YIELD AND SUSTAINABILITY OF LARGE SCALE SLANT WELL FEEDWATER SUPPLIES FOR OCEAN WATER DESALINATION PLANTS

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Abstract:

There is no theoretical upper limit of the yield and sustainability of slant wells used as a source of feed water supply to ocean desalination plants. Research and field testing over the past nine years suggest that slant wells extracting water from subsea alluvial aquifers can provide a high yielding and long-lasting sustainable water supply when designed, constructed and maintained properly. Furthermore, the total yield is a function of scale and the reliability is guaranteed by the ocean source. Slant wells are angled wells completed in aquifers beneath the ocean floor and receive a high percentage of recharge from both vertical leakage (through the seabed) as well as horizontal flow from offshore aquifers. Natural filtration in the subsea permeable deposits results in low turbidity and reduction or elimination of seawater reverse osmosis (SWRO) pretreatment. Environmental advantages include lack of impacts to fish and marine life and no surface visibility. Maximum supply limitations are a function only of the permeability of near shore and offshore aquifers, the areal and vertical extent of these deposits, the availability of land, and potential adverse impacts. Slant wells are merely vertical wells drilled on an angle. As such, sustainability of flow is assured by the same routine maintenance programs developed over the past seven decades and routinely utilized in vertical wells. Using the dual-rotary method of construction and incorporating a telescopic design, 4 mgd slant wells can be constructed with angles ranging from a few degrees to a few tens of degrees and achieve lengths of 1,000 ft or more. Variable angles allow targeting production from specific aquifers and longer well screen lengths result in higher production than vertical wells. A slant well layout may be comprised of a single well or group of wells within the same wellhead area (i.e., pod). Multiple slant well arrays may be constructed and “linked” together until the cumulative total discharge rate meets the feed water supply demand. Interference between wells governs the number and spacing and geohydrologic considerations and land availability govern limitation on spatial extent. For example, for typical California coastal aquifers, a feed water supply of nine slant well pods with each pod containing three 4 mgd slant wells can yield approximately 117 mgd from a two mile reach of coastline. The Monterey Peninsula Water Supply Project has recently completed a 724 ft test slant well at an angle of 19 degrees below horizontal north of Monterey, CA. The well is currently undergoing long-term testing to develop well and aquifer parameters and potential impacts for the 24 mgd full scale project which will consist of ten slant wells including standby capability. Routine maintenance employing mechanical cleaning on the order of every three to five years provides a long-term sustainable feed water supply. The current misconceptions that slant wells yield only low amounts of supply and that they contribute to seawater intrusion is false. Experience gained has shown that the primary constraint to development of subsurface feed water supplies is permitting. This paper discusses research and experience on slant well and well field design and upward scalability for large SWRO desalination feed water requirements exceeding 200 mgd.

I. INTRODUCTION

1.1 Background

The number of subsurface intakes throughout the world is relatively small compared to open ocean intakes; averaging approximately 12 mgd per facility as compared to approximately 52 mgd per facility for open ocean intakes (Table 2; Missimer, 2013 and GHD, 2012). Slant well feed water supplies for SWRO desalination plants is an emerging technology. Originating out of the necessity to explore subsea aquifers near Dana Point, CA, the first test slant well was constructed in 2006. Since then, a number of subsurface intakes for SWRO have been and are continuing to be evaluated along the California coast ranging in size from small systems (< 10 mgd) to very large systems (> 150 mgd). As of this writing, a 724 ft test slant well completed in March of 2015 near Monterey, California as part of the Monterey Peninsula Water Supply Project (MPWSP) is currently undergoing long-term test pumping.

Slant wells are simply vertical wells drilled on an angle and produce water from near shore and subsea aquifers. Drawing seawater from subsea and near shore aquifers provides natural filtration from suspended organic matter and sediment, particularly during storm surges and heavy precipitation. Slant wells receive recharge from vertical leakage through the sea floor (i.e., benthic zone) and horizontal flow from subsea and near shore aquifer systems. Field tests show that the engineered artificial filter pack surrounding the screened portion of the slant well intake results in very low turbidity (i.e., low SDI indices) which minimizes the need for RO pre-treatment. A slant well feed water supply typically consists of shallow angled wells[1] in a beach or near-coastal environment. The supply may consist of a single slant well, an array of wells or multiple arrays of wells grouped together into "pods"[2] extending beneath the ocean. As long as there are permeable subsea deposits, available land, and no undesirable impacts, there is no theoretical upper limit to the quantity of feed water which can be produced from slant wells. Environmentally sensitive, slant well systems are buried systems completed below the land surface eliminating both impingement and entrainment issues to marine life as well as undesirable aesthetic impacts (i.e., no visual impacts on the surface).

1.2 Subsurface Intakes - The Preferred Technology for SWRO Intakes in California

In a recent amendment to the Water Quality Control Plan for Ocean Waters of California (i.e., "Ocean Plan"), the California State Water Resources Control Board (SWRCB, 2014), recommended to "Establish subsurface intakes as the preferred technology for seawater intakes." In accordance with the Ocean Plan amendment, a number of desalination projects along the coast of California have evaluated or are in the process of evaluating the feasibility of subsurface intakes for feed water supply (see Figure 1).

Figure 1. Projects along the California coast which have considered or are evaluating the feasibility of subsurface intake systems

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[1] For purposes of this paper, the word angled well and slant well both refer to a non vertical well and are used interchangeably.

[2] A slant well pod is the common wellhead area for multiple slant wells with each well in the pod having varying azimuth angles.

Currently, only ten small desalination facilities are in operation along the California coast with 15 more in the feasibility phase and with a cumulative fresh water output ranging from 260–367 mgd (SWRCB, 2014).

II. KNOWLEDGE GAINED FROM THE DOHENY AND MONTEREY TEST SLANT WELL PROJECTS

The Doheny Ocean Desalination Project[3] near Dana Point, California has been summarized extensively in previous documents (Williams, 2007, 2008, 2011 and 2012; Charette, 2012; and GEOSCIENCE, 2007 and 2012). A few years after construction of a test slant well in 2006, an approximate two year extended pumping test ensued from 2010-2012. Since then, improvements on the technology have been made and applied to the recently completed MPWSP test slant well north of Marina in Monterey County, California. The Doheny test slant well represents the first successful high capacity slant well completed with an artificial filter pack beneath the ocean floor. At 23 degrees below horizontal and a total lineal length[4] of 350 ft, it was the longest dual rotary-drilled artificially filter packed slant well until recently, when the Monterey test slant well was drilled to a total MD of 724 ft. Continuing work on both the Doheny and Monterey projects is still in progress which will include additional testing, predictive ground water modeling, and final design of the full scale projects.

