REPORT ON THE CADIZ CARBONATE AQUIFER

John M. Sharp, Jr.
Department of Geological Sciences
Jackson School of Geosciences
The University of Texas at Austin
Austin, Texas USA

Some findings and generalizations

- The pumping test at TW-1 shows a karstic aquifer of very high permeability (K).
- This K is in the range of what has been found in similar karstic settings.
- This setting has the potential to produce a high volume of water for an extended period of time.

This is based primarily upon:

• The television borehole log of TW-1.
• Results of the pumping test conducted at this well.
• Knowledge of similar carbonate systems elsewhere
•Other:

- TW-2 pumping test results
- PEST model
- Head map
- Water balance studies

Televiewer log

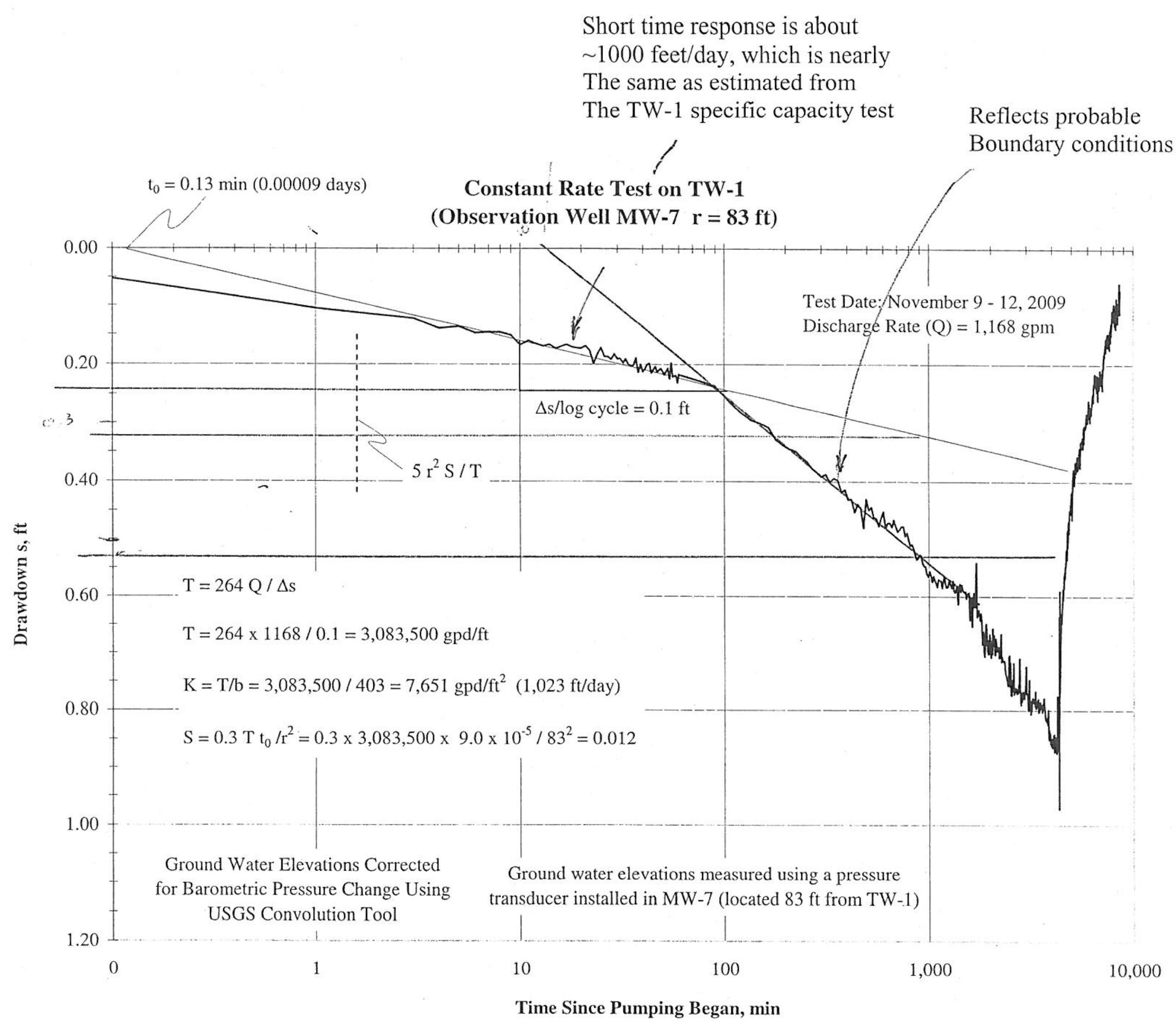
• Between well depths of ~454 to ~758 feet, there are numerous secondary porosity features.
• These features indicate extensive karstification.
• These appear to have been the result of regional paleo-karstification and not a recent or local event.
• Just a few of these features, if well connected, would create a highly permeable aquifer.

