APPENDIX I

Feasibility-Level Evaluation of ASR (Pueblo Water Resources, August 2016)

TECHNICAL MEMORANDUM

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Attn:	Elizabeth Drayer, Engineering Manager	Project No:	13-0050
Copy To:	Gerry Nakano, Vice President		
From:	Michael Burke, Principal Hydrogeologist		
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Subject:	Feasibility Level Evaluation of Aquifer Storage and Recovery (ASR), City of Modesto		

This memorandum presents a reconnaissance-level evaluation of the feasibility of the City of Modesto (City) implementing an aquifer storage and recovery (ASR) program whereby seasonally available surplus surface water supplies would be injected into aquifers underlying the City's service area, stored, and subsequently recovered. Considered and discussed in this technical memorandum is the hydrogeologic framework with respect to ASR operations and an assessment and ranking of candidate wells owned by the City that may be suitable for use as ASR facilities. Target aquifers and areas within the City's Sphere of Influence have been identified, and an analysis of the framework and constraints analysis associated with ASR is presented. This conceptual evaluation is intended to provide the City preliminary information regarding the potential capacity of an ASR program for the City.

BACKGROUND

ASR is a form of managed aquifer recharge that involves the seasonal banking of water in an aquifer during times when excess water is available (typically winter and spring), and subsequent recovery of the water from the aquifer when needed (typically fall and summer). ASR utilizes dual-purpose injection/recovery wells for the injection of water for storage and the recovery of the stored water by pumping. The advantage of ASR technology is that it allows recharge to be applied in those geographic areas or aquifer zones with the most need, or where available groundwater storage space is the greatest. In addition, ASR sites require minimal land use area, so they can be more easily located than spreading basins or other recharge facilities.

The City owns and operates 110 groundwater supply wells located throughout the City's service area. Of these 92 are located within the contiguous service area, and 18 are located in the outlying service areas. Conceptually, treated surface water purchase on a wholesale basis from MID could be used when seasonally available surplus supply is available to develop an ASR program for the City. The ASR program may provide to the City the benefits of system peaking, enhanced groundwater operational yield, and improved quality of groundwater supplies.

HYDROGEOLOGIC SETTING

The success of an ASR project depends on the ability to physically place water into the aquifer and to effectively store and retrieve this previously stored water. The hydrogeology of the aquifer system controls the rate at which water can be injected, the amount that can be stored, and the ability to recover the stored water. The hydrogeologic factors affecting the feasibility of an ASR program include groundwater basin structure and geometry, hydrostratigraphy, aquifer hydraulic parameters, and water-level conditions. For example, aquifer transmissivity affects the ability to get water into and out of the aquifer. The lower the transmissivity, the more head (drawup or mounding) will be required at the injection well to achieve a given flow rate. Not all of these factors must be maximized for an ASR project to be successful, as less than optimum conditions for a particular hydrogeologic criterion can be offset by another. For example, in a basin where depth to water is great, lower transmissivities are acceptable as greater drawup is available to convey more water into the target aquifer(s).

Regional Setting

The City's service area is located primarily within the Modesto Subbasin, and portions of the City's service area are within the Turlock Subbasin (to the south), the East San Joaquin Subbasin (to the north), and the Delta-Mendota Subbasin (to the southwest). The subbasins are located within the northern portion of the San Joaquin Valley Groundwater Basin, which is a north-south trending structural trough approximately 200 miles long and 70 miles wide. The trough contains as much as 36,000 feet of sediments derived from marine deposition during periods of inundation by the Pacific Ocean, and continental deposits derived from erosion of the surrounding mountains; the Sierra Nevada to the east and the Coast Ranges to the west. Of the 36,000 feet of sediments within the structural trough, only the upper 800 feet, approximately, are considered to be suitable for groundwater supply development.

The hydrogeologic features of the subbasins that comprise the study area are complex and represent a sequence of overlapping sediments derived primarily from the San Joaquin River, the Stanislaus River, and the Tuolumne River. In general, the subbasins consist of unconfined and confined aquifer systems. The presence of abundant clay layers within the unconfined systems results in semi-confined conditions in some areas. The most distinctive feature of the aquifer system within the study area, and through much of the San Joaquin Valley Groundwater Basin, is the Corcoran Clay, an aerially extensive diatomaceous lacustrine deposit that occurs within the southwestern portion of the study area. The Corcoran Clay is hydrogeologically significant in that it separates the upper and lower Turlock Lake Formation, and occurs at depths of approximately 200 feet in the vicinity of the City. The eastern margin of the Corcoran Clay generally transects the City's service area, trends northwest to southeast, and roughly parallels Highway 99.

In general, the study area is underlain by alluvial deposits of gravel, sand, silt and clay, ranging in age from Holocene to Tertiary. The principal hydrogeologic units in the study area consist of the following units (from youngest to oldest):

- Alluvium
- Modesto Formation

- Riverbank Formation
- Turlock Lake Formation
- Laguna Formation
- Mehrten Formation
- Valley Springs Formation
- Ione Formation

A brief description of these units and their hydrogeologic characteristics and significance is presented below:

Alluvial Deposits. The alluvial deposits consist of unconsolidated sand, silt and clay along rivers. These shallow deposits are generally not saturated and are considered to be non-water bearing.

Modesto Formation. The Modesto Formation is comprised of fluvial deposits of sand, gravel and silt, and is exposed at the surface throughout much of the study area. The Modesto Formation attains thicknesses as much as 120 feet, and generally yields moderate quantities of water where saturated.

Riverbank Formation. Fluvial deposits primarily of sand, with scattered gravel and silt lenses make up the Riverbank Formation. The thickness of this unit varies between 150 feet to 250 feet. Moderate well yields are typical for the Riverbank Formation.