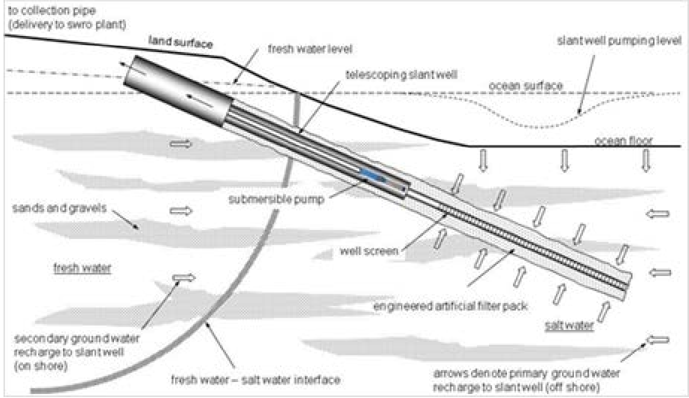

Figure 2. Telescoping Well Design

2.1 Telescoping Well Design

During the two year pilot testing, the Doheny test slant well produced approximately 3 mgd with relatively stable drawdowns. When it was constructed in 2006, it was test pumped at approximately 2,100 gpm[5] and displayed a well efficiency of 95%. During the extended pilot testing the well efficiency dropped from the original value of 95% in 2006 to 52% in 2012 (GEOSCIENCE, 2012).

Figure 3. Monterey Test Slant Well (19 degrees 724 ft)

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[3] Formerly the South Orange Coastal Ocean Desalination Project (SOCOD)

[4] In angled wells, the term lineal length or “Measured Depth” or MD is used. MD is the length of the well bore as determined by a measuring stick as compared to true vertical depth (TVD) which is a straight vertical line from the surface to the bottom of the borehole (or anywhere along its length).

[5] The pump used for the two year extended pumping test was a high speed, high capacity pump (2480 rpm) producing 2,200 gpm.

This loss of well efficiency was expected due to the inability to fully develop the well during construction. Specifically, due to limited funding, the Doheny test slant well project was completed with a uniform 12-inch diameter casing and screen without a larger diameter pump house chamber. Consequently, the largest diameter submersible test pump that could be installed in the well was ten inches with a maximum discharge rate of 1,700 gpm. The standard industry practice is to develop a well at 1.5 times the design discharge rate, or approximately 3,200 gpm for a design discharge rate of 2,100 gpm. Figure 2 shows a typical telescoping well design and Figures 3 and 4 show the telescoping well design used in the Monterey test slant well north of the town of Marina in Monterey County, California.

2.2 Larger Pump House Casings

Due to the pump house casing limitation experienced at Dana Point and the inability to fully develop the well, the MPWSP test slant well included a larger diameter pump house casing. The Monterey test slant well has an 18 in. pump house casing which can accommodate placement of large development pumps with capacities over 3,000 gpm. Properly developed wells constructed using corrosion resistant materials such as 2507 Super Duplex Stainless Steel minimize well deterioration due to corrosion and biofouling. As such, these design improvements result in less frequent well rehabilitation with intervals estimated at between 3–5 yrs. Redevelopment will include the use of a high capacity air lift/swab assembly as part of the on-going maintenance process.

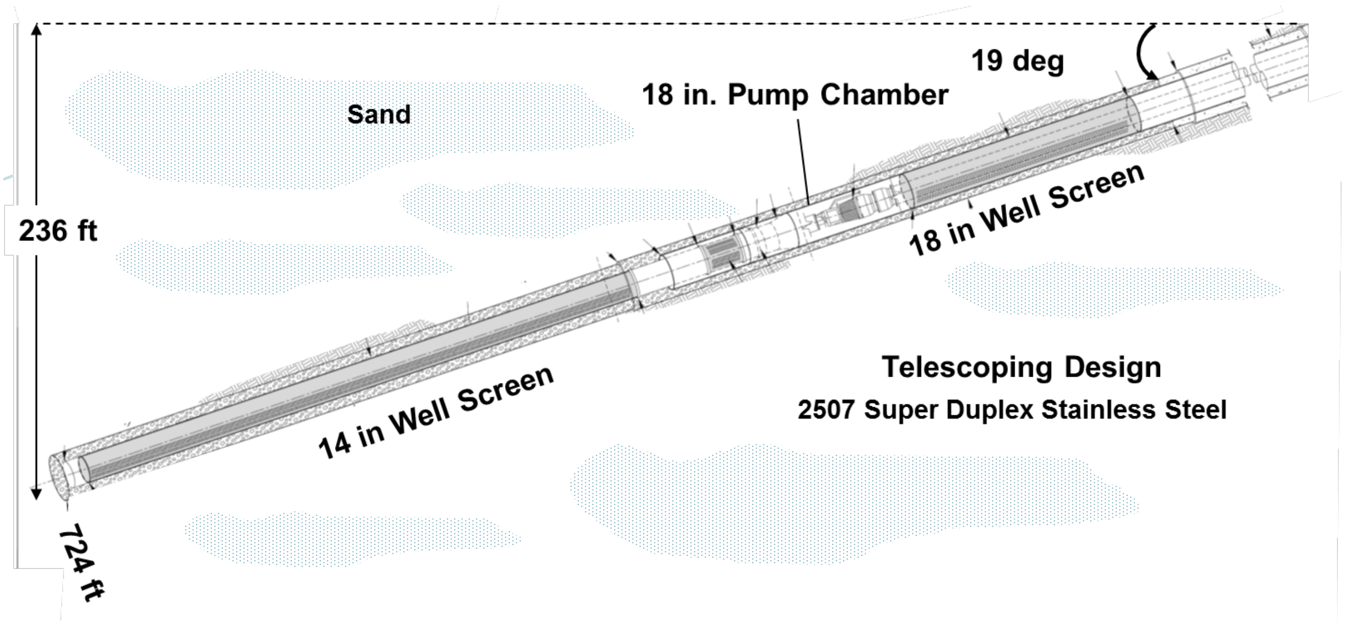

Figure 4. Telescoping design showing larger pump house casing used in the Monterey test slant well