Miscellaneous observations:

- Do not ignore the contributions of the crystalline bedrock. This will be (probably much) smaller than the young alluvium and carbonates, but the it will not be zero.
- The same is true for the older alluvium and adjoining rocks.
- The permeabilities at TW-1 and TW-2 are quite high even using different interpretation assumptions (e.g., Consider the effects of temperature).
- Unknowns different interpretations will always exist, but we have to honor the data we have.

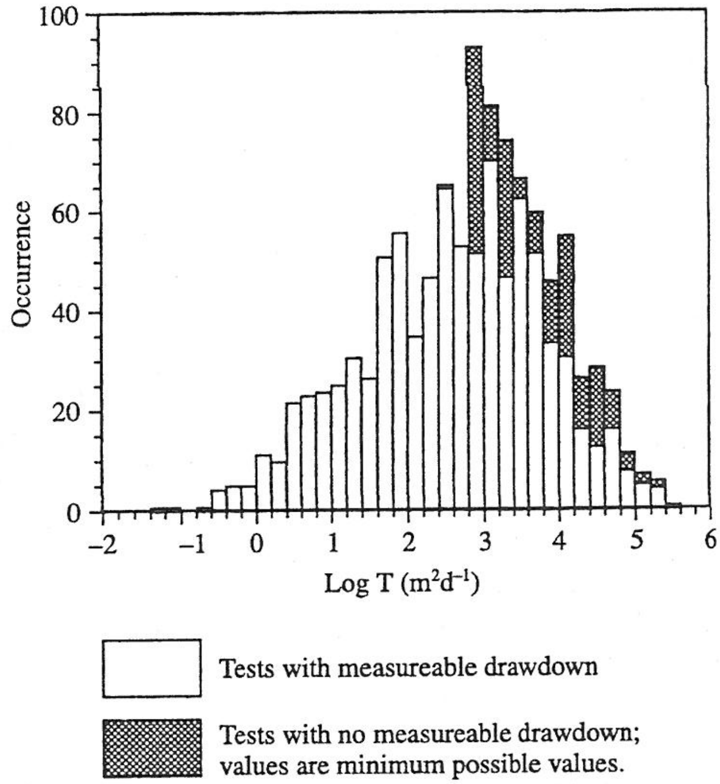
CONCLUSIONS

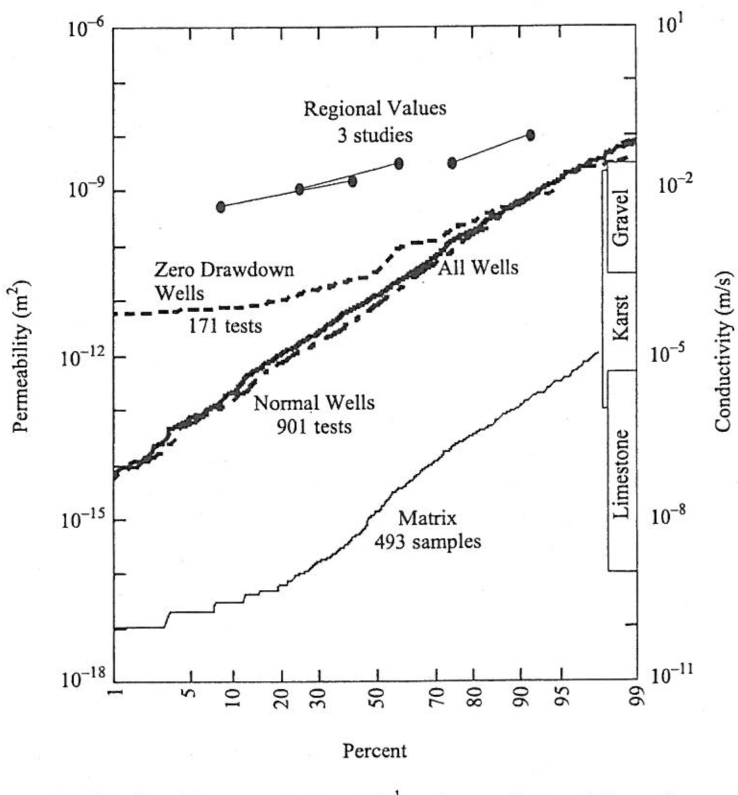
- The strata and, in particular, the karstic strata observed in TW-1, have superb aquifer characteristics.
- 600 feet/day is a reasonable (and perhaps conservative) estimate of the carbonate aquifer's hydraulic conductivity.
- We almost always want more data, but it is clear that this area hosts a significant groundwater resource.



