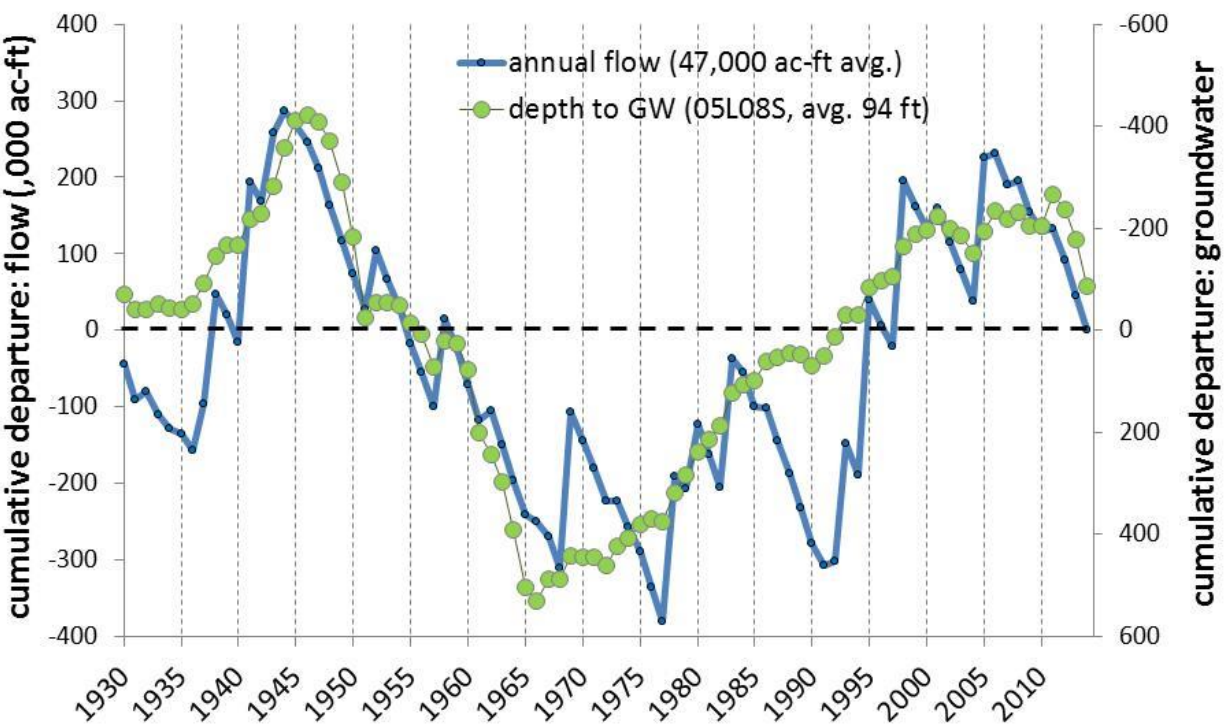
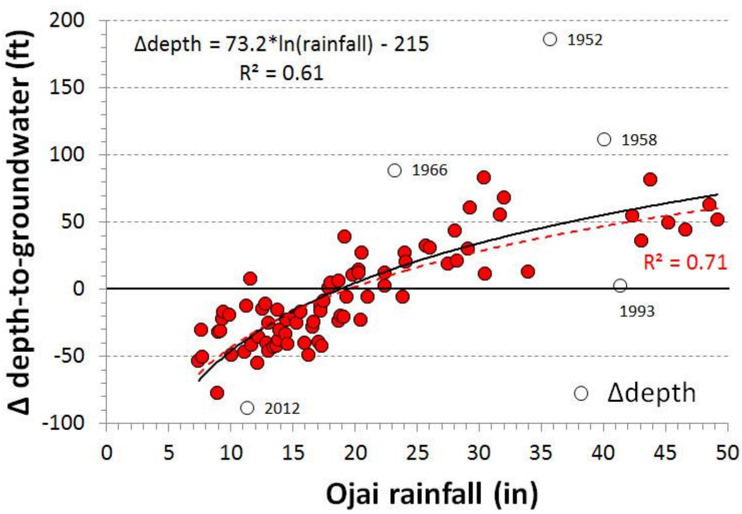