Turlock Lake Formation. The Turlock Lake Formation consists of alluvial deposits of silt, sand, and gravel derived from the Sierra Nevada. The thickness of the Turlock Lake Formation increases toward the western portion of the study, and is generally less than 600 feet maximum. In the western portion of the study area, the Turlock Lake Formation is divided into upper and lower units which are separated by the Corcoran Clay. The Corcoran Clay is an aerially extensive diatomaceous lacustrine clay that underlies portions of the Modesto area, and occurs at the base of the upper Turlock Lake formation. Beneath the City of Modesto, the depth to the top of the Corcoran Clay is approximately 200 feet, and the thickness of the clay is approximately 60 feet. Above the Corcoran Clay, groundwater is generally as unconfined to semi-confined, below the clay, groundwater is confined. The Turlock Lake Formation generally yields moderate to large quantities of water.

Laguna Formation. The Laguna Formation is comprised of alluvial deposits of gravel, sand and silt derived from re-worked Merhten Formation (dark volcanics) and Sierra Nevada (light colored) granitics. Upper and lower units of the Laguna Formation are separated by a strongly developed reddish brown a paleo soil. This formation supports variable well yields.

Merhten Formation. Derived from volcanic rocks, the Merhten Formation consists of sandstone, breccia, conglomerate, tuff, siltstone and claystone. Generally described as ‘black sands’ on driller’s logs, coarser grained units are capable of producing large quantities of water. There are some reports of saline water in western portion of study area within the Merhten Formation, and locally in some other parts of the study area.

Valley Springs Formation. The Valley Springs Formation is a non-marine sequence of tuff, sandstone, siltstone, and claystone, with ash, sand, and gravel generally in a clayey matrix. Generally low to moderate yielding wells are associated with the Valley Springs Formation, but reportedly this unit provides good water quality.

Ione Formation. The Ione Formation consists of lacustrine, lagoonal, and marine deposits consisting of clay, sand, sandstone and conglomerates. Coarse grained units within this formation are cemented or have high clay content, which generally results in low to moderate yields to wells.

Aquifer Systems

Groundwater in the study area occurs under unconfined, semi-confined, and confined conditions. The unconfined aquifer above the Corcoran Clay is comprised of alluvial sediments of the Modesto, Riverbank, and upper Turlock Lake Formations. To the east where the Corcoran Clay does not exist, the unconfined aquifer becomes semi-confined at depth due to the presence of discontinuous clay lenses and extensive paleosols. Toward the east, the unconfined/semi-confined system includes sediments of the Riverbank and Turlock Lake Formations, and also includes sediments from the upper Mehrten formation. The thickness of the unconfined aquifer system increases to the west, and in the vicinity of the City’s service area, the thickness of the unconfined aquifer ranges between approximately 150 feet and 200 feet. Groundwater within the unconfined system generally flows to the west and southwest toward the center of the valley, except in localized areas where pumping troughs have developed.

The freshwater confined aquifer system includes alluvial sediments of the Turlock Lake and Merthen Formations. Confinement of this aquifer system in the western portion of the study area is provided by the Corcoran Clay. The bottom of the freshwater confined system has been defined as the boundary where the specific conductance of groundwater increases above 3,000 microsiemens per centimeter. Near Modesto, the depth of the freshwater confined systems appears to be approximately 400 feet to 500 feet. There are insufficient data to characterize the direction of regional groundwater flow in the confined system; however, because of recharge to the overlying unconfined aquifer system and pumping from the aquifers below the Corcoran Clay, there is likely some degree of downward vertical flow to the confined system.

Water Levels

Groundwater levels in the study area have declined since the 1960’s in response to increases in pumping since that time. Hydrographs prepared by the USGS for select wells representing unconfined and semi-confined aquifers in the vicinity of the City’s service show a steady decline in water levels between the period 1969 through the early 1990’s. Beginning in the early 1990’s, a series of wet years and the completion of the MRWTP in 1995, which provided additional water supply, resulted in water level recovery since that time.

Review of groundwater elevation contour maps for the unconfined aquifer of the Modesto Groundwater Basin dating back to 1958 show the development of a pumping depression over time. Water elevations in the vicinity of the City in 1958 ranged between approximately 70 feet msl to 90 feet msl with no apparent development of a trough at that time. The contours show a westerly to southwesterly flow direction. The development of the trough appears to begin in the early- to mid-1970's, reaching maximum development in the early 1990's when the groundwater surface elevation at center of the trough near the southwest portion of the City was as low as 20 feet msl. Relatively recent groundwater elevation contours (Winter 2011) show that the water surface elevation in the northern portion of the City was about 55 feet msl, and groundwater appeared to flow south/southeast across the City to a pumping trough where the water surface elevation was approximately 25 feet msl.

Groundwater elevation contours for the Modesto Subbasin for selected periods between 1958 and 2010 are presented in the City of Modesto Water Master Plan (West Yost Associates) as Figures 4-4 through 4-7.

Aquifer Hydraulic Parameters

The key aquifer hydraulic parameters affecting groundwater flow and well performance are transmissivity (the product of hydraulic conductivity and saturated thickness) and storativity. These factors affect the ability to move water into and out of the aquifer. For example, the lower the transmissivity, the more head (water level drawup or mounding) will be required at the ASR well to achieve a given injection rate. During injection, excessive well pressures must be limited to avoid fracturing of confining layers or raising offsite water levels to an unacceptable level (e.g., raising ground water levels above ground surface at offsite wells).