Short time response is about
~1000 feet/day, which is nearly
The same as estimated from
The TW-1 specific capacity test
Reflects probable
Boundary conditions
t_0 = 0.13 min (0.00009 days)
Constant Rate Test on TW-1
(Observation Well MW-7 r = 83 ft)
Test Date: November 9 - 12, 2009
Discharge Rate (Q) = 1,168 gpm
Δs/log cycle = 0.1 ft
$5 r^2 S / T$
T = 264 Q / Δs
T = 264 x 1168 / 0.1 = 3,083,500 gpd/ft
K = T/b = 3,083,500 / 403 = 7,651 gpd/ft^2 (1,023 ft/day)
S = 0.3 T t_0 /r^2 = 0.3 x 3,083,500 x 9.0 x 10^{-5} / 83^2 = 0.012
Ground Water Elevations Corrected
for Barometric Pressure Change Using
USGS Convolution Tool
Ground water elevations measured using a pressure
transducer installed in MW-7 (located 83 ft from TW-1)
Drawdown s, ft
0.00
0.20
0.40
0.60
0.80
1.00
1.20
0
1
10
100
1,000
10,000
Time Since Pumping Began, min

TYPICAL KARSTIC AQUIFER PERMEABILITIES

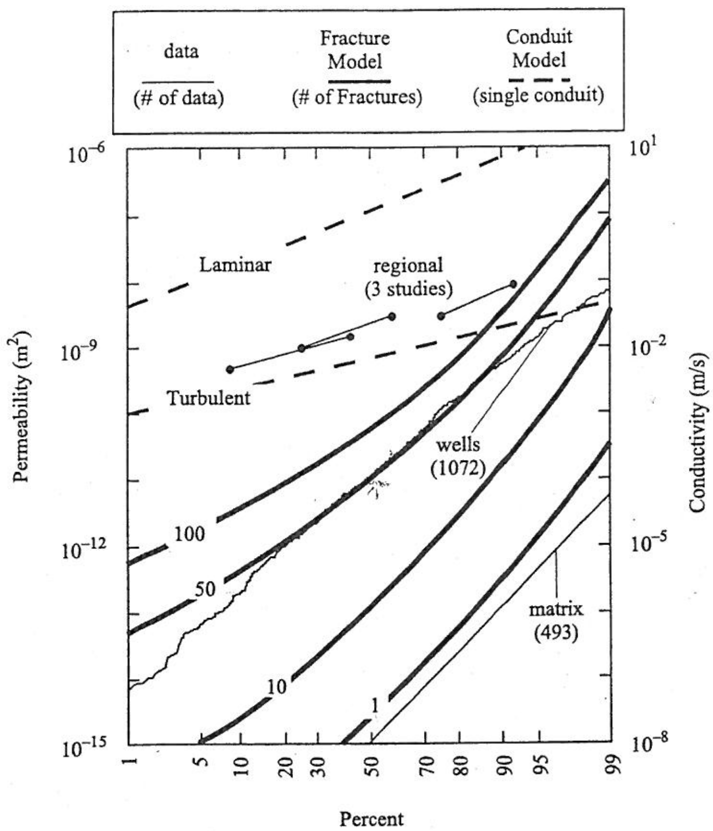




1000 feet/day = ~3.5 x 10^{-1} m/s = ~3.5 x 10 cm/s

Jun1 2010

TYPICAL KARSTIC AQUIFER PERMEABILITIES



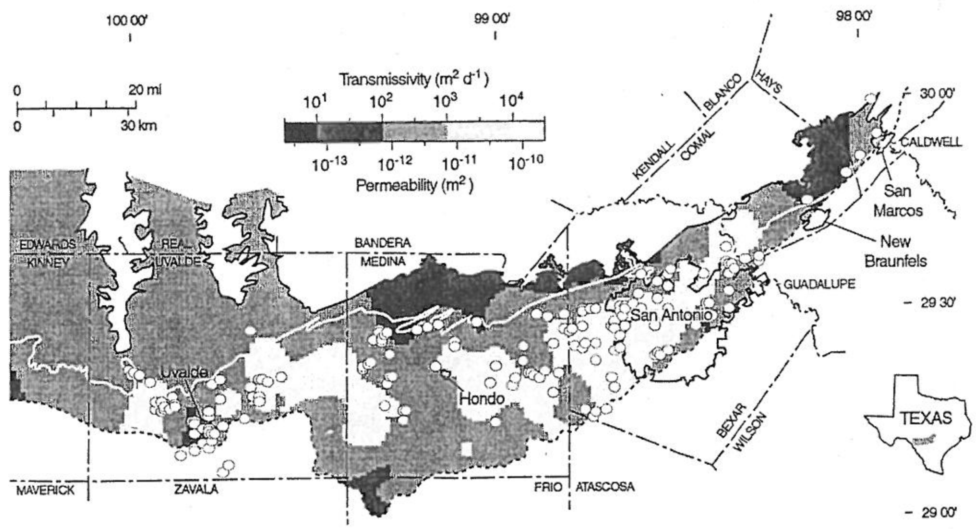


Figure 4. Map of the San Antonio segment of the Edwards aquifer. Location of zero drawdown wells (wells with no measurable drawdown during pumping) is shown with white circles. Smoothed kriging of the transmissivity field included for comparison with locations of zero drawdown wells (Mace, in press; Hovorka et al., 1988). Legend for transmissivity includes estimate of permeability using average aquifer thickness of 170 meters to convert values. Solid dark line indicates northern physical boundary for the San Antonio segment of the Edwards. Dashed line indicates the bad water line which forms the southern chemical boundary for the aquifer. The white line indicates the recharge boundary which approximates the confined/unconfined boundary for the aquifer.