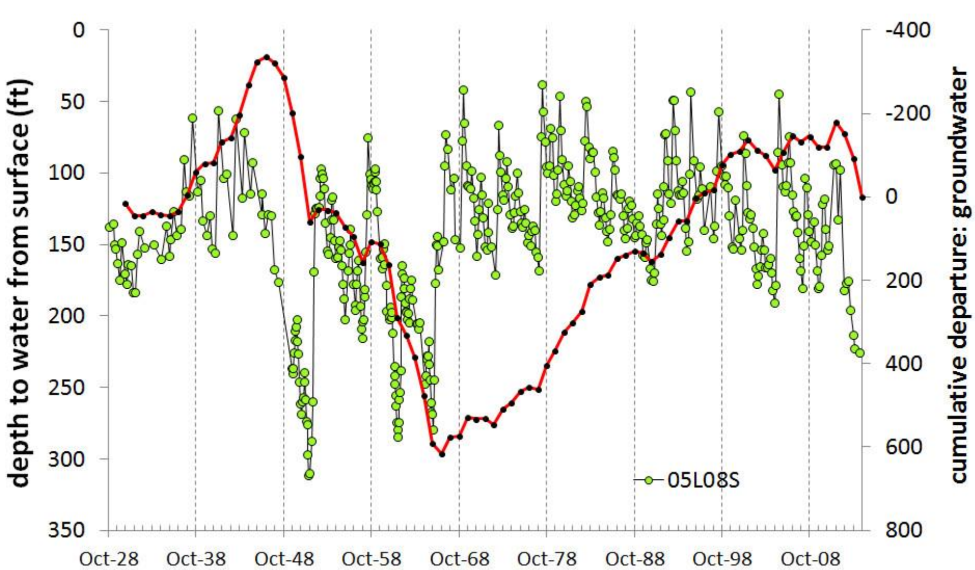
Figure 6. Cumulative departure of the end-of-water-year depth-to-groundwater is plotted for well 05L08 in the Ojai basin along with cumulative departure of Ojai rainfall (upper) or cumulative departure of annual Foster Park flow (lower). [The initial starting point of the cumulative groundwater curve was adjusted (i.e. the last point no longer ends at zero) and the right-hand scale is reversed (a *decrease* in rainfall leads to an *increase* in depth-to-water).]

much greater drop in elevation than during a wet period; simply put, the bottom half of the bowl holds less water than the top. And annual groundwater pumping undoubtedly varied over the 85-year time span being considered, most likely increasing over time.