Site specific aquifer parameter data can only be developed from controlled pumping tests. The storativity value of an aquifer requires a controlled pumping test and an associated observation well. Absent formal tests of City wells, aquifer parameter data from published reports on the regional aquifer system are available. Transmissivity values may also be estimated using the specific capacity value (pumping rate divided by total drawdown) of a well and a simplified empirical formula (Jacob) that associates well specific capacity to aquifer transmissivity.

Transmissivity values for the unconfined aquifer above and to the east of the Corcoran Clay have been estimated to be within the range of 60,000 gallons per day per foot (gpd/ft) to 80,000 gpd/ft. The USGS has estimated that specific capacities of wells in the unconfined aquifer system within the study area average approximately 56 gallons per minute per foot of drawdown (gpm/ft), which results in a specific capacity of 84,000 gpd/ft. In unconfined aquifers, the storativity is equivalent to the specific yield of the materials, which for the unconfined aquifer has been estimated to range between 7 and 17 percent.

Transmissivity values for the confined aquifer has been estimated to be within the range of 28,000 gpd/ft to 35,000 gpd/ft. The USGS has estimated that specific capacities of wells in the confined aquifer system within the study area average approximately 24 gallons per minute per foot of drawdown (gpm/ft), which results in a specific capacity of 48,000 gpd/ft. The storativity of the confined aquifer is estimated to be within the range of 0.0001 to 0.000001 (dimensionless).

Groundwater Production Wells

As of October 2014, the City had a total of 110 groundwater production wells located throughout the City's entire service area. Of these, 92 wells are located within the City's contiguous service area, with the others located in outlying service areas. The locations of the City's wells within the City's service area are shown on **Figure 1** – Well Location Map. Figure 4-3 in the City of Modesto Water Master Plan (West Yost Associates) shows the locations of the City's wells in relation to the boundaries of the Modesto Subbasin, the Turlock Subbasin, and the Delta Mendota Subbasin.

Construction of the City's wells dates back to the 1920's, although intensification of well drilling and construction began in the 1950's and continues to the present day. The large majority of the City's wells were drilled and constructed by the cable tool method. Construction of City wells by the reverse rotary method, which is the preferred and most common method used today, began in the late 1980's. Since the early 1990's the majority of the wells for the City have been drilled by the reverse rotary method.

Almost all of the City's groundwater production wells are constructed using mild steel casings. More recently, some of the well casings are comprised of a slightly more corrosion resistant grade of steel, for instance copper bearing steel. Due to the age of many of the City's wells and the corrosion and failure of well casings in the past, casing liners have been installed in many of the City's wells. Several wells have been destroyed.

The City's wells generally range in depth between 80 feet and 500 feet, although the depths of most of the City's wells are in the range of approximately 100 feet to 400 feet. Within the City's contiguous service areas, the wells are located in one of two hydrogeologic regimes: in area where the Corcoran Clay is present; and east of the eastern margin of the Corcoran Clay. The majority of the wells within the Corcoran Clay area are completed in the shallower unconfined aquifer that occur above the Corcoran Clay. There are some wells that have well screens that straddle the Corcoran Clay and are completed in the unconfined zone above and within the confined aquifer below. Only two wells (MOD063 and MOD066) are thought to be completed solely in the deeper confined aquifer below the Corcoran Clay. East of the Corcoran Clay, the wells are completed in unconfined to semi-confined aquifer units.

The aquifers in which the City's wells are completed can be quite prolific in terms of well yields. There is a wide range in pumping rates among the City's wells, but some of the wells are capable of producing as much as 2,500 gpm. Specific capacities of the City's wells are within the range of less than 5 to as much as 230 gpm/ft.

Groundwater quality issues exist for many of the City's wells. High concentrations of arsenic, nitrate, uranium, perchloroethylene (PCE), trichloroethylene (TCE), dibromochloropropane (DBCP) have required blending where allowed or have resulted in wells being taken out of service.

The data pertaining to the City’s wells, including depth, casing design, screened intervals, hydrogeologic location, completion details, production capacity, and specific capacity were evaluated to preliminary suitable candidate wells for this preliminary ASR assessment.

SCREENING LEVEL ASR FEASIBILITY ANALYSIS

Existing Wells Injection Capacities

For purposes of providing initial screening-level estimates of injection capacities of all existing City-owned wells within the contiguous service area, a methodology is used where the per-well injection capacity is estimated based on the following factors:

- Reported existing pumping capacity.
- Specific injectivity is assumed to be one-half of existing specific capacity.
- Available freeboard for water level drawup within well casings is based on the distance between Spring 2011 static water levels and ground surface (i.e., no pressurized injection).

The estimated injection capacity is the minimum of the three factors (i.e., injection capacity is not allowed to exceed pumping capacity). The resulting estimates are summarized in **Tables 1 and 2** and are discussed below. **Table 1** presents estimates for wells located within the unconfined area east of the area where the Corcoran Clay is present, and Table 2 presents estimates for wells in the Confined area (the area where the Corcoran Clay exists). These wells are either in the shallower unconfined aquifers above the Corcoran Clay or completed across the Corcoran Clay, in both the shallower unconfined aquifers and the confined aquifer below the Corcoran Clay. Only two wells (MOD063 and MOD066) are thought to be completed solely in the deeper confined aquifer below the Corcoran Clay.