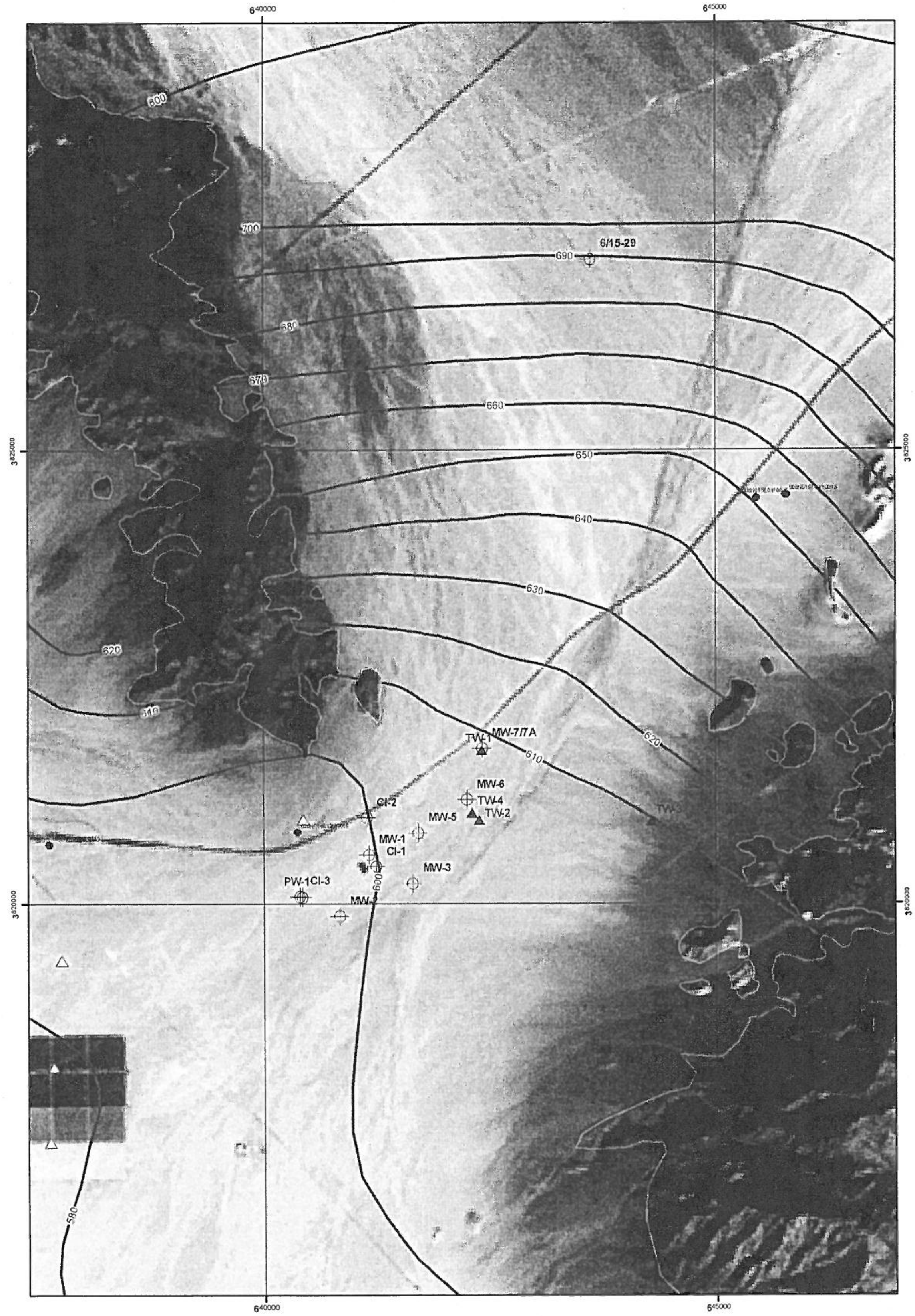
1000 feet/day = ~3.5 x 10^{-1} m/s = ~3.5 x 10 cm/s

Table. 1. Conversion factors for hydraulic conductivity (K) and intrinsic permeability (k) (modified from Ground Water, 1997). **Bold** units are preferred S.I. Note that K is dependent upon the density and viscosity of the fluid that are, in turn, functions of fluid temperature, pressure, and salinity. These values are for fresh water (ρ_w = 1000 kg m^{-3}) and surface conditions (T = ~20 °C and p = ~1 atmosphere).

	K [cm/s]	K **[m/s]**	K [m/day]	K [ft/s]	K [ft/day]	K [ft/yr]	K [gpd/ft²]	k [darcy]	k [cm²]	k **[m²]**	k [ft²]
[cm/s]	1	1.00E-02	8.64E+02	3.28E-02	2.83E+03	1.03E+06	2.12E+04	1.16E+03	1.15E-05	1.15E-09	1.24E-08
[m/s]	1.00E+02	1	8.64E+04	3.28	2.83E+05	1.03E+08	2.12E+06	1.16E+05	1.15E-03	0.000000115	1.24E-06