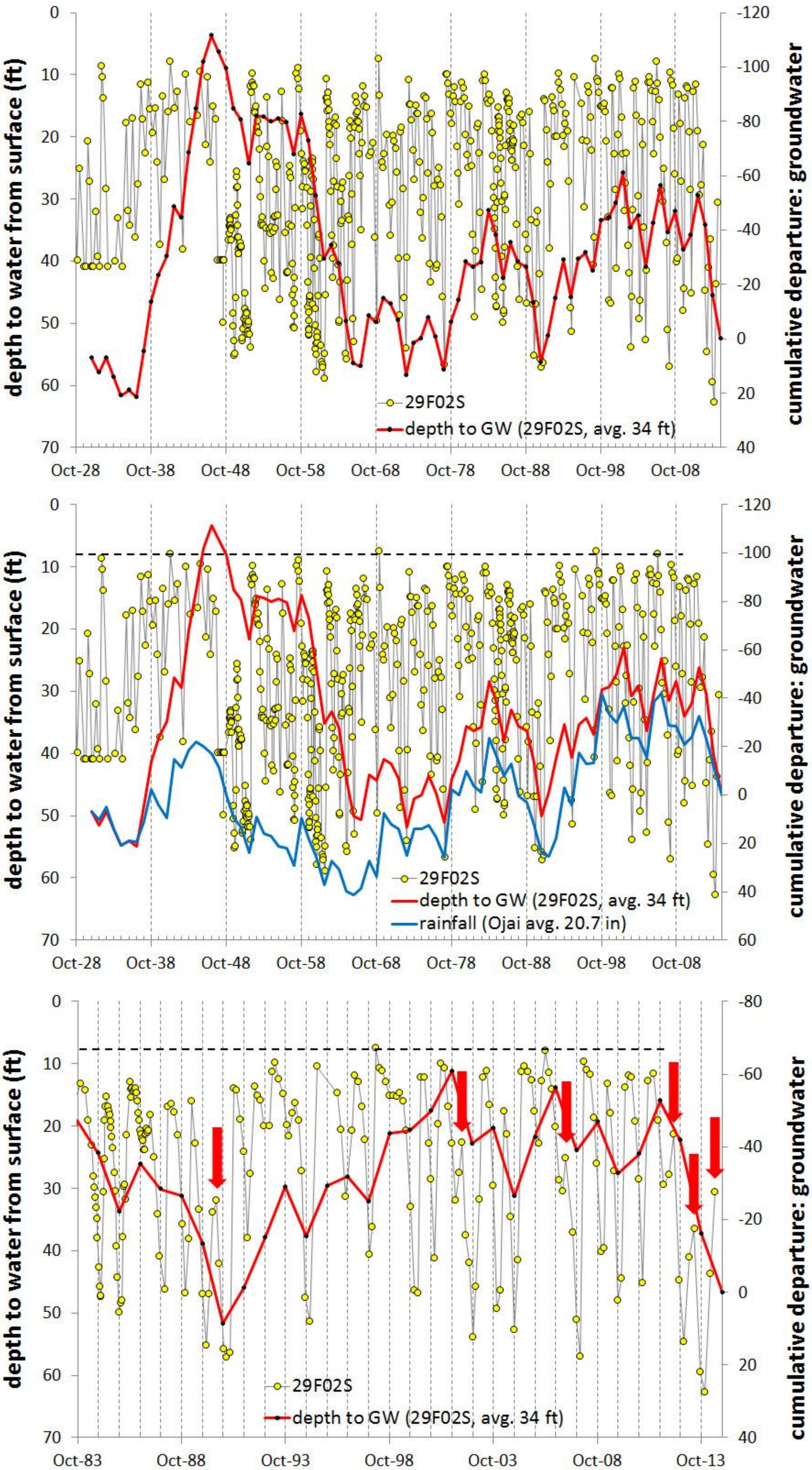


On the left, the annual change in depth-to-groundwater for well 05L08 is plotted against winter rainfall. The logarithmic relationship shown on the graph is the line of best fit (black line); rainfall explains about 60% of the variation in depth. [71% if I remove data for the years shown as hollow circles from the regression (the dashed red line).] The curve of the line likely represents the "bowl" effect mentioned earlier. Including depth-to-water at the beginning of the water-year improved the regression (another factor related to the bowl business) and, more importantly, brought those errant years back into the fold. The final model explained ¾ of the observed variations in depth.

Still, the combined affect of most of these reservations would seem to reduce wet-year increases, which makes the virtual disappearance of the 1987-91 drought from the cumulative groundwater graph even more of a puzzlement. Perhaps the problem here lies in 19-20 inches of annual rainfall region of the graph (just slightly lower than the 21 inch Ojai average): note that some years with this amount of rainfall show a decrease in groundwater depth while others show an increase (in contrast, the situation is much clearer for years with greater or lesser rainfall). As it happened, only one of those drought years produced a substantial decrease in groundwater elevation at this well.



Before moving on it might be a good idea to further illustrate the difference between individual depth-to-groundwater measurements (green circles in the graph on the left) and the cumulative end-of-year variation (the red line—the black dots represent each year's cumulative total). Whatever the method's imperfections, the message, should the present trend continue is clear; we may well be at the beginning of a long dry period.