2.3 Pumping Out Old Marine Ground Water

Geochemical tracers used to quantify water sources to the Doheny test slant well during an almost two year pumping test from 2010-2012 were used to estimate slant well connectivity to the ocean and relevant amounts of water sources (Charette, 2012). Testing found that old marine ground water is slightly acidic, anoxic, and enriched with dissolved iron and manganese. Dissolved iron and manganese concentrations increased in the pumped water to a peak of 11 milligrams per liter (mg/L) and 5 mg/L by the end of the test. It was estimated that the concentration of dissolved iron in the old marine ground water exceeds 41 mg/L. These results support the increased capture of shallow, young marine ground water. Natural isotope data showed after one year of pumping, recharge to the slant well consisted of a mixture of brackish ground water (which showed a decreasing trend), ocean water (which showed an increasing trend), and old marine ground water which initially increased and then slightly decreased as it was being removed from the aquifer. This reflected the fresh/salt interface being induced to migrate toward the well. The geochemical data combined with a three-dimensional variable density flow and solute transport model predicted that the old marine ground water would be fully removed from the subsea aquifer within approximately one year at the full scale production rate (30 mgd). Furthermore, upon reaching steady state conditions, (approximately one year), and after removal of the old marine ground water, the source of water to the feed water supply wells was predicted to consist of 95% “younger” ocean water (with very low levels of dissolved iron/manganese, ~ 2 µg/l), and 5% brackish ground water (~2 mg/l of dissolved iron/manganese), resulting in a blended concentration of approximately 0.10 mg/l. Results from the Doheny project suggest that the project may be constructed in two stages:

1- Initial Stage: Well field, conveyance and disposal system to pump out old marine ground water[6],
2- Final Stage: Construction of the project once the feed water quality is known.

Comparison of iron and manganese results from the Doheny test slant well and the current Monterey test slant well shows that the old marine water present in the Dana Point area is not found in the Monterey area. Iron and manganese concentrations from the MPWSP test slant well are very low suggesting that the subsea environment containing old marine ground water may not be present in coastal aquifers (such as Monterey), and may only be associated only with subsea paleochannels such as the Dana Point area.

III. SLANT WELL HYDRAULICS

3.1 Universal Drawdown Equation (UDE)

Development of an equation to calculate the drawdown distribution in the vicinity of angled wells was developed out of the necessity to understand water level distributions in the vicinity of angled wells without having to develop a distributed parameter ground water flow model. Conventional drawdown equations for vertical or horizontal wells are inadequate to properly describe the drawdown distribution in the vicinity of slant wells. Williams (2013) used the principle of superposition combined with standard well hydraulics to develop universal drawdown equations (UDE) which calculate the drawdown distribution in the vicinity of angled production wells with inclination angles ranging from 0 degrees (horizontal wells), to 90 degrees (vertical wells). The method is computationally simple and,

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[6] During this phase, pilot plant testing would be undertaken to finalize feed water quality for treatment process design.

other than the normal assumptions for standard well equations, only requires that the calculated drawdown represent the drawdown which would be measured in a fully penetrating observation well. Solutions using the UDE are developed for confined, unconfined and semi-confined (leaky) aquifers. Figures 5 and 6 below illustrate the variables used in the UDE and their notations.

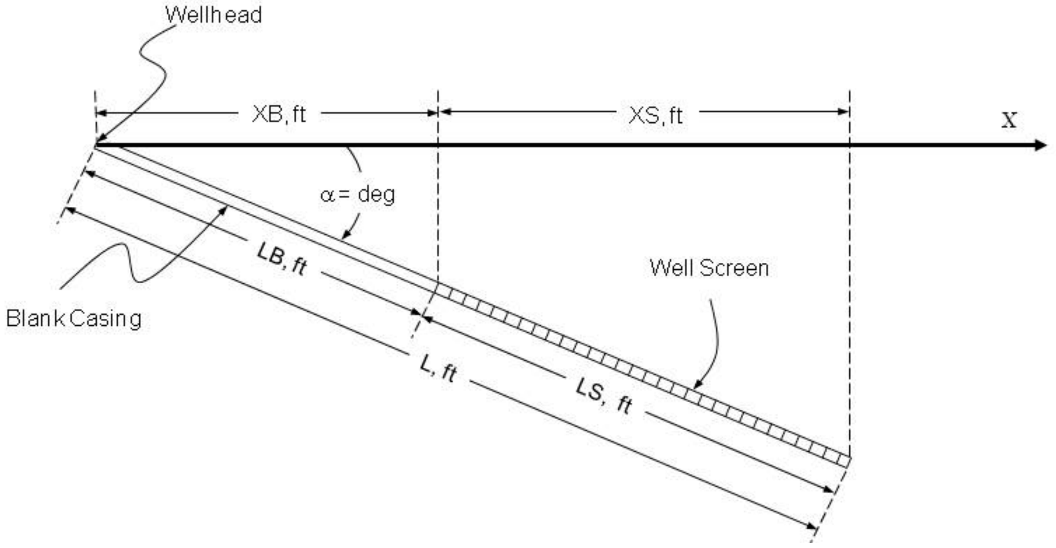

Figure 5. Cross section of an angled well showing notation used in the UDE

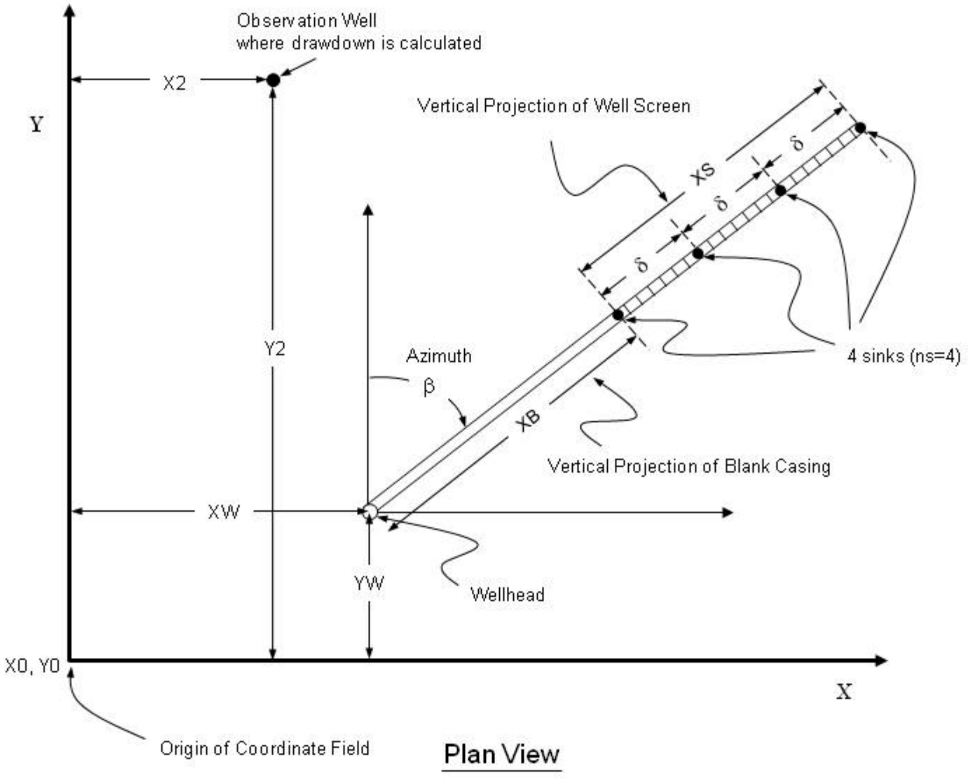

Figure 6. Plan view of angled well and notations used in the UDE

The following equation calculates the drawdown distribution around an angled well for a confined aquifer using Jacob's equation (Williams, 2013):

$$s = (264\ Q/T)\ [\ \log (0.3Tt/S) - (2/ns) \log (RP_1 \times RP_2 \times RP_3 \times \ldots RP_{ns})\ ] \tag{1}$$

where:

s = drawdown, ft
Q = well discharge rate, gpm
T = aquifer transmissivity, gpd/ft
S = aquifer storativity, fraction
t = time since pumping started, days
ns = number of sinks in the vertical projection of the well screen
RP_i = horizontal distance from point where drawdown is desired to the "ith" sink, ft