Table 1. Screening-Level Injection Capacity Estimates for Existing Wells East Unconfined Area

Well ID	Aquifer	Pumping Rate (gpm)	Specific Capacity (gpm/ft)	Assumed Specific Injectivity (gpm/ft)	Avail. DUP[1] (ft)	Theoretical Injection Rate (gpm)	Estimated Injection Rate (gpm)
65	Unconfined	2500	69.0	34.5	56	1932	1932
39	Unconfined	1850	138.0	69.0	53	3657	1850
16	Unconfined	1700	131.0	65.5	48	3144	1700
45	Unconfined	1550	74.0	37.0	59	2183	1550
21	Unconfined	1500	94.0	47.0	44	2068	1500
25	Unconfined	1500	136.0	68.0	44	2992	1500
41	Unconfined	1500	94.0	47.0	68	3196	1500
48	Unconfined	1608	50.0	25.0	58	1450	1450
54	Unconfined	2200	48.0	24.0	59	1416	1416
52	Unconfined	1400	50.0	25.0	58	1450	1400
46	Unconfined	1150	96.0	48.0	56	2688	1150
47	Unconfined	1150	164.0	82.0	62	5084	1150
225	Unconfined	1140	57.0	28.5	60	1710	1140
267	Unconfined	1140	52.0	26.0	46	1196	1140
62	Unconfined	1900	40.0	20.0	56	1120	1120
17	Unconfined	1100	92.0	46.0	42	1932	1100
61	Unconfined	1644	42.0	21.0	49	1029	1029
204	Unconfined	1000	167.0	83.5	60	5010	1000
211	Unconfined	1000	167.0	83.5	54	4509	1000
277	Unconfined	1000	77.0	38.5	83	3196	1000
282	Unconfined	980	89.0	44.5	36	1602	980
307	Unconfined	950	79.0	39.5	62	2449	950
43	Unconfined	925	132.0	66.0	47	3102	925
40	Unconfined	900	90.0	45.0	61	2745	900
286	Unconfined	850	142.0	71.0	87	6177	850
310	Unconfined	824	52.0	26.0	72	1872	824
269	Unconfined	800	80.0	40.0	53	2120	800
278	Unconfined	800	133.0	66.5	57	3791	800
302	Unconfined	800	80.0	40.0	98	3920	800
18	Unconfined	750	125.0	62.5	50	3125	750
279	Unconfined	750	68.0	34.0	68	2312	750
308	Unconfined	750	29.0	14.5	82	1189	750
51	Unconfined	2500	46.0	23.0	31	713	713
50	Unconfined	688	172.0	86.0	48	4128	688
212	Unconfined	682	52.0	26.0	80	2080	682
312	Unconfined	1000	17.0	8.5	80	680	680
59	Unconfined	1280	17.0	8.5	78	663	663
6	Unconfined	600	43.0	21.5	47	1011	600
291	Unconfined	587	19.0	9.5	77	732	587
292	Unconfined	530	33.0	16.5	84	1386	530
300	Unconfined	700	19.0	9.5	53	504	504
245	Unconfined	495	62.0	31.0	102	3162	495
64	Unconfined	1963	24.0	12.0	41	492	492
265	Unconfined	475	59.0	29.5	63	1859	475
247	Unconfined	450	30.0	15.0	66	990	450
309	Unconfined	440	113.0	56.5	104	5876	440
242	Unconfined	404	135.0	67.5	91	6143	404
244	Unconfined	400	67.0	33.5	97	3250	400
255	Unconfined	400	29.0	14.5	55	798	400
262	Unconfined	400	28.0	14.0	52	728	400
275	Unconfined	400	133.0	66.5	78	5187	400
289	Unconfined	700	14.0	7.0	57	399	399
295	Unconfined	500	17.0	8.5	45	383	383
259	Unconfined	360	28.0	14.0	55	770	360
58	Unconfined	900	17.0	8.5	40	340	340
303	Unconfined	320	53.0	26.5	91	2412	320
274	Unconfined	218	31.0	15.5	19	295	218
256	Unconfined	200	15.0	7.5	51	383	200
271	Unconfined	200	50.0	25.0	45	1125	200
272	Unconfined	192	48.0	24.0	105	2520	192
306	Unconfined	155	14.0	7.0	65	455	155
						Min	**155**
						Max	**1932**
						Average	**811**
						Total	**49475**

Notes:

1 - Available Draw up (DUP) based on Spring 2011 water levels.

Table 2. Screening-Level Injection Capacity Estimates for Existing Wells Confined Area

Well ID	Aquifer	Pumping Rate (gpm)	Specific Capacity (gpm/ft)	Assumed Specific Injectivity (gpm/ft)	Avail. DUP[1] (ft)	Theoretical Injection Rate (gpm)	Estimated Injection Rate (gpm)
38	Shallow	1190	60.0	30.0	34	1020	1020
1	Shallow	1000	125.0	62.5	49	3063	1000
7	Shallow	1000	67.0	33.5	43	1441	1000
36	Shallow	925	231.0	115.5	41	4736	925
57	Shallow	1350	38.0	19.0	48	912	912
4	Shallow	900	90.0	45.0	47	2115	900
299	Shallow	1350	64.0	32.0	27	864	864
284	Shallow	840	84.0	42.0	55	2310	840
305	Shallow	830	42.0	21.0	66	1386	830
3	Shallow	800	44.0	22.0	50	1100	800
29	Shallow	1000	50.0	25.0	30	750	750
283	Shallow	750	47.0	23.5	39	917	750
287	Shallow	700	44.0	22.0	62	1364	700
297	Shallow	1375	44.0	22.0	29	638	638
30	Shallow	1050	42.0	21.0	30	630	630
100	Shallow	600	100.0	50.0	42	2100	600
10	Shallow	511	57.0	28.5	43	1226	511
250	Shallow	1050	33.0	16.5	30	495	495
223	Shallow	475	95.0	47.5	44	2090	475
217	Shallow	450	28.0	14.0	47	658	450
237	Shallow	450	32.0	16.0	33	528	450
49	Shallow	438	27.0	13.5	46	621	438
216	Shallow	425	28.0	14.0	48	672	425
229	Shallow	448	19.0	9.5	40	380	380
232	Shallow	850	29.0	14.5	24	348	348
241	Shallow	300	23.0	11.5	33	380	300
213	Shallow	247	49.0	24.5	57	1397	247
304	Shallow	525	7.0	3.5	31	109	109
56	Shallow	550	6.0	3.0	29	87	87
301	Shallow	385	4.0	2.0	34	68	68
						Min	**68**
						Max	**1020**
						Average	**598**
						Total	**17942**
33	Shallow/Deep	1925	175.0	87.5	37	3238	1925
42	Shallow/Deep	1121	93.0	46.5	43	2000	1121
63	Deep	1845	49.0	24.5	36	882	882
298	Shallow/Deep	1300	50.0	25.0	30	750	750
290	Shallow/Deep	617	206.0	103.0	29	2987	617
66	Deep	1525	13.0	6.5	42	273	273
313	Shallow/Deep	826	14.0	7.0	31	217	217
281	Shallow/Deep	500	10.0	5.0	32	160	160
						Min	**160**
						Max	**1925**
						Average	**743**
						Total	**5945**