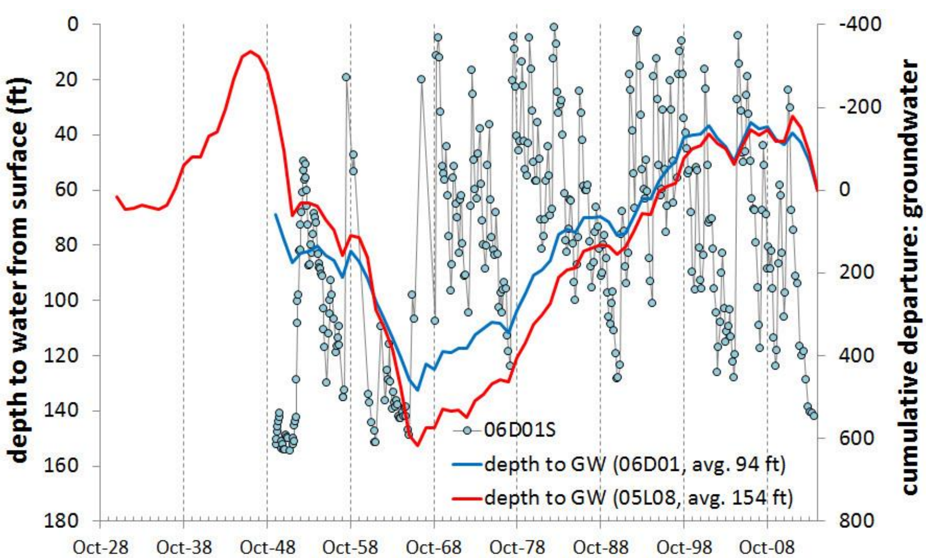


Moving to well 29F02, the first graph on the left presents a different picture than the one previously shown for 05L08: an annual water-table fluctuation that yo-yos back and forth from close to the surface to substantial depth, and a cumulative departure curve with many abrupt, short-term transitions. The difference lies in a much smaller volume and proportionally greater amounts of inflow for this basin (the upper Ventura River) compared with that for Ojai (explained further in *Thinking about Ventura Groundwater*, Dec. 2014).

In the middle panel I've modified the graph by adding the cumulative departure curve for Ojai rainfall (the same as shown in Fig. 6, top, but with signs reversed, e.g. positive values were changed to negative), and drawing a dashed line touching all of the maximum water-table elevations (roughly 8 ft from the surface as measured in the Spring of big rainfall years). Note that all the ups and downs of cumulative groundwater departure match those of rainfall, the only strange difference being the magnitude of that initial circa 1930-50 pulse.

Although I can't be positive, it would appear that up to around 1950 a much lower rate of groundwater withdrawal (i.e. pumping—the lower rate can be seen in the reduced annual fluctuation during these earlier years) allowed the basin to respond much like Ojai's—smoothing out the cumulative rainfall signal. Since then the basin response has been very tightly correlated with the variation in annual rainfall.

In the lower graph the time scale has been expanded to show more recent years; the dashed line of probable maximum water-table height is also included. Red arrows mark maximum early dry-season water-table heights during major dry years (1990, 2002, 2007, 2012, 2013, 2014) and clearly show that the basin rarely completely fills. A new low of 34 feet below the surface for this well was set in 2013. Extremely low water-table elevations are caused by both low winter rainfall and *business-as-usual* pumping during the preceding dry-season: Even years like 2002 and 2012, both preceded by high rainfall years (28 and 29 inches, respectively) show this effect. And business-as-usual pumping during a dry year sets the stage for a record setting low point (e.g. 2013) should the following winter also have low rainfall.



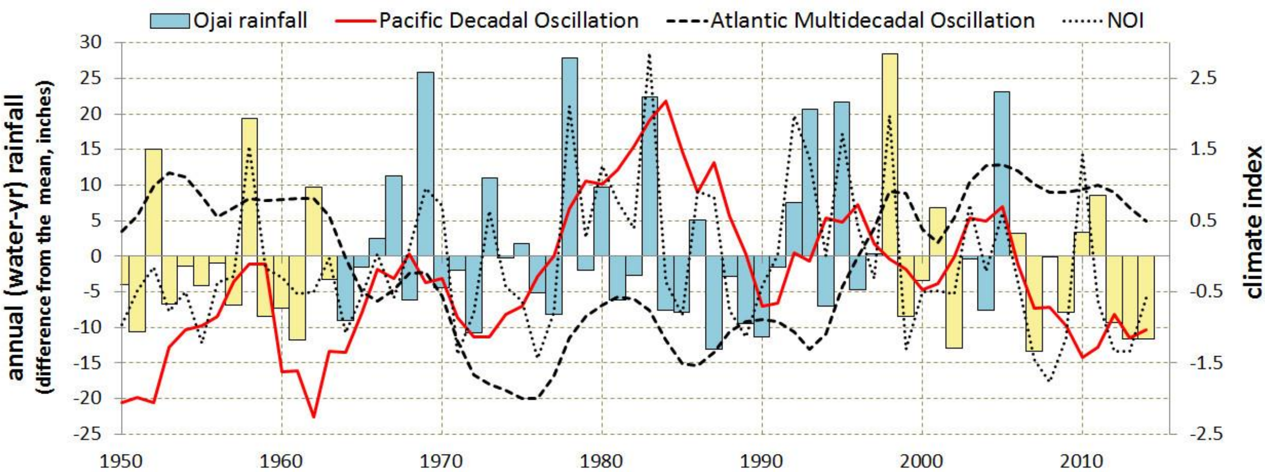
The next graph shows data for my third well, 06D01, also in Ojai. As you can see, its cumulative departure curve for depth-to-groundwater matches extremely well the curve previously shown for 05L08. I show both to illustrate that all wells in the Ojai basin will exhibit this same relationship since it's based on basin characteristics and annual rainfall and not on what may or may not be happening with any individual well.