[m/day]	1.16E-03	1.16E-05	1	3.80E-05	3.28	1.20E+03	2.45E+01	1.35	1.33E-08	1.33E-12	1.43E-11
[ft/s]	3.05E+01	0.305	2.63E+04	1	8.64E+04	3.15E+07	6.46E+05	3.55E+04	3.50E-04	3.50E-08	3.77E-07
[ft/day]	3.53E-04	3.53E-06	0.305	1.16E-05	1	3.65E+02	7.48	0.411	4.06E-09	4.06E-13	4.36E-12
[ft/yr]	9.66E-07	9.66E-09	8.35E-04	3.17E-08	2.74E-03	1	2.05E-02	1.13E-03	1.11E-11	1.11E-15	1.20E-14
[gpd/ft²]	4.72E-05	4.72E-07	4.07E-02	1.55E-06	0.134	4.88E+01	1	5.49	5.42E-10	5.42E-14	5.83E-13
[darcy]	8.58E-04	8.58E-06	7.42E-01	2.82E-05	2.43	8.88E+02	1.82E+01	1	9.87E-09	9.87E-13	1.06E-11
[cm²]	8.70E+04	8.70E+02	7.51E+07	2.85E+03	2.47E+08	9.00E+10	1.84E+09	1.01E+08	1	1.00E-04	1.08E-03
[m²]	8.70E+08	8.70E+06	7.51E+11	2.85E+07	2.47E+12	9.00E+14	1.84E+13	1.01E+12	1.00E+04	1	1.08E+01
[ft²]	8.08E+07	8.08E+05	6.98E+10	2.65E+06	2.29E+11	8.36E+13	1.71E+12	9.38E+10	9.29E+02	9.29E-02	1