Notes:

1 - Available Draw up (DUP) based on Spring 2011 water levels.

Unconfined Area. The initial estimated injection capacities of the existing wells located in the Unconfined Area (i.e., wells located east of the Corcoran Clay) range between approximately 155 to 1,930 gpm, averaging approximately 810 gpm (1.17 mgd). Further review of **Table 1** reveals that Well 65 has the highest initial estimated injection capacity of approximately 1,930 gpm (2.78 mgd). The total combined estimated injection capacity of all 61 existing City wells in the Unconfined Area is approximately 49,500 gpm (71.3 mgd).

Confined Area - Shallow Aquifer. The initial estimated injection capacities of wells completed in the Shallow Aquifer (i.e., above the Corcoran Clay) in the Confined Area range between approximately 70 to 1,020 gpm, averaging approximately 600 gpm (0.864 mgd). Further review of **Table 2** reveals that Well 38 has the highest initial estimated injection capacity of approximately 1,020 gpm (1.47 mgd). The total combined estimated injection capacity of all 30 existing City wells in the Shallow Aquifer in the Confined Area is approximately 17,940 gpm (25.8 mgd).

Confined Area - Deep Aquifer. The initial estimated injection capacities of existing City wells completed in the Deep Aquifer (i.e., below the Corcoran Clay) in the Confined Area range between approximately 160 to 1,925 gpm, averaging approximately 740 gpm (1.07 mgd). It is noted that of the 8 City wells that penetrate the Deep Aquifer, only two are solely completed in this aquifer, with relatively moderate estimated injection capacities ranging between approximately 270 to 880 gpm. Further review of **Table 2** reveals that Well 33 (completed in both the Shallow and Deep Aquifers) has the highest estimated injection capacity of approximately 1,925 gpm (2.77 mgd). The total combined estimated injection capacity of all 8 existing City wells that penetrate the Deep Aquifer is approximately 5,950 gpm (8.57 mgd).

Existing Wells Injection Capacities – Site-Specific Analyses

The above initial screening-level analysis identified the following three wells as having the highest preliminary estimated injection capacities in each of the three aquifers within the City's contiguous service area:

- Well 65 (Unconfined Aquifer)
- Well 38 (Confined Area – Shallow Aquifer)
- Well 33 (Confined Area – Shallow / Deep Aquifers)

Based on our review of the Well Completion Reports for these wells, we find no apparent fatal flaws with regards to their as-built constructions that would preclude them as potential candidate ASR testing sites (e.g., screen consists of torch-cut slots, missing or incomplete information regarding well completion, lithology, etc.); therefore, these wells have been selected as potential candidates for ASR testing and are analyzed further utilizing a more in-depth site-specific methodology compared to the above initial screening-level methodology. Key as-built construction and well performance data most relevant to ASR capacity analysis for the three selected wells are summarized in **Table 3** below:

Table 3. Summary of As-Built Construction and Well Performance

Well	Total Depth (ft. bgs)[1]	Seal Depth (ft. bgs)	Screen Intervals (ft bgs)		Total Screen (ft)	Q[2] (gpm)	s[3] (ft.)	Q/s (gpm/ft)
			Top	Bottom				
65	379	131	165	374	91	2,500	36	69.4
38	221	108	105	213	108	1,190	20	59.5
33	278	102	96	278	182	1,925	11	175

Notes:

1 - feet below ground surface (bgs).

2 - discharge rate (Q).

3 - total drawdown after 24 hours (s).

The injection capacity of any given dual-purpose ASR well is dependent on a variety of site-specific factors, which can be generally categorized into issues associated with; 1) well response to injection, and 2) aquifer response to injection. Examples of issues associated with the well response include allowable drawup within the well casing before some head limitation is reached, and the available drawdown for well backflushing. Issues associated with aquifer response to injection involve the available "freeboard" in the aquifer for water levels (piezometric head) to be increased without inducing undesirable results. To the extent possible, ASR wells should be designed and operated to maximize injection and production rates while operating within the constraints of these site-specific factors. A discussion of each of these factors and their influence on the theoretical injection capacities of ASR wells based on the hydraulic parameters developed from data generated at the identified City-owned well sites is presented below.

Well Response to ASR

One method of estimating the injection capacity limits of an ASR well is to determine the amount of drawup available within the well casing for injection, and calculate the maximum injection rate based on the theoretical water level response to injection utilizing the Theis equation (Theis, 1935).