3.2 Slant Wells Completed Beneath the Ocean

The drawdown solution in the vicinity of a slant well completed in subsea aquifers behaves exactly like a leaky artesian aquifer. The benthic zone (i.e., the zone of the sea floor and a few feet below), is generally a lower permeability zone than underlying subsea aquifers and behaves as a semi-pervious layer. This semi-pervious layer (i.e., leaky layer) has a vertical hydraulic conductivity of K' and a thickness of b' consistent with the leakance term of K'/b' as defined by Hantush (1964). Thus, the UDE concept of superposition may be applied to subsea leaky aquifers using the Hantush-Jacob leaky aquifer equation (Hantush, 1955). Figure 7 illustrates the concept of sea-floor leakage.

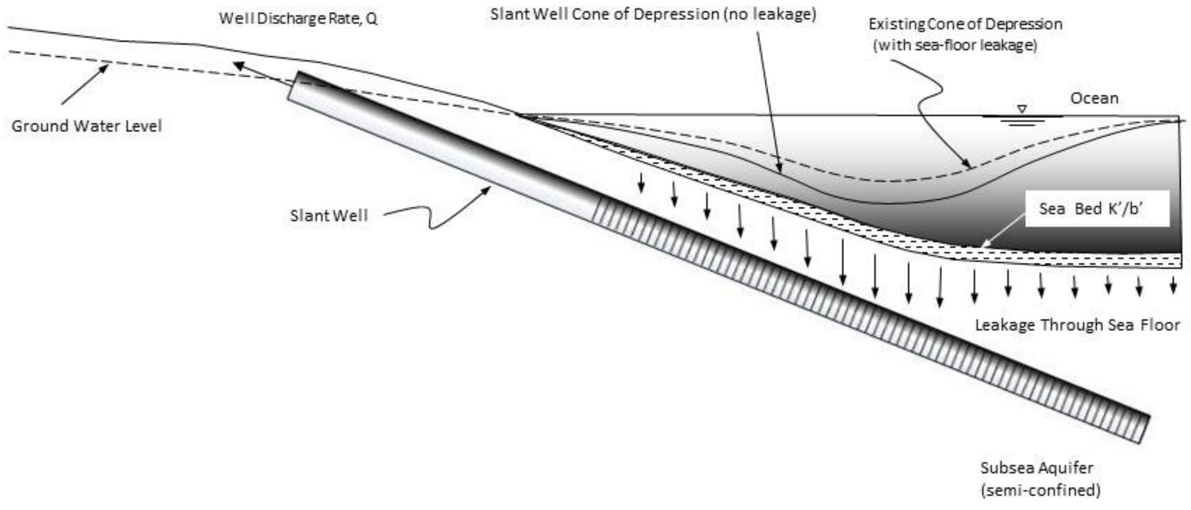

Figure 7. Induced infiltration to slant wells from vertical leakage through the sea floor

3.3 Slant Well and Vertical Well Production Comparison.

The cone of depression in the vicinity of production wells is a function of aquifer hydraulic properties, discharge rate, and time since the start of pumping. Vertical wells have a concentric cone of depression with the highest drawdown being in the vicinity of the well and declining outward. In angled wells, the cone of depression is ellipsoidal and the drawdown distribution “bowl “shaped centered around the vertical projection of the well screen. As such, for the same aquifers, slant wells produce more water than vertical wells for the drawdown available above the top of the well screen. Specifically, in slant wells, the formation loss (i.e., drawdown in the aquifer), is “spread out” over the vertical projection of the well screen length. In vertical wells, it is concentrated in a logarithmic cone centered on a point. Mathematical support for this statement can be seen by comparing the non-steady state equation in a confined aquifer for a vertical well (i.e., Jacob’s equation), with that of an angled well (UDE-Jacob – see eq. 6 in Williams, 2013 with ns=4). When the discharge rate is varied in both cases (vertical and slant), and limiting the maximum drawdown to the top of the well screen, slant wells have discharge rates approximately 1.5 to 2 times greater than vertical wells[7].

$$Q2 / Q1 = \log (B) / [\log(B) - 0.5 \log (XS^4 / 144)] \tag{2}$$

where: $Q1$ = vertical well discharge rate, gpm
$Q2$ = slant well discharge rate, gpm
B = $(0.3 \times T \times t) / S$, ft^2
T = transmissivity, gpd/ft
S = storativity
t = time, days
XS = vertical projection of slant well screen, $LS \times \cos(\alpha)$, ft
α = slant well angle, degrees below horizontal