The root cause . . . and some predictions

Simply stated, long-term trends are caused by climate cycles. But the climate cycle we're most familiar with, El Niño/La Niña, is not long-term, generally cycling back and forth every 3 to 7 years. However there are others that operate on much longer time frames. The Pacific Decadal Oscillation or PDO is perhaps the best candidate. Like the El Niño cycle, the PDO involves the alternation of cooler and warmer ocean waters but in the northeastern Pacific, i.e. along the Pacific coast from just below the Baja Peninsula to above Alaska. When this water turns warm (and it's just a matter of a degree or so above the long-term average) it drives the jet stream in a more southerly direction bringing us more rain. When it turns cool it has the opposite effect. A warm or positive PDO gives us El Niño-like conditions; a cold or negative PDO can resemble La Niña. The complete cycle – warm to cold and back again – takes anywhere from 17 to 28 years; 23 years being a ball-park average.

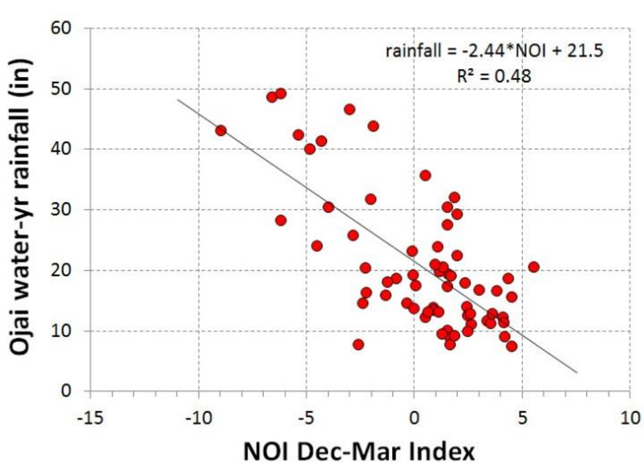
Another possibility is the Atlantic Multidecadal Oscillation, an approximately 70 year cycle of shifting temperatures in the North Atlantic (roughly from the Equator to Greenland) that's particularly interesting because of its association with drought in the western US. (Climate cycles in the Atlantic and Arctic oceans exert influence via air pressure differences that determine the magnitude and path of major storm systems that affect us.) The shift is minor, only about 0.6 °C (keep these magnitudes in mind whenever anyone suggests that a degree or two of global warming is nothing to be concerned about).

A paper by McCabe and others (McCabe et al., 2004) proposed that the combination of a positive (or warm) AMO combined with a negative (or cool) PDO produces drought throughout the west (with a 40% increased chance of a dry year in our region).