Available Drawup. During injection, the water level (head) in the well and aquifer will increase due to mounding in the aquifer. The available drawup in the well casing for injection is determined based on the depth to water prior to injection (static water level) plus the amount of wellhead pressurization considered reasonable (if any).

As discussed above, the available water-level data indicate that depths to water at City wells range between approximately 25 and 50 feet, depending on location and aquifer. A wellhead pressure of 30 psi (approximately 70 feet equivalent head of water) is considered a reasonable maximum for pressurized injection, based on conservative estimates of the conventional grades of casing, pump seals, and instrument components. A summary of the available drawup constraints for each well based on the above limiting criteria is presented below in **Table 4**.

Table 4. Available Drawup Summary

Well	Available Drawup (ft.)	
	Minimum (DTW)[1]	Maximum (30 psi)
65	56	125
38	34	103
33	37	106

Notes:

1 - Depth to Water (DTW) based on Spring 2011 levels.

As shown in **Table 4**, the available drawup within the well casings (under Spring 2011 conditions) below ground surface ranges between approximately 35 and 55 feet. For pressurized injection scenarios, the total available drawup ranges between approximately 105 to 125 feet. It is noted that following periods of drought or increased levels of seasonal extraction when water levels in the basin are lower, more drawup for injection would be available. For purposes of this preliminary analysis, however, pre-drought spring-time high water levels are utilized to conservatively constrain the injection capacity estimates.

Well Response to Injection. The theoretical drawup response of a well to injection can be calculated utilizing the Theis equation and aquifer parameters of transmissivity and storativity. As discussed previously, transmissivity estimates for the various aquifer formations that City wells penetrate range between approximately 30,000 to 80,000 gpd/ft, depending on location and aquifer formation(s). Storage coefficient values similarly vary, ranging between approximately 1×10^{-1} to 10^{-6} (dimensionless). For test well sites with pumping test data, the site-specific transmissivity values are utilized. For this analysis, assumed aquifer parameter values are used based on the aquifer penetrated as follows:

- Unconfined and Shallow Aquifers:
  - T = 70,000 gpd/ft
  - $S = 1 \times 10^{-1}$
- Deep Aquifer:
  - T = 30,000 gpd/ft
  - S = 1 x 10-5

For purposes of this preliminary analysis, it is assumed that essentially continuous injection operations would occur over a six month wet / low-demand period, e.g., from December through May (183 days continuous, interrupted only briefly for periodic backflushing).

The theoretical calculations based on the Theis equation assume a perfectly efficient well without hydraulic losses in the well casing, well screen, gravel pack or well bore. In practice, however, properly constructed new municipal and ASR wells typically have efficiencies of approximately 60 to 80 percent. For purposes of this preliminary analysis, the current well efficiencies based on Spring 2011 performance testing are utilized.

Based on these relationships and assumptions, the resulting injection rate that would raise water levels within the well casing to: 1) ground surface, and, 2) result in 30 psi of wellhead pressure, after 183 days of injection are presented in **Table 5** below:

Table 5. "Theoretical Well Response" Injection Rate Summary

Well	Theoretical Injection Capacity (gpm)		Well Efficiency (%)	Injection Rate w/ Efficiency Losses[1]	
	Min (gs)	Max (30 psi)		Min (gs)	Max (30 psi)
65	1950	4360	60	1170	2616
38	1200	3600	61	732	2196
33	375	1070	60	225	642
Notes:					
1 - Well hydraulic efficiency based on Spring 2011 performance testing.					

As shown in **Table 5**, it is estimated that theoretical injection rates (accounting for efficiency losses) ranging between 225 to approximately 1,170 gpm would create drawup within the ASR well casings that would raise water levels up to ground surface after 183 days of continuous injection (with routine backflushing to limit plugging). Allowing for pressurized injection (up to 30 psi of wellhead pressure), injection rates ranging between approximately 640 and 2,615 gpm are theoretically feasible. In general, wells in the Unconfined Area and Shallow Aquifer of the Confined Area tend to have greater theoretical capacities (e.g., Wells 65 and 38, respectively) whereas the well located in the Confined Area and completed in the Deep Aquifer appears to be less favorable.

Backflushing Capacity. This constraint considers the amount of drawdown available above the perforations for backflushing. No source of injection water is completely free of particulates; therefore, backflushing (i.e., pumping) of injection wells is routinely performed to create flow reversals in the well, which removes particles introduced into the well during injection (this is analogous to backwashing of media filters to affect particulate removal). Periodic, vigorous backflushing is absolutely necessary to maintain injection capacity. The ability to adequately backflush ASR wells while maintaining a flooded perforated section is, therefore, a critically important consideration when designing and operating ASR well facilities.

Based on experience at other injection wells, it has been shown that it is desirable to backflush injection wells at rates of at least twice the rate of injection in order to maximize backflushing effectiveness. This is done to create pore throat velocities that are sufficient to remove particulates introduced during injection that have filled pore spaces and cling to grains of sand. This criterion is considered to be the most conservative and important for maintaining long-term injection performance, and is, therefore, at least initially, adopted as the limiting backflushing criteria utilized for this project. For purposes of this preliminary analysis, it is assumed that an ASR well at any given site would have comparable perforated intervals as the existing City well. A summary of the factors related to backflushing capacities for the potential ASR sites is presented in **Table 6** below:

Table 6. "Backflushing Capacity" Constraint Summary

Well	SWL[1] (ft bgs)	Top of Screen (ft bgs)	Available Drawdown (ft)	Q/s (gpm/ft)	Capacity (gpm)	
					Backflush	Injection
65	**56**	165	109	69.4	7569	3785
38	**34**	105	71	59.5	4225	2112
33	**37**	96	59	175.0	10325	5163
Notes:						
1 - Static Water Level (SWL)						

As shown in **Table 6**, theoretical injection rates as constrained by backflushing capacity range between approximately 2,110 gpm up to 5,160 gpm.