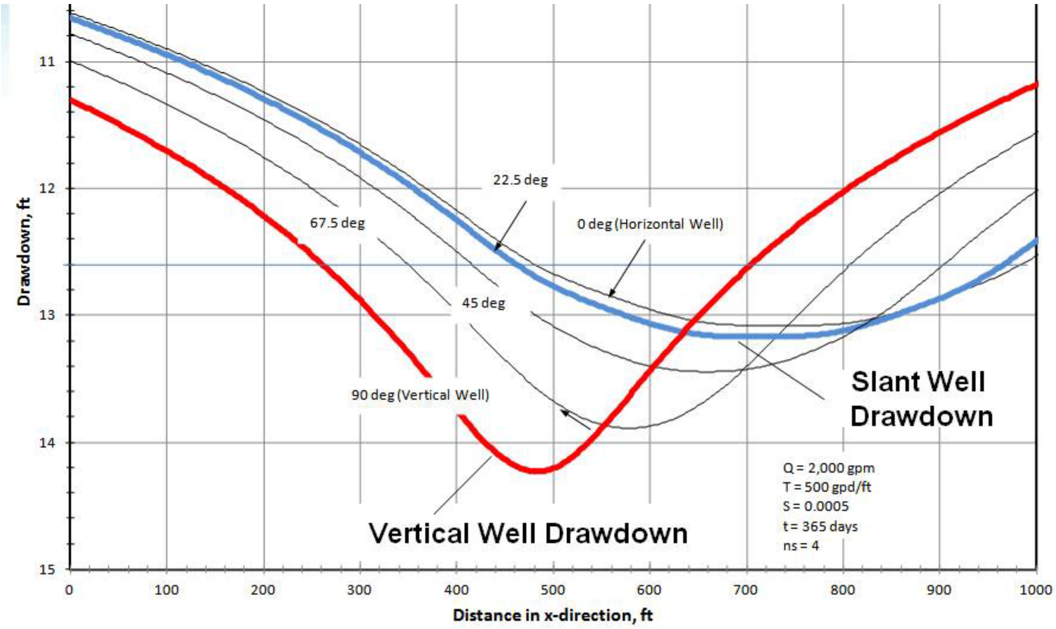

Figure 8. Vertical Well and Slant Well Drawdown Comparisons

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[7] Comparisons are for the same drawdowns and a typical range of aquifer parameters and slant well angles. Also, this comparison is for the laminar flow loss component of the total drawdown only.

3.4 Large-Scale Well Field Hydraulics (UDEM)

An extension of the principle of superposition used to calculate the drawdown distribution around nonvertical wells (Williams, 2013), is presented here to calculate the drawdown distribution around multiple slant wells. The UDEM stands for *Universal Drawdown Equation for Multiple Wells* and is merely a calculational algorithm used to develop regional drawdowns around multiple slant wells and slant well fields. The UDEM calculates the drawdown distribution in the vicinity of multiple slant wells by algebraically adding drawdown distributions from individual wells over a finite difference grid network. The UDEM is useful in the initial planning and layout of slant wells and well pod spacings as well as a first approximation to potential impacts to sensitive habitat and inland ground water resources. As the UDEM obeys the basic assumptions of the underlying equations, regional boundary conditions need to be included by further refinement using a formal three dimensional ground water flow model and solute transport model.

3.4.1. Leaky Aquifer Approximation

As slant wells producing from subsea aquifers receive vertical leakage through the sea floor as well as lateral recharge, to properly simulate drawdown effects, the UDEM calculates drawdowns using the Hantush-Jacob leaky aquifer equation (Hantush, 1955). However, when calculating drawdowns for a large number of slant wells with multiple sinks over a large grid network, the calculation may be quite laborious and time consuming due to the approximation of the leaky aquifer well function. This was overcome by using a site specific relationship between the non leaky and leaky aquifer solutions. Specifically:

$$\Delta = a \text{ x } \exp(b \text{ x } r) \tag{3}$$

where:

Δ = non leaky aquifer drawdown - leaky aquifer drawdown, ft
a, b = constants from best fit equation
exp(x) = the exponential function, also denoted as e^x
e = base of the natural logarithm (e = 2.718)
r = distance from pumping well (or sink), ft

For most problems of practical interest, the exponential relationship between Δ and r yields excellent correlation.

IV. UPWARD SCALABILITY OF SLANT WELL FEEDWATER SUPPLIES

4.1 Siting, Permitting, Access and Maintenance

Large scale slant well feed water supplies need a number of permits including land acquisition and access which are dependent upon environmental and operational factors, which if not complied with, could prohibit the project altogether. For example, many of these projects are limited to a maximum percentage of slant well recharge derived from inland water supplies (i.e., basin water vs. ocean water recharge). If this percentage is exceeded, expensive mitigation or provision of supplemental supplies may be required, adding to the overall cost of the project. Other factors affecting wellhead placement may include setbacks due to coastal erosion, a 100-year flood event, sea level rise and proximity to sensitive habitat (CCC, 2003; OPC, 2011 and 2013). Each slant well location should also consider well construction footprints and access to the drilling site and equipment staging area (during construction and routine maintenance).

4.2 Environmental concerns

Environmental factors during construction and operation are primarily concerned with adverse impacts to the natural environment (e.g., sensitive ecological or environmental areas inhabited by a particular species of animal, plant, or other type of organism). In areas of sensitive vegetation, fish habitat or other wildlife, well drawdowns (i.e., ground water level changes), from pumping may restrict placement or hinder construction and maintenance. Other environmental impacts may include visual impacts of facilities during construction or after completion, such as unsightly facilities on the beach or in near shore areas where recreational or other high uses occur.

4.3 Common Wellhead Areas

To minimize unnecessary infrastructure in conveying feed water to the desalination plant site, multiple slant wells can be constructed in close proximity to one another (i.e., common wellhead area or slant well “pod”). The common wellhead areas also minimize disturbance and access during both construction and routine maintenance.

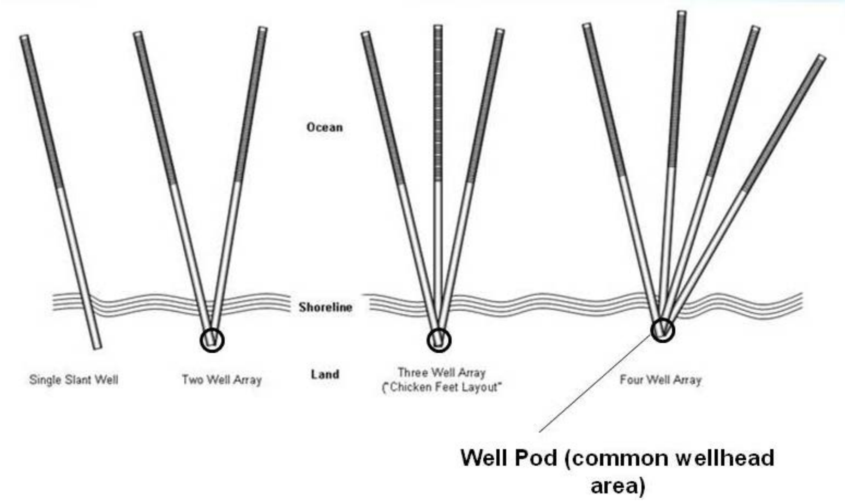

Figure 9. Multiple slant wells from common wellhead areas

4.4 Seawater Intrusion Control

Wells pumping at the coast or from subsea aquifers beneath the ocean floor do not contribute to seawater intrusion. On the contrary, slant wells help prevent seawater intrusion through creation of an extraction trough that intercepts seawater as shown on Figure 10. Modeling studies of full scale slant well projects in California (e.g., Dana Point, Monterey, Cambria, and San Diego) show that the slant well pumping trough acts as a seawater intrusion control mechanism.