Table. 2. Conversion factors for transmissivity (modified from Ground Water, 1997).
Bold units are preferred S.I.

	[m^2/s]	[m^2/min]	[m^2/day]	[ft^2/s]	[ft^2/day]	[gpd/ft]
[m^2/s]	1	6.00E+01	8.64E+04	1.08E+01	9.30E+05	6.96E+06
[m^2/min]	1.67E-02	1	1.44E+03	1.79E-01	1.55E+04	1.16E+05
[m^2/day]	1.16E-02	6.94E-04	1	1.25E-04	1.08E+01	8.05E+01
[ft^2/s]	9.29E-02	5.57	8.03E+03	1	8.64E+04	6.46E+05
[ft^2/day]	1.08E-06	6.45E-05	9.29E-02	1.16E-05	1	7.48
[gpd/ft]	1.44E-07	8.62E-06	1.24E-02	1.55E-06	1.34E-01	1



Legend
DESCRIP
Existing Cadiz Wells
GW Elevation contour (ft msl)*
Exploratory Drilling/Test Well Location
CADIZ AG Wells
Springs
Wells
Interstates
Alluvium-Bedrock Contact

0 0.25 0.5 1 Miles
0 0.25 0.5 1 Kilometers
Projected Coordinate System: NAD 1983 UTM Zone 11N meters

* Refer to Table 4 for summary of groundwater elevation measurements

Figure 4
Groundwater Elevation Contour Map

REPORT - PERMEABILITY OF THE CARBONATE AQUIFER AT CADIZ

The telephone conversation of 29 April 2010 raised a question on the value of hydraulic conductivity of the carbonate aquifer as inferred from the TW-1 pumping tests. One participant stated that a value of 183 ft/day and 170 ft/day (essentially that of a well-sorted fine to medium sand) for the alluvium and carbonate aquifer, respectively, at TW-1 were obtained based upon the pumping test as reported in CH2MHill (2010). I have not seen the analysis that provided these values. I consequently, I cannot comment on this analysis. Well TW-1 penetrated a carbonate system that had not been analyzed heretofore. It is assumed that these data reflect the properties of the Bonanza King formation

My charge has been to examine at the data provided and evaluate the properties of this well and compare it with general characteristics that would be expected in a carbonate aquifer. Specifically, I addressed the question – are this well and the aquifer responding in manner consistent with a karstic carbonate system. My analysis is based primarily upon the following:

1. Well logs and, in particular, the television log;
2. Reported results of the pump test of the well; and
3. Knowledge of carbonate systems in other locales.

The findings/inferences of my previous memo included:

1. The television log shows significant secondary porosity and permeability. There are ~300 feet with many vugs, cavities/conduits, terra rosa (?), and veins that have been re-opened. The karstic features occur over this long reach from 454' to 758' of depth. Some appear to be along relict bedding planes. Some appear to be veins that are nearly normal to these. These indicate widespread karstification; it is a regional, not a local phenomenon. Therefore, these secondary porosity features would be expected to have a reasonable connectivity

The log indicates a well of approximately 1001 feet of depth. A static water level is at a depth of ~330' and the bottom of the well screen is at 454'. The materials above the screened interval are alluvial sediments. From 454' to a depth of approximately 758' there are numerous vugs and dissolution zones. Some of these appear to be along beds (dipping at ~20-45° - note this is approximate); others are subvertical. Some of these appear to be conduits. There is some sparry calcite and calcite (?) druse in some of the conduits, fractures, and veins

Many of these features are sufficiently large to provide very highly transmissive zones. A single fracture with an aperture (opening) of 1/16th of an inch would transmit as much water as a permeable sand layer of a thickness of between 10 to 100 feet. Just a few of these secondary features can provide a very high transmissivity and there are many such potentially productive features apparent in the well log.