Downhole Velocity. The well's internal diameter is another limiting factor on the injection capacity. Experience at other injection wells has shown that excessive downhole velocities can lead to the entrainment of air bubbles, sweeping them into the well screen and formation, which results in air binding and plugging of the well. The internal casing diameter is directly proportional to the downhole velocity (DHV) of the injected water. Limiting downhole velocities below the rate at which average size air bubbles rise (1.0 ft/sec; Olsthoorn, 1982), has been shown to be a prudent injection well operational constraint. A summary of the downhole velocity constraints for the selected wells is presented in **Table 7** below:

Table 7. Downhole Velocity Constraint Summary

Well	Casing Diam. (in)	Injection Rate (gpm)
65	18	793
38	18	793
33	16	627

As shown in **Table 7**, the injection rates are limited to approximately 630 to 790 gpm by the downhole velocity constraint.

Aquifer Response to ASR

Utilizing the aquifer parameters presented previously, the theoretical water-level mounding response to injection within the aquifer system can also be calculated utilizing the Theis equation. These aquifer parameters relate to other potential constraints in ASR well operations, as described and analyzed below.

Hydrofracturing Limits. As discussed previously, the target aquifers for injection are generally semi-confined to confined. During injection, the injection heads must not exceed pressures that would create vertical cracks in the confining layers (hydraulic fracturing) through which injected water may flow upward into overlying sediments or to the ground surface ('daylighting'). The pressure in the confined aquifer must not exceed vertical grain pressures of the materials overlying the confining layer to avoid hydraulic fracturing. Based on soil mechanics, Huisman and Olsthoorn (1983) suggest that the maximum allowable drawup to avoid hydraulic fracturing can be calculated using the equation:

$$s < 0.22\ (A+B)$$

Where:
s = total drawup (ft)
A = depth from ground surface to the top of the confining layer (ft)
B = depth from ground surface to static water level (ft).

The depths to the top of the confining layer above the completed aquifer at each well were determined based on review of the lithologic logs. Utilizing the Theis equation and the aquifer parameters presented previously, the estimated injection rates that would be within the hydrofracturing limits at the borehole wall (1.0 ft radius) for the subject well is presented in **Table 8** below:

Table 8. "Hydrofracturing" Constraint Summary

Well	Depth to Confining Layer (ft)	Static Water Level (ft bgs)	Total Available Drawup (ft)	Max. Injection Rate (gpm)
65	156	56	47	1650
38	72	34	23	800
33	77	37	25	250

As shown in **Table 8**, injection rates as constrained by hydrofracturing potential limits range from approximately 250 gpm up to 1,650 gpm.

Offsite Impacts Limits. This constraint is based on estimates of the maximum injection rate that can be achieved without causing water levels in the aquifer system offsite to rise above some level that would cause undesirable results. Typically, this means raising water levels above the ground surface at an offsite well and causing it to become artesian and start flowing at the surface (i.e., daylighting). Utilizing the Theis equation and the aquifer parameters presented above, the maximum injection rate that can be sustained for 183 days without raising water levels above ground surface at the nearest known offsite well is summarized in **Table 9** below:

Table 9. "Offsite Impact Limits" Constraint Summary

Well	Distance to Nearest Offsite Well (ft)	Allowable Drawup (ft)	Max. Injection Rate (gpm)
65	2295	55	16250
38	1975	35	9000
33	3800	35	975

As shown in **Table 9**, injection rates as constrained by offsite impact limits range from as low as 975 gpm up to 16,250 gpm.

Summary of Injection Well Capacity Constraints

A summary of all the site-specific injection capacity constraints presented above for the three ASR candidate City well sites is presented in **Table 10** below:

Table 10. Injection Capacity Constraints Summary

Well	Injection Capacity (gpm) vs. Constraint					
	Well Response		Backflushing Capacity	Downhole Velocity	Hydro-Fracturing	Offsite Impacts
	Min (gs)	Max (30 psi)				
65	1170	2616	3785	**793**	1650	16250
38	**732**	2196	2112	793	800	9000
33	**225**	642	5163	627	250	975
Notes:						
Primary limiting factors shown in **bold** type.						

In summary, evaluation of the various hydrogeologic and operational factors that constrain the injection capacities of the three identified potential candidate ASR testing sites reveals that the primary limiting factor on the injection capacity of Well 65 is the downhole velocity criterion (i.e., is limited by the 18-inch-diameter casing), which limits the **injection rate to approximately 790 gpm (1.14 mgd)**, regardless of the theoretical capacity as constrained by any other criteria.

The evaluation also reveals that the well response to injection (without pressurized casing injection) criterion is the primary limiting factor at Wells 38 and 33, which limits **injection rates to approximately 730 and 225 gpm (1.05 and 0.324 mgd), respectively**. This finding is not surprising given the relatively shallow depths to water in the area (both of these wells are located in the Confined Area in the western portion of the service area). If pressurized casing injection is determined to be an acceptable practice, then the downhole velocity criterion becomes the limiting factor at Well 38 and the hydrofracturing criterion becomes the limiting factor at Well 33, with injection rates of approximately 790 and 250 gpm (1.14 and 0.360 mgd), respectively.