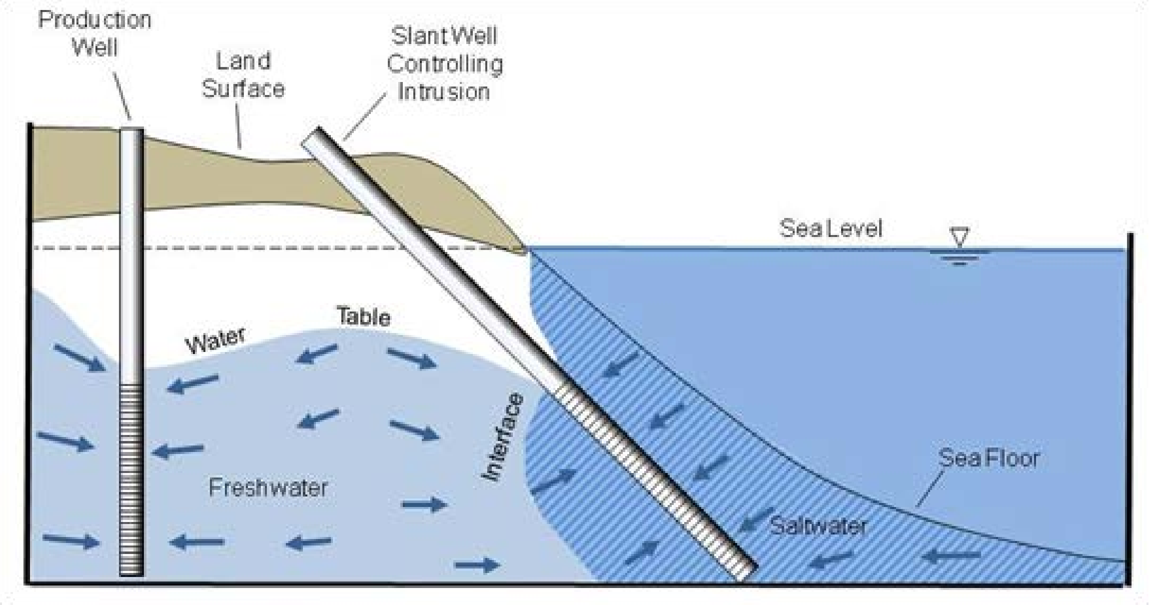

Figure 10. Slant Wells Intercepting Seawater Providing Seawater Intrusion Control

4.5 Large Scale Feed Water Supplies - 78 mgd, 117 mgd, and 233 mgd

For typical California coastal aquifers, a feed water supply of nine slant well pods with each pod containing three 4 mgd slant wells can yield approximately 117 mgd from a two mile reach of coastline. The following interference drawdown plots were generated using the UDEM and field data from a site along the coast of California. The following parameters were used in the calculations:

Slant well length (L) = 1,000 ft
Length of well screen (LS) = 860 ft
Angle below horizontal α = 15 degrees
Transmissivity (Kb) = 246,000 gpd/ft
Storativity (S_s b) = 0.045
Saturated thickness(b) = 223 ft
Slant Well Discharge Rate (Q) = 3,000 gpm
Time since start of pumping (t) =365 days
Sea bed leakance (K’/b’) = 0.014/day
Number of sinks per slant well (ns) = 4
Number of wells per pod = 3

Figures 11, 12 and 13 illustrate the concept of modular addition of slant well pods to achieve a feed water production of 78 mgd, 117 mgd, and 233 mgd respectively.

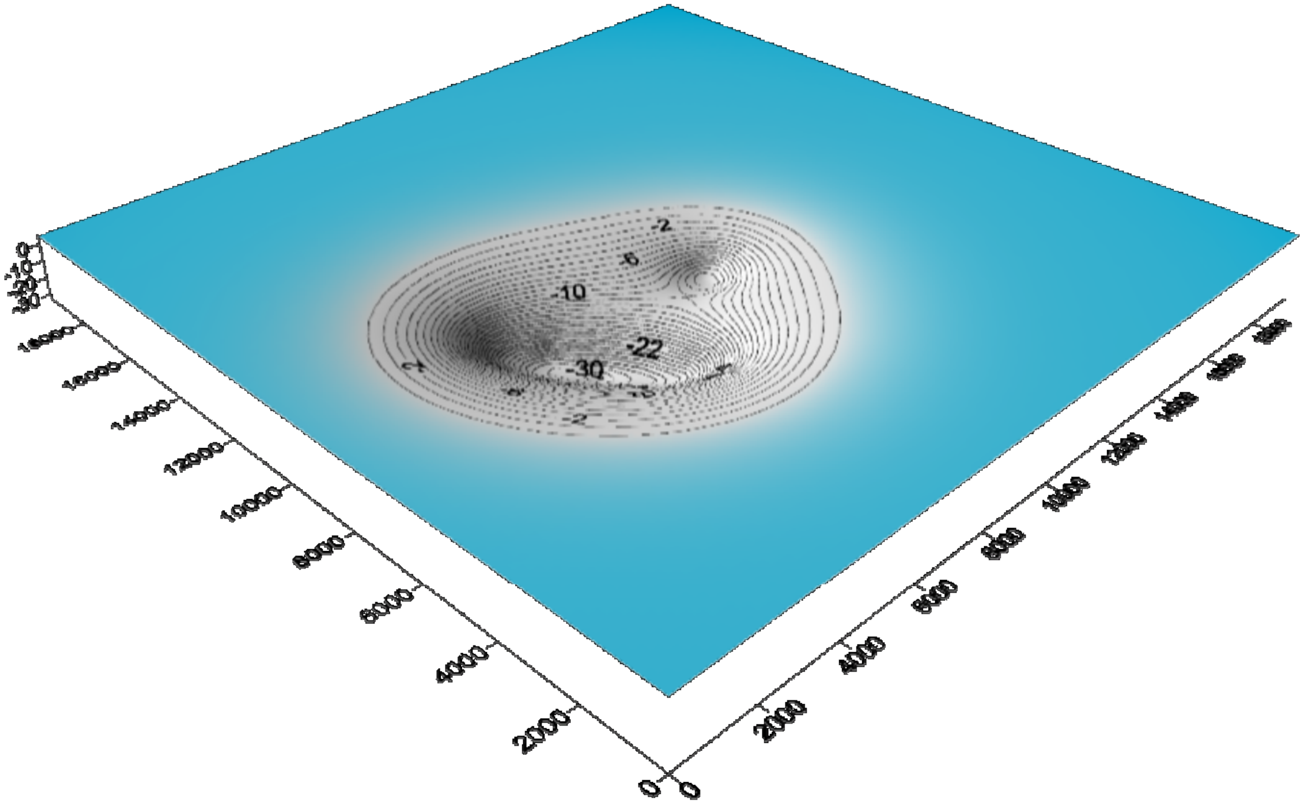

Figure 11. 78 mgd SWRO slant well feed water supply. Six slant well pods and 18 wells. Drawdown distribution in Subsea Aquifers, ft.