From about 758' to ~900-910', there are still small vugs, but the karstic features are not as prevalent. From 910'-920' to the bottom of the well, there are only few, scattered, small karstic features

2. The pump test data are included in the reports of CH2MHill (2010) and GSS (Geoscience Support Services) (2010) showed little drawdown in both the pumping well TW-1 and the

monitoring well (MW-7). The standard analytical procedures can be utilized in the monitoring well, but it must be noted that we are making inferences on very small drawdowns. These are such that it is reasonable to treat the aquifer mathematically as confined as the drawdown (~0.5 feet or less) is much less than the saturated thickness (whether using 403 feet in the GSS, 300 feet of intensely karstified section, or ~650 feet of total saturated thickness). The general rule is that confined test analyses yield accurate results where the ratio of drawdown to saturated thickness is less than 0.02, which is case here.

Carbonate aquifers are highly anisotropic and heterogeneous so extrapolation of one pumping or piezometric test to an entire aquifer must be done with caution. However, the results indicate the TW-1 and MW-7 are well connected. With this mind, consider the results of a Cooper-Jacob time drawdown analysis at MW-7 and TW-1.

2.1. MW-7. The GSS analysis (Fig. 18) is generally correct and a hydraulic conductivity (K) of ~1000 ft/day is indicated. Deviations beginning at t=100 minutes probably reflect boundary conditions. The first straight line portion using the Cooper-Jacob method is the best direct measure of hydraulic conductivity that we have for this unit. The GSS estimates for time up to 10^2 minutes are reasonable. I did use the time drawdown analysis for time between 10^2 and 10^3 minutes; this yields K= ~340 ft/day and S=~0.001. Even this K, which is reflecting boundary conditions, is twice the suggested rate of 170 ft/day. The analyses indicate that for the time of the pump test the aquifer is semi-confined. CH2MHill estimates K = ~1100 ft/day and S = ~10^3.

2.2. TW-1. Because of carbonate aquifer variability, the response at the pumping well gives the best test of aquifer properties. However drawdown was minimal and a draw-up actually occurred because of thermal changes. Storativity cannot be determined by analysis of the pumping well. However, using specific capacity we can estimate a T if we assume s. Using Q = 1168 gpm = 2.25 x 10^5 ft^3/day; t = 1 day, aquifer thickness of 400 ft, well radius = 0.4 ft, and a well efficiency of 100%, we get for an assumed

S= 10^{-3} and s = 0.5, that K = ~870 ft/day
S= 10^{-3} and s = 1.0, that K = ~420 ft/day
S= 0.012 and s = 0.5, that K = ~770 ft/day

There are, of course, and infinite number of such hypothetical scenarios that can be utilized. CH2Mhill estimates K = ~1100 ft/day. However, all the above results indicate that K = 600 ft/day for the carbonates is reasonable and probably conservative.

2.3 Comparison with TW-2 results. CH2MHill estimates K between 304 and 980 ft/day and S = ~10^{-3} with a saturated thickness of 478 ft. GSS estimates K = ~ 654 ft/day and S = 0.002. These are consistent. The fact that during the pumping tests the total drawdown at TW-2 was 6.6 feet after 72 hours and the total drawdown at TW-1 was less than 0.5 feet after 66 hours indicates that the transmissivity and hydraulic conductivity (strata thicknesses – 403-548 at TW-1 and 439-478 at TW-2 - and pumping rates – 1168 at TW-1 and 1130 at TW-2 - are similar) of the carbonate aquifer must be greater than in the alluvial aquifer.

The above observations, the existing data, analyses, and the general nature of karstic aquifers indicate that wherever present:

1. these strata will provide a superb aquifer and

2. 600 feet/day is a reasonable and conservative estimate of the carbonate aquifer's hydraulic conductivity.