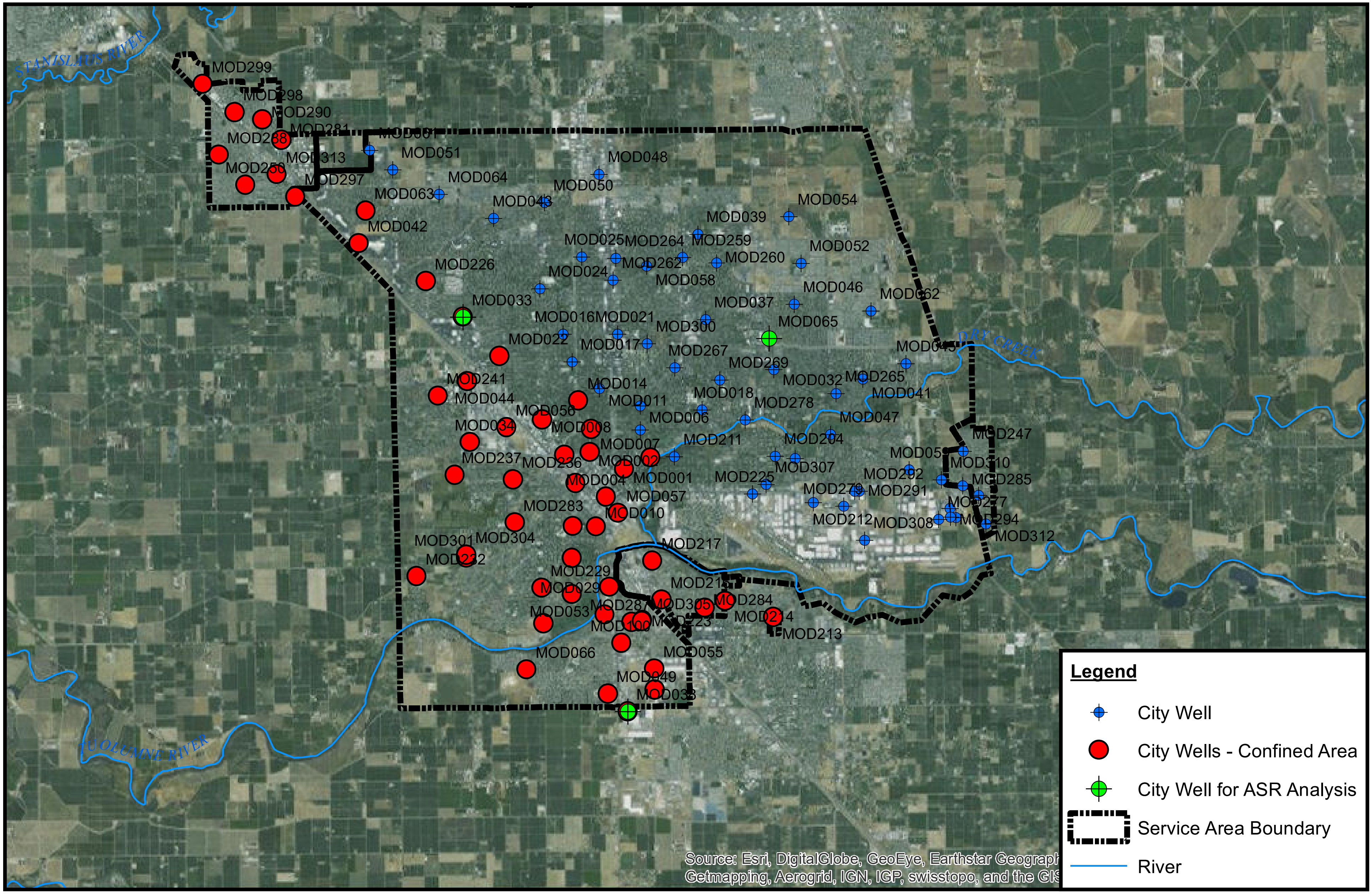
CONCLUSIONS AND RECOMMENDATIONS

Pueblo’s primary conclusion developed through the Feasibility Level Evaluation of Aquifer Storage and Recovery for the City of Modesto is that ASR appears to be viable water supply management tool available to the City. We recommend that the City further advance the establishment of an ASR program with a focused evaluation of the various components integral to ASR operations, such as: analysis of source water availability and source water quality; geochemical interactions between source water and native groundwater; and regulatory issues associated with ASR operations. Pilot ASR testing (ASR Demonstration Test Program) is also recommended in order to empirically verify the conclusions of the initial study and to develop site-specific data regarding the effectiveness, impacts, and economics of ASR. These test program data would then serve as the basis for evaluating, planning, and permitting a full-scale ASR program within the City. The City may choose to perform the demonstration project using an existing well, or by upgrading a new well (such as the upcoming Tivoli Well slated to be designed as a municipal extraction well).

The goals of the ASR Demonstration Test Program would include the following:

- Demonstrate/verify the beneficial impacts to water levels in the basin from ASR operations.
- Demonstrate/verify that beneficial injection rates can be maintained for sustained periods of injection (i.e., no significant loss in well efficiency).
- Demonstrate/quantify the effectiveness of periodic well flushing on well performance (i.e., specific capacity).
- Verify/quantify that the recovered water meets all Title 22 drinking water standards.
- Verify/quantify that the recovered water does not create or exacerbate any consumer acceptance issues (i.e., taste, odor, visual clarity, effervescence, etc.).
- Verify/quantify that injected water remains geochemically stable during storage and recovery.
- Quantify the benefits to aquifer water quality (including stability and salt balance issues) from ASR operations.

August 2016
Project No. 13-0051



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographi
Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS

PUEBLO
water resources

N
W E
S

1 inch = 10,000 feet

0 5,000 10,000 20,000
Feet

FIGURE 1. WELL LOCATION MAP
Reconaissance-Level Evaluation of ASR Wells
West Yost Associates / City of Modesto