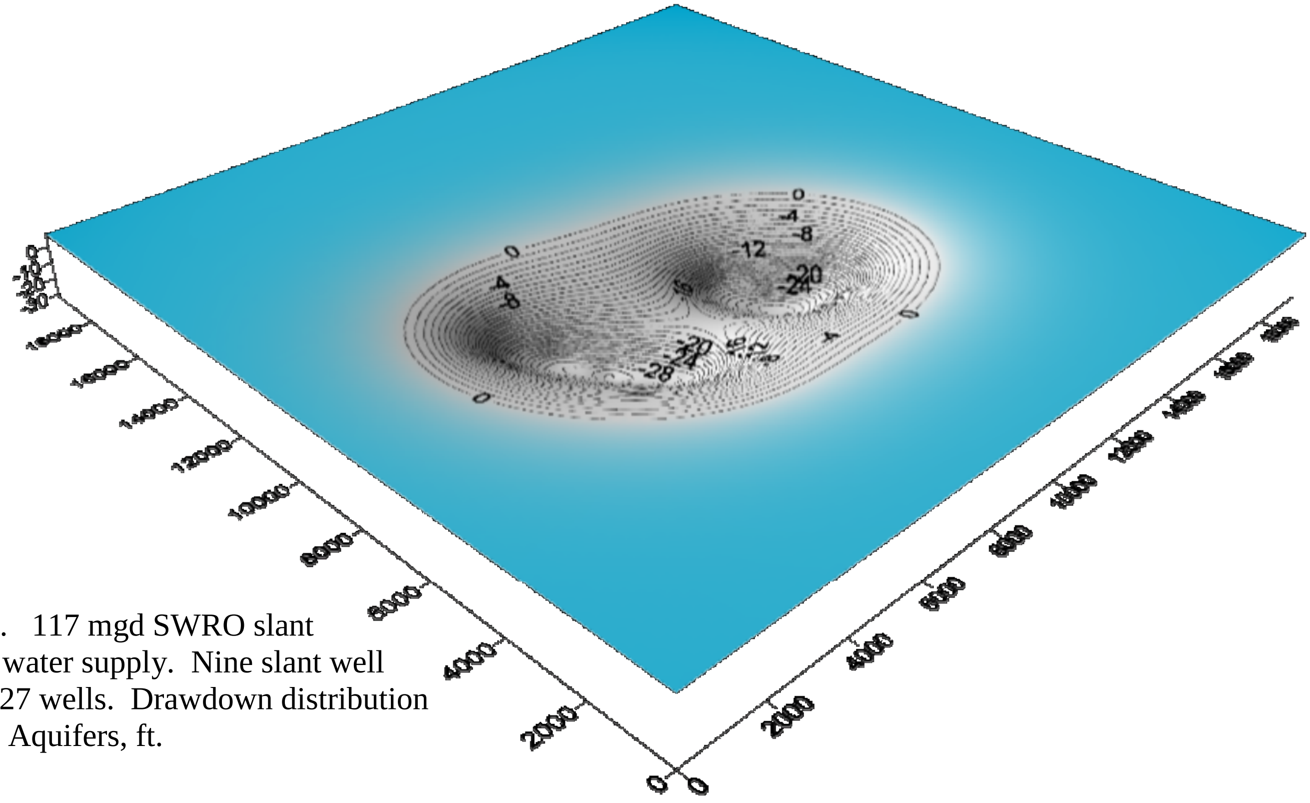

Figure 12. 117 mgd SWRO slant well feed water supply. Nine slant well pods and 27 wells. Drawdown distribution in Subsea Aquifers, ft.

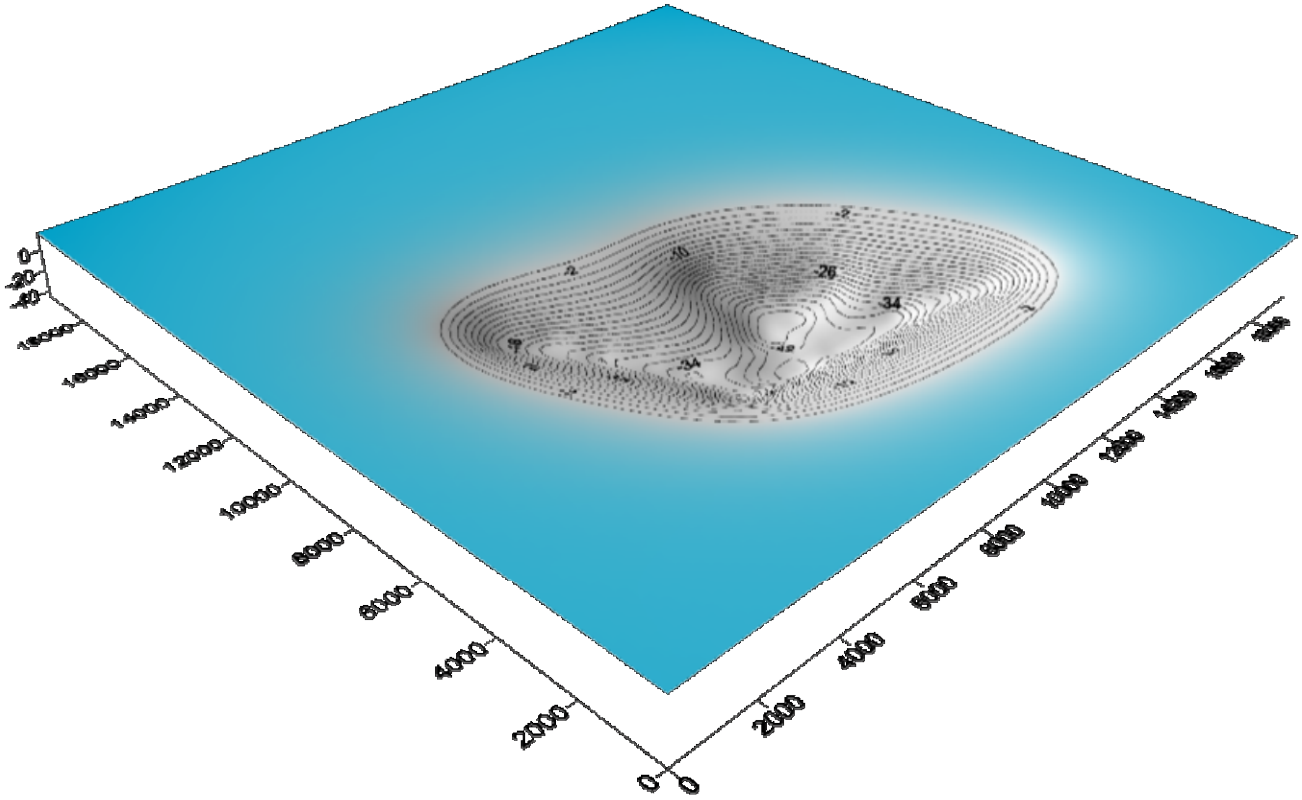

Figure 13. 233 mgd SWRO slant well feed water supply. Eighteen slant well pods and 54 wells. Drawdown distribution in Subsea Aquifers, ft.