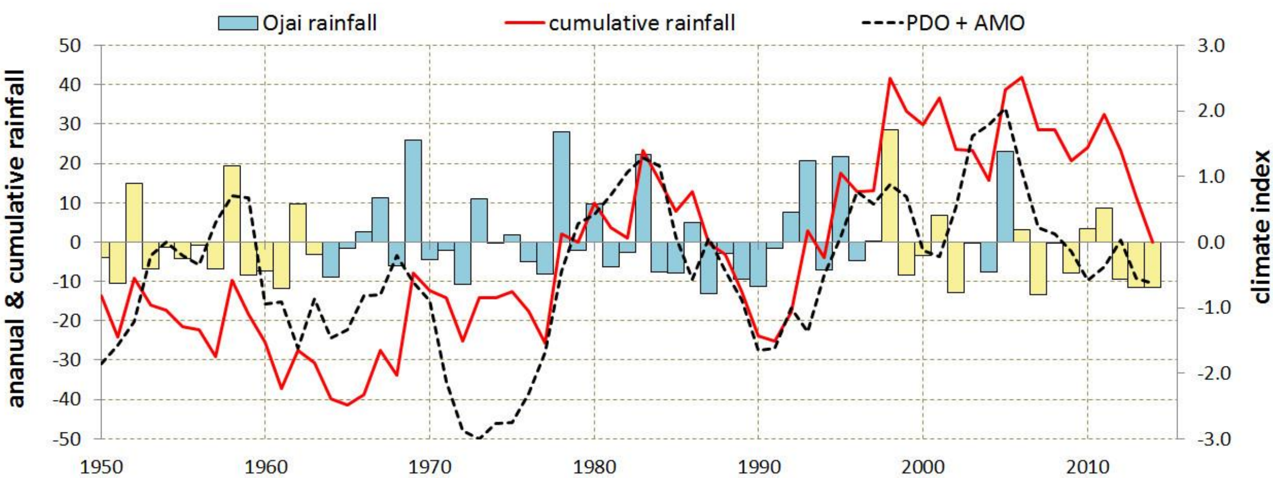
The above graph shows Ojai rainfall (as the water-year difference from the mean) along with variation in the PDO (Oct-Mar moving average) and AMO (Oct-Mar moving median) indices. The yellow -colored rainfall years are those during which the PDO was negative (cool) and the AMO positive (warm) a la McCabe, i.e. those years most likely to produce low rainfall in our area. It kinda works: the “yellow” years had, on average, 4 inches less rainfall than those colored blue. It would work even better if the marginal (only slightly negative PDO) 1998 were excluded; 1958 and 1952 are other major exceptions. It’s also possible that El Niño events might be a factor confounding my nice story.

The third index on the graph, the Northern Oscillation Index (NOI), is a new, possible replacement for the Southern Oscillation Index (SOI—the index originally used to define the El Niño cycle), presented in a recent paper as a better predictor of consequences for southern California (Costa-Cabral et al., 2014). Whereas the SOI measured sea-level pressure differences between Tahiti and Darwin, Australia, the NOI records differences between an oceanic location about 500 miles west of Santa Maria and Darwin. As you can see, peaks in the NOI correlate well with our big El Niño winters (the graph shows NOI values with the sign reversed; El Niño conditions lower sea-level pressures in the eastern Pacific). The figure to the left shows how good the correlation is: a r-square value of 0.48, meaning the NOI



can explain about half the variation seen in annual rainfall. (Climate cycles and their influence on Ventura rainfall were discussed in greater detail in my *Graphic Tales, July* 2013, study.)

As for this winter, the prognosis is promising for those looking forward to more rain: the PDO turned positive in May and showed a big increase in Oct., it's now estimated at +1.3; the AMO remains positive and the combination of +PDO & +AMO usually implies greater than average rainfall; the NOI turned negative in Oct. in general agreement with the consensus view that, while not quite into a full-blown El Niño, we're right on the edge. But, as stressed earlier in this piece, we are in an uphill battle against statistics that generally favor less-than-average rainfall—particularly during a dry period (and we are undoubtedly in one of those). And there is a joker in the deck: climate change. Irrespective of what increasing greenhouse gasses in the atmosphere may do to our rainfall (the mantra "*dry places will get drier*" doesn't convey much promise) it is raising our temperatures, which will, in turn, increase evaporation. And increased evaporation means whatever rainfall we do get will go less far. But that's a subject for another analysis.



Two final points: The above graph compares cumulative Ojai rainfall with a combined PDO + AMO index. The fit is not great (the combined index can only explain about a third of the long-term rainfall pattern), but there is an overall similarity that I wanted to show. And back on page 9, I mentioned an improved equation for predicting the change in depth-to-groundwater from the end of one dry-season to another for well 05L08. At this point in time that end of season measurement has already been made but I don't know what it is. So it's only fair to test the equation by predicting what it might be: my guess is 240 ft below the surface—and we'd have to go back to 1965 to find a lower value.

McCabe, G. J., M. A. Palecki, and J. L. Betancourt. 2004. Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States. *PNAS, 101*, 4136–4141. http://www.pnas.org/content/101/12/4136.full

Costa-Cabral, M., J. Rath, W.B. Mills, S.B. Roy, P. Bromirski, R. Coats and C. Milesi. 2014. The Northern Oscillation Index as a Predictor of Precipitation in California. Abstract GC51A-0387 presented at 2014 Fall Meeting, AGU, San Francisco, Calif., 15-19 Dec.

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