V. SUSTAINABILITY OF SUPPLY

In order to maintain feed water production, planned rehabilitation of a slant well subsurface supply will periodically be necessary. All wells (vertical and angled), need redevelopment from time to time to maintain performance. This periodic redevelopment typically consists of mechanical and/or chemical redevelopment using the same “tried and true” methods developed in the water well industry for vertical wells over the past 70 yrs. As access to the wellhead area is required, provision must be made during siting to minimize disturbance during routine maintenance. This is especially important if the well is sited in an environmentally sensitive area, or in areas where recreation or other high uses exist (e.g., on a State Beach). The frequency between rehabilitation depends on both site-specific conditions and operational schedules. However, it is generally expected to range between approximately three to five years for properly constructed and developed slant wells with corrosion resistant casing and screen.

5.1 Maintaining Well Efficiency

In order to maintain feed water production, planned rehabilitation should be performed when the well efficiency shows an unacceptable decline. Well efficiency is defined as:

$$E = (BQ / s_w) \text{ x } 100 \qquad (4)$$

where:

E = well efficiency, %
B = formation loss coefficient, gpm/ft
Q = well discharge rate, gpm
s_w = drawdown in the pumping well, ft

The formation loss coefficient and well efficiency can be calculated from variable rate pumping tests (i.e., step drawdown tests - Roscoe Moss, 1990) which is a straight-forward procedure involving at least three different discharge rates. Periodically, step drawdown testing can be performed, efficiency calculated and comparisons made against historical values.

As a general rule, when well efficiencies decline to 50% of the maximum value (at the design production rate), it is a good idea to take the well out of service and perform a video inspection and a rehabilitation plan. Based on limited data from the Doheny test slant well, it is expected that in wells properly designed, developed and consisting of corrosion resistant steels, the frequency between well rehabilitation would be on the order of three to five years. However, depending on other constituents in the ground water (e.g., iron and manganese), rehabilitation frequency may vary.

VI. MONTEREY PENINSULA WATER SUPPLY PROJECT

Slant wells are drilled using the dual-rotary method of drilling with angles below horizontal typically ranging from 10 degrees to 30 degrees. A telescoping well design allows construction of slant wells up to 1,000 ft or more with an artificial filter pack typically yielding 3-4 mgd/well. In the Monterey area north of the town of Marina, a 724 ft long test slant well 19 degrees below horizontal has recently been constructed as the first phase of testing of the MPWSP. Prior to construction of the test slant well, a number of exploratory borings were made to define the near-shore aquifers. The test slant well is currently pumping 3 mgd and is being monitored daily for coastal and inland water level and salinity impacts. The full scale feed water supply of 24 mgd will be met using an array of ten slant wells including standby capability. Slant well angles can vary depending on site conditions to allow targeting specific aquifer thicknesses. In the case of the Monterey area, aquifers being tested include the shallow Dune Sand and the deeper 180-FTE aquifers. Field testing has validated theoretical analysis and show that shallow angled slant wells have higher discharge rates than vertical wells for the same aquifer thickness due to their increased aquifer efficiency (i.e., broader cones of depression than vertical wells). Data from the long term testing is being used to refine a three dimensional variable density ground water flow and solute transport model which is being used to predict coastal and inland impacts from the full scale project.

VII. SUMMARY

- There is a current misconception that subsurface intakes using slant wells are limited to small scale facilities typically less than 3 mgd. Research and field testing over the past nine years have shown that in typical coastal aquifers in California, slant well feed water supplies can provide approximately 50 mgd of feed water supply per mile of coastline.

- Maximum yield of slant well intakes for SWRO feed water supplies is only limited by the availability of coastline and potential adverse impacts to riparian and onshore resources.

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- With improved drilling technology and telescopic designs, slant well lengths can reach and exceed 1,000 ft with individual well yields of 4 mgd and greater.

- Since the first SWRO slant well was constructed off the coast of Dana Point, California in 2006, continuing research and field testing has led to larger scale systems currently in the planning and testing stage. A 724 ft test slant well is currently under construction off the coast of Monterey as part of the first phase of the Monterey Peninsula Water Supply Project.

- Comparison of results from the Doheny test slant well pumping test and the current Monterey test slant well pumping shows that the old marine water present in the Dana Point area is absent in the Monterey area. This suggests that widespread subsea coastal aquifers such as present in the Monterey area do not have the same conditions as subsea paleochannels.

- Permitting is the number one constraint to development of subsurface feed water supplies.

- Coastal erosion, 100-yr floods and sea level rise must be considered in the siting and layout of slant well feed water supply systems.

- The Dual Rotary drilling method is a proven technology for construction of artificially filter packed slant wells under the ocean.

- Telescoping slant well design allows for larger pump house casings, proper development and yields of 4 mgd and more per well.

- Slant wells typically produce over 95% of their supply from ocean water sources (vertical leakage through the sea floor) and lateral flow from subsea aquifers.

- Regular maintenance on the order of every three to five years may be necessary to maintain slant well feed water supply production. Well efficiency declines can be monitored from routine step drawdown testing.

- Slant well maintenance is not complex nor is it more difficult than what is required for conventional vertical wells and typically includes mechanical and chemical rehabilitation.

- The drawdown distribution in the vicinity slant wells is the algebraic sum of drawdowns for a finite number of point sinks distributed along the vertical projection of the well screen.

- Simplified solutions for the drawdown distribution in the vicinity of slant wells and slant well fields can be developed using the UDEM.

- Variable density ground water flow and geochemical models can provide estimates of the time to pump out old marine ground water that is enriched with dissolved iron/manganese and estimate steady state water quality conditions.

- Due to slant well geometry, slant wells produce 1.5 to 2 times as much flow as vertical wells for the same available drawdown.

- Silt density indices, one of the major design parameters in desalination feed water supply, are typically < 1 for properly designed and constructed slant wells Williams.

- Coupon testing in a seawater environment show materials such as 2507 Super Duplex Stainless Steel provide long life and minimal corrosion for slant well casing and screens.

- Pumping troughs created by large scale slant well feed water intercept seawater providing seawater intrusion control.

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